AN AGENT-BASED MODEL FOR THE WATER ALLOCATION AND MANAGEMENT OF HYDRAULIC FRACTURING

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ABSTRACT

An agent-based model (ABM) is developed to simulate the impacts on streamflow and groundwater levels by the dramatic increase of hydraulic fracturing (HF) water use. To develop the agent-based model, institution theory is used to model the regulation policies, while evolutionary programming allows agents to select appropriate strategies when applying for potential water use permits. Cognitive maps endow agents' ability and willingness to compete for more water sales. All agents have their influence boundaries that restrict their competitive behavior toward their neighbors but not to non-neighboring agents. The decision-making process is constructed and parameterized with both quantitative and qualitative information. By linking institution theory, evolutionary programming, and cognitive maps, our approach is a new exploration of modeling the dynamics of coupled human-natural systems (CHNS) to address the high complexity of the decision-making process involved in the CHNS. The ABM is calibrated with HF water-use data, and the calibration results show that it is reliable in simulating water depot number, depot locations, and depot water uses. The SWAT (Soil and Water Assessment Tool) model of the Little Muddy River basin and the MODFLOW of the Fox Hill-Hell Creek regional aquifer are coupled with the ABM to simulate the changes in streamflow and groundwater level, respectively, under different scenarios such as HF water demand, climate, and regulatory policies. The integrated modeling framework of ABM, SWAT, and MODFLOW can be used to support making scientifically sound policies in water allocation and management for hydraulic fracturing.

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DEDICATION

This dissertation work is dedicated to my family.

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1. INTRODUCTION

1.1. Background

Unconventional oil and gas production using hydraulic fracturing (HF) and horizontal drilling techniques has greatly increased since 2008. From 2008 to 2014, U.S. monthly crude oil production rose by 3.2 million barrels per day, with about 85% of the increase coming from shale and other tight oil formations in Texas and North Dakota (Ratner, 2015). The low permeability of these shales requires HF to use large volumes of pressurized water to crack the rocks. For instance, the average water use in the Bakken shale is around 2.0×10^6 gals/well (Scanlon, 2014). The rapid expansion of unconventional oil and gas extraction and the cumulative water needs of HF have raised concerns in water management in local areas.

Western North Dakota is a region experiencing a dramatic increase in water demand by the Bakken shale oil production. Since 2004 when the first horizontal well was drilled in the Bakken shale, about 10,000 horizontal wells had been drilled from 2004 to 2014. The total estimated annual freshwater requirements for the Bakken shale are about 13,000 to 23,000 acre-feet per year (Schuh, 2010). The accessible freshwater sources in western North Dakota for HF include surface waters and groundwater aquifers, but the water is not equally available at all locations. Surface water sources in North Dakota consist of rivers, lakes, potholes, and wetlands. However, wetlands, potholes, and freestanding lakes do not provide viable sources for large-scale dependable water supplies. North Dakota major rivers and their tributaries carry 98.4% of the surface water leaving the state (Ripley 1990). Most of the state's surface waters except the Missouri River system are heavily appropriated for their normal (yearly-round) flows and are not good prospects for large-scale long-term sustainable water supplies. Most of the state's aquifers are also nearly or fully appropriated and are unavailable for additional future allocations.

In much of western North Dakota, the Fox Hills - Hell Creek (FH-HC) aquifer is the only groundwater source capable of producing large amounts of freshwater. Historically it has provided a new source of water for many municipal, domestic, livestock, and industrial users in local areas (Fisher, 2013). In valleys along the Yellowstone, Little Missouri, and Knife rivers, the potentiometric surface of the FH-HC aquifer is above the land surface, generating flowing head wells. These flowing wells are easily accessible water resources because they can be installed without the need for electricity for pumping. Many farms and ranches in rural North Dakota and Montana are dependent on flowing wells completed in the FH-HC aquifer.

However, the FH-HC aquifer pressure head is currently declining at an average rate of approximately one foot per year in western North Dakota because of excessive extraction of water (Fisher, 2013). The depth to the FH-HC aquifer ranges from land surface to approximately 2,000 feet below the land surface, and the recharge to this groundwater system is limited. Since the 1980s it has been the North Dakota State Water Commission's (NDSWC) policy to avoid the use of FH-HC for large-scale industrial use whenever possible. But, as the only reliable groundwater source in the region, FH-HC can become a major water supply when fierce water competition arises.

Increasing concerns about the future use of FH-HC groundwater have been raised when HF water demand started increasing in the Bakken region. A MODFLOW-2005 groundwater model for the FH-HC aquifer had been developed and calibrated by NDSWC hydrologists to gain a better understanding of the hydrogeology of the FH-HC aquifer (Fisher, 2013).

Water in North Dakota is stated as a public resource by the Constitution of the State of North Dakota. Any citizens with physical access to an aquifer or surface water in the state can apply to the Office of the State Engineer (OSE) for a water permit to put the water into beneficial uses (Schuh, 2010). The waters of the state are allocated for beneficial uses according to the doctrine of prior appropriations. In principle, water permits are granted based on a priority date, established by the date on which the completed application for a permit is received by the OSE. Water permit applications for the same water source filed within 90 days are considered as competing for water rights. When the water supply is insufficient to supply all applicants, it will be given preference by the order of use priority: (1) domestic, (2) municipal, (3) livestock, (4) irrigation, (5) industrial, and (6) recreation. Water permit applications are processed by the hydrologists of NDSWC's Water Appropriation Division. The application process normally takes months to years to complete so that the industrial users (oil production companies) usually buy water for HF-related operations from the water depots in western North Dakota (Kusnetz, 2012; Scheyder, 2013).

A water depot in western North Dakota is a business that mainly sells water to oil companies for hydraulic fracturing and occasionally to agricultural service companies for fertilizer and pesticide/herbicide mixing. The water depots are owned by individuals or institutions that have access to water resources with approved water permits. Between 1980 and 2007, the state issued just 10 water permits to water depots for irrigation water use. At the height of the oil boom, there were 254 water depots primarily serving at the Bakken shale in western North Dakota in 2014. Many private water depots also hold temporary water permits, meaning their permits will expire within 12 months. On the other hand, some water depot owners apply for conditional water permits, meaning their water permits may last for a longer time and guaranteed water rights. However, it takes much longer for the NDSWC hydrologists to review these applications. The owners normally will have to wait for several years to get their permits approved (Mike Hove, Personal Communication).

North Dakota state water laws do not allow automatic transfers of water permits from a higher use priority to a lower use priority. For example, a water permit owned by a farmer for irrigation (a higher use priority) cannot be used to sell water to the oil industry (a lower use priority) without formal authorization from the OSE. Since 2010, the OSE has developed a policy granting 12 months of temporary authorization for the holders of existing irrigation water permits to use water for industrial purposes (NDSWC, 2011). Besides, several local cities, e.g. Williston, had also built water depots to sell excess municipal water to increase the city's revenue (Kusnetz, 2012). Furthermore, a government-backed cooperative, the Western Area Water Supply Project (WAWSP) decided to sell 20 percent of its water to the oil industry to help keep water prices low and pay back project loans. The WAWSP was originally designed to deliver high-quality drinking water to the residents of western North Dakota. The WAWSP currently has 15 water depots in the area and is planning to build more water depots throughout the Bakken region.

1.2. Objectives

Effective water management planning or policymaking needs to be informed by an understanding of how individual water users make decisions, and how their decisions may affect and be affected by the environment. To address the growing concerns about the water competition in the Bakken region of western North Dakota and to support making scientifically sound policies in water allocation and management for hydraulic fracturing, this study aims at achieving the following objectives:

1) To explore different behavior theories in developing an agent-based model of simulating the dynamics of the water depot-based water allocations system;

2) To apply the agent-based model in the Bakken area of western North Dakota by calibrating the model against real-world hydraulic fracturing water use data and conducting sensitivity analysis for model parameters; and
3) To integrate the agent-based model with the SWAT model, and groundwater model to simulate the streamflow and groundwater level changes under different scenarios, and to make policy recommendations to manage the water resource.

2. LITERATURE REVIEW

There was a growing concern about the HF water use in the Bakken region and water management in western North Dakota as North Dakota became the second oil-producing state in the U.S. since 2012. In western North Dakota, the industrial water use in the Bakken for unconventional oil development is exclusively allocated through water depots. In this case study, we plan to employ an agent-based modeling approach to understand the dynamics and emergent patterns of these water depots.

2.1. Agent-Based Modeling

An agent-based model (ABM) or individual-based model (IBM) consists of a set of elements (or agents), characterized by their attributes, which interact with each other through the definition of appropriate rules in a given environment (North, 2007). The purpose of agent-based modeling is to understand the properties of complex social systems through the analysis of simulation (Axelrod, 1997). At an aggregated level, the use of ABMs can help understand general properties and patterns concerning the whole scenario (Billari et al., 2006) that could not be deduced nor forecasted by the observation of each agent, due to the complexity of the interactions occurring among the elements of the system.

Traditional modeling approaches such as system dynamics, discrete-event simulation, optimization, statistical modeling, and risk analysis are developed to address specific types of problems. Each modeling approach is the best approach for the specific purpose for which it was originally intended. However, in developing a complicated model for a very complex system, it is often useful to combine one or more of these modeling approaches, employing each technique for that part of the model where it makes the most sense. Agent-based modeling is a modeling process that borrows much from traditional modeling approaches and it can be thought of as a more inclusive modeling approach than the traditional ones. In other words, agent-based modeling provides a framework, in which several modeling techniques can be combined for maximally effective modeling of a complex system (North, 2007).

For example, systems dynamics is useful for identifying the important variables and causal linkages in a system and for structuring many aspects of model development. ABMs can benefit by beginning with systematic identification and analysis of the important variables in the system and their causal relationships. Discrete-event simulation offers methods by taking a process view of the system, and it can be employed in developing a model for an agent. Optimization is a technique designed to model optimal individual and organizational decision-making. It has been commonly seen in ABMs that agents optimize their benefits on an individual basis or agents can be collectively used to search for optimal system states. Statistical modeling approaches will be useful when it is not realistic to develop a comprehensive agent model with clear causal factors and relationships. Simpler statistical modeling could also be used for effectively estimating behavioral decision rules for agents. For the connection between ABMs and risk analysis, then the risk could be a property of a system as a whole, an emergent property. Then a comprehensive system-wide assessment of the causal factors that lead to risk throughout the system needs to be addressed.

According to the definition of Wooldridge and Jennings (1995), an agent is a computational system interacting with an environment. An agent must have the following features: (1) independence, which means each agent acts without the direct control of human beings or other devices; (2) social ability, which means agents interact with each other to satisfy the designed objectives; (3) re-activeness, which means agents respond to signals coming from the environment; and (4) pro-activeness, which means agent take the initiative to satisfy their designed objectives.

According to Billari et al. (2006) and Weiss (1999), the development of an ABM needs a complete description of a set of basic building blocks. The first building block is the object, the problem to be solved by the ABM, which also defines the space where the simulation takes place. The second one is the agents' population. Agents can be grouped in different categories with common characteristics reproducing the various components of the system. The third basic building block is adaptive capability. Agents of each category should present a specific adaptive capability. The fourth one is the interaction paradigm among agents. Each agent can interact with agents of the same and other categories. In the literature, several interaction paradigms have been defined, such as cooperation, competition, and negotiation (Weiss, 1999), through which the agents evolve in the simulation space in different ways. Especially, agent-based modeling has been broadly used in coupled human-nature systems (CHANS). An et al. (2012) summarized and categorized nine types of decision models based on ABM. These decision models include microeconomic models, space theory-based models, psychosocial and cognitive models, institution-based models, experience- or preference-based decision models (rules of thumb), participatory agent-based modeling, empirical- or heuristic rules, and evolutionary programming, and assumption and/or calibration-based rules.

2.2. Modeling Agent's Behaviors

The core of developing an agent-based model is to model the agent's behaviors in ways that produce realistic and useful system behavior. There are many ways to model the behaviors of different kinds of agents – people, organizations of people, animals, plants, etc. Different fields of science adopt different approaches to modeling agent behavior (Railsback, 2010). For instance, in the fields of behavioral economics and behavioral finance, researchers are trying to figure out how people make decisions that are often represented in ABMs. The literature shows that people often make complex decisions in uncertain contexts via simple rules that usually produce good, but not optimal, results (North,2007).

2.2.1. Discovering Agent Behaviors

To develop realistic agent behaviors, knowledge engineering is commonly used to discover agent behaviors by collecting related information about agents. Knowledge engineering is a collection of techniques for eliciting and organizing the knowledge of experts while accounting for reporting errors and situational biases (Wilson 1993). It originally arose from the study of expert systems in artificial intelligence (North, 2007). Knowledge engineering uses structured interviews to elicit information. The participants should be the experts who understand the various parts of the system to be modeled (North and Macal, 2007) or the real agents who are operating in the system. Limiting the number of participants is critical since it reduces wasted time and simplifies the flow of communication. Once a knowledge engineering session is completed, the results should be documented for later review.

As human behavior modeling is growing, knowledge engineering has seen its growth in the last two decades. The process was systematized in the 1990s and recently became highly structured because large amounts of data expert knowledge are available to be elicited (Bharathy, 2006).

2.2.2. Describing Agent Behaviors

Once agent behaviors are discovered, they can be described by sets of rules in an ABM that allow them to take in information, process the inputs, interact with and communicate with other agents as well as respond to their environment. These rules can provide agents with responsive capabilities at different levels from simple reactions to complex decision-making. Simple rules can also result in an emergent organization and complex behaviors (Macal and North, 2005).

Agent behaviors generally follow three steps. First, agents evaluate their current state and then determine what they need to do at the current moment. Second, agents execute the actions that they have chosen. Third, agents evaluate the results of their actions and adjust their rules based on the results from the previous actions (North, 2007).

In general, agent behavior rules can be divided into two levels. The first level is the base level of rules. This level of rules specifies how agents respond to routine events. The agents that only hold the first level rules are called “proto-agents”. The second level of rules contains “rules to change the base-level rules”. These second-level rules provide adaptation by allowing the routine responses to change over time. The agents with the second-level rules are called “full agents”. Both agents followed three steps.

2.2.3. Advanced Techniques for Agent Behavior Description

Rules are sometimes not sufficient to represent agent behaviors. In this case, advanced techniques can be combined with rules to model agent behaviors. These advanced techniques include statistical techniques, artificial intelligence methods, evolutionary, and optimization methods (North, 2007).

Statistical methods are normally used within agents to do forecasting. McClave (1994) built market agents using linear regression to forecast the market prices based on the ratio of demand to supply predicted by the market clearinghouse. Artificial intelligence methods include logic programming, neural networks, advanced search techniques, distributed problem solving, and no monotonic reasoning.

Agents may “evolve” their mathematical traits to reproduce observed patterns of individual and system-level behaviors (e.g., Strand et al. 2002). In the agent-based models, techniques based on biological evolution can eventually produce traits that are successful at overcoming challenges imposed onto the agents (Mitchell 1998). Individual agents with successful traits will survive, reproduce, and pass on their traits. Optimization methods are used within agent behavior rules to find the “best” value among a large number of possible values. Optimization methods could be categorized into algorithms (Baase 1988) and heuristics (Ginsberg 1993).

In the case study for Wolong Nature Reserve in China, a person agent may consider marriage at the age of 22, the minimum age for marriage legally mandated in China (An et al.,2005). In the human-environment integrated land assessment model that simulates households’ land-use decisions in southern Yucatan (Manson and Evans, 2007), the household agents could not perform their production activities outside their units or sell land to outsiders because of the neoliberal policy. Conforming to policies from local governments, the pastoralist enterprises in Australian rangelands adopt different strategies (Gross et al.,2006). In the simulation model of whale-watching tours in the St.Lawrence Estuary in Quebec, Canada, boat agents are required by regulation to share whale location information among other agents(Anwar et al., 2007). Buyer and seller agents have to set minimum parcel size subject to local policy and regulation, in the process of seeking maximum economic profits (Lei et al.,2005). In these case studies, institution theory is used to simulate the part of agents’ behaviors guided by government regulation.

Holland (1975) was the first to use evolutionary programming for the characterization of agents and their decision-making. Since then, evolutionary programming and genetic algorithms have had plenty of applications in ecological or biological studies (Bousquet and Le Page, 2004) and also social organizations (Epstein and Axtell, 1996). In the field of coupled human and nature systems, few but increasing applications merged. Manson (2005) explored evolutionary programming in developing a human-environment integrated land assessment (HELIA) model that simulates households' land-use decisions in southern Yucatan. In this model, household agents use evolutionary programming to search for a suitable location on the simulated landscape for activities such as clearing forests and planting crops. Each agent creates plenty of parental strategies and these strategies go through multi-step evaluation processes (Manson, 2006). During the estimation process, multiple parental land-use strategies compete and evolve to produce offspring strategies through imitating interbreeding, and mutation (Manson, 2005). Through the genetic and evolutionary programming process, the output strategies are found to be consistent with those obtained from local interviews (Manson and Evans, 2007). This consistency increases the reliability of the evolutionary programming methods, and evolutionary programming and genetic algorithms can be a good choice for simulating water depot agents' behaviors of location selection.

Decision-making theories are broadly classified into normative and descriptive perspectives. Classical normative decision theories articulate how people make rational decisions (Simon, 1990). Descriptive decision theories describe how people make decisions under inevitable limitations, such as information, cognitive factors, and activity boundary. Cognitive mapping is a descriptive theory to structure an individual's mental model in decision making. The term "cognitive map" goes back to Tolman (1948), who first used it to describe the mental construct that humans and animals use to search for alternative pathways. Axelrod (1976) was the first to use cognitive mapping as a method to understand decision-making. After that, cognitive mapping has been applied in many areas related to decision making, such as natural resource management (Kolkman and Van der Veen, 2005), strategic management (Eden and Ackermann, 1998), and marketing (Reynolds and Gutman, 2001). Kolkman (2005) used cognitive mapping as a tool to analyze the use of information in the decision-making process in integrated water management. Elsawah (2015) applied cognitive maps to represent how a group of irrigators make strategic and operational vineyard management decisions in a case study of viticulture irrigation in South Australia. The study shows cognitive mapping is useful for structuring complex decision-making processes, and it is suited for stakeholder engagement in policy-making progress.

The human decision or behavior models in related ABMs range from highly empirically-based ones (e.g., derived through trend extrapolation, regression analysis, expert knowledge-based systems, etc.) to more mechanistic or processes-based ones (e.g., econometric models, psychosocial models). It is clear that all approaches for modeling human decisions have their strengths and weaknesses and should be employed to best suit the corresponding contexts (e.g., objectives, budget, and time limitations) and complement each other.

2.3. Environment

The environment for an agent-based model is the virtual world in which the agents act. It may be an entirely neutral medium with little or no effect on the agents, or in other models, the environment may be as carefully crafted as the agents themselves. Commonly, environments represent geographical spaces, for example, in models concerning residential segregation, where the environment simulates some of the physical features of a city, and in models of international relations, where the environment maps states and nations (Cederman, 1997). Models in which the environment represents a geographical space are called spatially explicit. Space or environment can be represented continuously or represented “discretely” by cells or patches, usually on a square grid (Railsback et al, 2010). In other models, the environment is a space without representing geography. For example, scientists can be modeled in a ‘‘knowledge space’’ (Gilbert, Pyka, & Ahrweiler, 2001).

In the spatially explicit agent-based models, the agents have coordinates to indicate their locations. Another option is to have no spatial representation at all but to link agents together into a network in which the only indication of an agent’s relationship to other agents is the list of the agents to which it is connected by network links (Scott, 2000). Spaces may also be discrete, continuous, or characterized by networks. Depending on the nature of the space, rules should be written for how they move around and/or interact with other agents. Specifying environments and spaces for agents forces us to be more explicit about the assumptions that we make. For example, we may specify that agents move in a discrete, square grid. This is not because the square grid represents the physical space in which individuals move, but because we believe nothing essential is lost by representing individuals with agents that interact in a 2-dimensional discrete space.

2.4. Interactions

Local interaction is one of the defining characteristics of ABMs. The term “interaction” refers to how agents communicate with or affect each other, such as by exchanging information, competing for resources, helping or competing with each other, or conducting business. “Interaction” was also used for how agents affect and are affected by their environment because environmental interactions such as consuming and producing resources are very important in many ABMs (Railsback, 2010).

In traditional system-level models, the same equations and parameters are used to represent the effects of interaction on all members of the system. In contrast, interactions in the ABMs are modeled explicitly as ways by which individual agents affect each other and their environment. Consequently, the effects of interaction, and even the kinds of interaction, can depend on the state of the agents (e.g., location) and their environment. Interaction in ABMs is often local, that is, each agent affects only a few nearby others and only its local environment; whereas interaction in traditional system-level models is global, that is, all members of the system affect all other members.

The ABMs interactions commonly used in ABMs are direct interactions and indirect interactions. A direct interaction means one model entity can affect another by changing its state. However, in an indirect interaction, agents can affect each other by affecting some shared resources. One especially common kind of indirect interaction is competition for a shared resource (Railsback, 2010). Competition for a shared resource is commonly programmed by making the resource a variable, with the agent reducing the resource variable nearby. Agent interactions also involve relationships, that is, the same pair of agents interact with each other repeatedly.

In many models, agents are simply assumed to have access to the variables of certain other agents. However, in some models, it may be more realistic and useful to assume that interaction is imperfect, for example, by assuming a certain level of errors in the information that agents obtain. The most common approach is that agents can simply read information from nearby agents and the environment.

2.5. ABM Protocols

When developing ABMs, it can be difficult to describe all of the model's characteristics. At the early stage of ABM development, many descriptions of ABMs in the literature are incomplete, which makes it impossible to re-implement the models and replicate their results. Moreover, ABM descriptions are often a wordy mixture of factual descriptions and lengthy justification, explanations, and discussions of all kinds. Researchers have to read pages and even the code itself to assess the model. ABMs standardization has been proposed to solve this problem. A group of experienced modelers (Grimm et al., 2006) developed the first ODD (Overview, Design concepts, and Details) protocol for describing ABMs. ODD is designed to create factual model descriptions that are complete, quick and easy to grasp, and organized to present information consistently. ODD is now gaining widespread acceptance in the ecological and social science literature (Polhill et al., 2008), and there is a newly updated guide for using ODD (Grimm et al., 2010). Just as differential equations provide a way to describe mathematical models, and frequentist and Bayesian theories provide ways to think about statistical models, ODD provides a way to describe agent-based models.

There are seven elements of the ODD protocol, which starts with three elements that provide an overview of what the ABM model is about and how it is designed, followed by the design concepts that depict the ABM's essential characteristics, and its end with three elements that provide the details necessary to make the description complete. Specifically, the seven elements of the most updated ODD protocol (Grimm et al., 2010) are: 1) purpose, 2) entities, state variables, and scales, 3) process overview and scheduling, 4) design concepts, 5) initialization, 6) input data, and 7) submodels. The design concepts are normally extended into different sections, including basic principles, emergence, adaption, objectives, learning, prediction, sensing, interaction, stochasticity, collectives, and observation (Railsback, 2010).

Because the ODD protocol is mainly originated from ecological sciences with less emphasis on representing human decisions in ABMs, Müller et al. (2013) expanded and refined the ODD protocol to establish a standard for describing ABMs that includes human decision-making processes. The new protocol is termed ODD+D (Decision), with an emphasis on human decisions including the empirical and theoretical foundations for the choice of decision models.

2.6. ABM Platforms/Software

Many platforms or software have been developed to facilitate the development of agent-based models for specific problems. Some of these platforms include MASON (Luke et al, 2003), NetLogo (Wilensky, 1999), Repast (North et al, 2005), Swarm (Chris, 1999), StarLogo (Wendel, 2005), and Agent Analyst (Kevin et al., 2013). Table 2.1 compares these platforms.

Table 2.1. Comparison of agent-based model platforms.

Name	Pros	Cons	Language	Applications
MASON	A clear focus on computationally intensive models	Lack of documentation and specific functionalities	Java	Animal science (Panait, 2004) Transportation (Luke, 2006) Social science (Cioffi-Revilla, 2010)
NetLogo	Excellent documentation, user friendly	Code is less organized	Extension of Logo programming	Social science (Gilbert, 2000) Education (Wilensky, 2003) Statistics (Abrahamson, 2004) Diseases control (Aschwanden,2004) Manufacturing (Sallez, 2004) Psychology (Blikstein, 2005) Transportation (Lassarre, 2005) Animal Science (Sondahl, 2006) Economics (Zhang,2007) Landscape Construction (Popov,2007) Physiology (Katzper, 2007) Ecology (Voinov, 2008) Electricity (Sengupta, 2008) Biology (Hunt, 2009) Biomedical research (Wilensky, 2009) Environmental conservation (Niazi, 2010) Disaster management (Singh, 2011) Natural resources management (Le Page,2012) Water resources management (Abrami,2012) Neuroscience (Soylu,2014)
Repast	Complete, short execution time	Basic elements poorly designed	Java/Python/ Microsoft.Net	Market (Macal, 2004) Environment (Parry,2004) Water resources management (Gunkel,2005) Social science (Parker, 2006) Tourism (Yin, 2007) Land use (Adla, 2010)
Swarm	Stable, well organized	Difficult to debug runtime error	Objective – C/ Java	Computer Science (Madey, 2002) Animal science(Iba,2013) Traffic (Hitoshi, 2013)
StarLogo	Simple, easy to use	Constrained functionality	Extension of Logo programming	Social Science (Gilbert, 2002)
Agent Analyst	Strong GIS function	Requires ArcGIS Desktop	NQPy	Animal Science (Johnston, 2013)

MASON is a good choice for experienced programmers who work on computationally intensive models, but it lacks good documentation and has a relatively small user community. It lacks specific functionalities that the users may be seeking, especially in terms of GIS integration. It also lacks other general functionalities such as charting, although the MASON website claims a good charting package is available (Railsback, 2006).

NetLogo has excellent documentation. It is easy to use when the simulation time is not an issue. NetLogo is the highest-level platform, providing a simple yet powerful programming language, built-in graphical interfaces, and comprehensive documentation. It is designed primarily for ABMs of mobile individuals with local interactions in a grid space, but not necessarily clumsy for others. NetLogo is highly recommended, even for prototyping complex models.

Repast is the most complete platform and has a comparatively short execution time of simulations. Repast provides a lot of tools, good examples, and a large, active user community (Tobias and Hofmann, 2003). It has poor documentation in some places, and also some "average" software engineering design choices.

The Objective-C version of Swarm is a small, stable, and well-organized ABM platform and can support very complex models. But it suffers from some of the limitations of Objective C, including a lack of novice-friendly development tools and garbage collection function (Serenko, 2002). StarLogo is simple to use but has constrained functionality. Agent Analyst is an ABM tool integrated with ArcMap, it is appropriate for developing ABM applications associated with GIS data.

In summary, MASON, Repast, and Swarm are "framework and library" platforms, providing a conceptual framework for organizing and designing ABMs and corresponding software libraries. MASON is least mature and designed with execution speed as a high priority. The Objective-C version of Swarm is the most mature library platform and is stable and well organized. Objective-C seems more natural than Java for ABMs but weak error-handling and the lack of developer tools are drawbacks. Java Swarm allows Swarm's Objective-C libraries to be called from Java; it does not seem to combine the advantages of the two languages well. Repast provides Swarm-like functions in a Java library and is a good choice for many, but parts of its organization and design could be improved. A rough comparison of execution speed found MASON and Repast usually fastest (MASON 1–35% faster than Repast), Swarm (including Objective-C) fastest for simple models but slowest for complex ones, and NetLogo intermediate (Railsback, 2006).

Areas for improvement for these platforms include completing the documentation (for all platforms except NetLogo), strengthening conceptual frameworks, providing better tools for statistical output and automating simulation experiments, simplifying common tasks, and researching technologies for understanding how simulation results arise. Besides, there are growing legitimate concerns about StarLogo and other non-Open Source platforms (NetLogo) about the hidden nature of algorithms, lack of serious ability to extend, and possible non-repeatability of scientific (modeling) experiments (Railsback, 2010). Due to different project requirements, new platforms can be developed along with GIS functions.

2.7. Model Calibration and Validation

Model calibration and validation are essential parts of the model development process if models are to be accepted and used to support decision-making. The goal of model calibration and validation is to make the model useful in the sense that the model addresses the right problem and provides accurate information about the system being modeled. ABMs calibration and validation can be a complex process involving many steps and iterations. The difficulties are often underestimated. An excellent reference on calibration and validation of traditional simulation models is the book by Law (2007). ABMs presents additional challenges to models in agent behaviors, agent interaction mechanisms, and the processes and structures that emerge (North, 2007).

Model calibration is to execute a model many times, each time using different values of its parameters, and then analyze the results to see which parameter values caused the model to best reproduce some patterns observed in the real system (Railback, 2010). However, overfitting is a common problem with calibration. By fine-tuning many parameters, we can cause the model to match a few patterns very closely while making the model less accurate in general. To avoid this problem in the ABMs calibration process, it is good to understand that there is a cost to calibrating more instead of fewer parameters. We need to use, if possible, techniques such as validation via prediction and robustness analysis to assess how well the calibrated model represents the system in general.

Model validation consists of validating the model's input data, the model's outputs, the process included in the model, and for ABMs in particular, and agent behavior and interaction mechanism. Several perspectives can be taken in approaching model validation:1) requirement validation, 2) data validation, 3) face validation, 4) process validation, 5) agent validation, and 6) theory validation (North, 2007). However, experiments on the real system cannot be designed or implemented to produce the data required for validating the model. Unlike physical systems, for which there are well-established procedures for model validation (AIAA, 1998). No such guidelines currently exist for ABMs. Thus in ABMs, model validation tends to be a subjective process. The challenge for validation is to develop a high degree of credibility for the model so that people will have collective confidence in the model and the results it produces. In the case of ABMs models that contain elements of human decision making such as ABMs business applications, validation becomes a matter of establishing credibility in the model.

2.8. Applications in Water Resources Management

Originated from the field of artificial intelligence, agent-based modeling has gained increasing attention over the past decades in the application of modeling coupled human and natural systems (Macal and North, 2009). Applications of agent-based modeling in various fields have been thoroughly reviewed by Bonabeau (2002) in human systems, Bousquet and Le Page (2004) in ecosystem management, and Matthews et al. (2007) in land-use modeling. In water resources planning and management, agent-based modeling has been applied to explore, simulate, and predict the performance of infrastructure design and policy decisions as they are influenced by human decision-making, behaviors, and adaptations (Berglund, 2015).

Water resources management requires an insightful balance between water demand and water supply, and the sustainability of water resources mainly depends on the dynamic interactions among the environmental, technological, and social characteristics of the water system. ABM applications in water resources management are relatively new (Xiao et al., 2018), However, it is also receiving increasing attention. Berglund (2015) provided a review of more than 30 ABM studies of water resource management in the last 20 years. These ABM applications are used to address problems in water allocation systems (see also Akhbari and Grigg, 2013; Zhao et al., 2013; Hu and Beattie, 2019), river basin water management (see also Becu et al., 2003; Kock, 2008; Yang et al., 2011), municipal water supply and water demands (see also Chu et al., 2009; Galán et al., 2009; Kandiah et al., 2016; Tourigny and Filion, 2019), and water infrastructure systems (see also Kotz and Hiessl, 2005; Montalto et al., 2013; Liu et la., 2016). Kock (2008) showed institutional capacity and water conflict dynamics are highly related in socio-hydrological systems. Zechman (2011) proposed a multi-agent modeling framework to analyze threat management strategies in water distribution systems. Barthel et al. (2010) developed a multi-actor model and simulated water supply decision-making which considered critical regions requiring climatic adaptation strategies. Integrating system dynamics and ABM, Nikolic et al. (2013) developed a management tool that captured the temporal and spatial dynamics of a physical-social-economic-biologic system. Combining an ABM with a continuous simulation model makes it capable of evaluating the influence of implementing water allocation schemes or regulation scenarios on quantity and quality of flows or domestic water consumption (Akhbari and Grigg, 2013). Some other examples of ABM in water resources management can be found in Berger et al. (2007), Yang et al. (2009), Nikolic et al. (2013), Yuan et al. (2014), and Tamene et al. (2014). The applications of the ABM in water resources management predominantly focus on solving water allocation problems in either a market-based or an administered system (Zhao et al, 2013). Akhbari and Grigg (2013) list such application examples in river basin water management (e.g. Becu et al., 2003; Kock, 2008) and domestic water distribution in urban areas (e.g., Chu et al, 2009; Galan et al., 2009). Shared vision approaches can be facilitated through ABM, which is popular for the simulation of complex water systems (Bandini et al. 2009).

Agents involved in water decisions normally include agricultural, industrial, urban/domestic, environmental, hydropower generation, recreation, and regulators. They can be characterized based on their attributes, behavioral rules, memory, decision-making sophistication, and resources/flows (Macal and North 2006). Decision-making sophistication means the amount of information an agent requires to make decisions and can be classified as simple, medium, and high.

Kock (2008) developed two agent-based models to explore the institutional dynamics of water resources conflict. The two agent-based models simulate two water systems, one for Albacete, Spain, and the other for the Sanke River, eastern Idaho. The study explored the societal effects of water management policies and their relationship with water resources conflict through adding and testing new institutions to the developed agent-based models for the simulated water systems. The agent-based models defined three types of agents, regulators, water users, and power companies. Water user agents include surface water irrigators, groundwater irrigators, and spring users. Water user agents are denoted as cognitive active agents. The study used a cognitive model, the Belief-Desire-Intention model (BDI), to simulate agents' decision-making behaviors. An agent is assigned with beliefs, desires, and intention attribute. Belief describes the agents' existing internal set of knowledge about the current state of the world. Desire describes the agents' desired state of the world. Intentions describe the plans of action that the agent may take for the next steps. The BDI model is an efficient and effective way to implement human-like reasoning capabilities. Additionally, each active agent is assigned to emotions. Emotion is a primitive variable with a range of 0.0 to 10.0. and corresponds to the concepts such as happiness, calm, apathy, curiosity, conservatism, and suspicion. There are two mechanisms designed to govern the modification and impact of emotions: fuzzy logic engines and stimulus-response pairs. Each emotion has several fuzzy patterns associated with it. When modifying the state of that emotion, some combination of external environmental or internal agent variables will be changed. Income stress and water stress have a larger number of fuzzy logic patterns than most other emotion variables. The model simulation results and analysis suggest that institutional capacity and water conflict dynamics are strongly related, but the direction of influence can vary. The cognitive model represents the net effect of people's thought processes, and the model help understands how human evaluate the environment and make subsequent decisions. More research should be devoted to the role of social networks in affecting human decisions.

Akhbari and Grigg (2013) developed an agent-based model to manage water resource conflicts in California's Sacramento-San Joaquin Delta region. The water conflicts are rising in the region because of increased salinity rates in the rivers caused by agricultural return flows. The study used the agent-based model to search for effective strategies that encourage conflicting parties in the region to cooperate. In this agent-based model, the environment is the San Joaquin watershed. There are two types of agents simulated in the model, regulators (policymakers) and water users. Water users include farmers and the environmental sector (demanding enough water flowing along the river with acceptable quality), and they are both simulated as reactive agents set with certain behavior rules. In this study, the authors applied institutional theory to simulate water user agents' interaction with the regulator agents. The institutional theory is accomplished in the form of providing incentives, penalties, and new regulation policies. The regulator agent determines available water for allocations to farmers and the environmental sector agents. This model also used the experience-based model to simulate the agent's behaviors, especially the interactions between farmers and environmental sector agents. The behaviors are designed based on their perception of the system. The interaction between water user agents determines total agricultural water demands for the environment. By indicating their water demands, there are two types of behaviors set for farmer agents: cooperative, and non-cooperative. In the case of cooperation, farmer agents' total water demand will be compatible with the system's capability of water supply and it will not harm the environment. Therefore, the conflicts between the farmer agents and the environmental sector might be reduced to an unimportant level. On the other hand, farmers' non-cooperative behavior may result in three possible reactions from the environmental sector. If the impact regarding quantity and quality of the river water is minor or negligible, the environmental sector agent may compromise; otherwise, it may file a lawsuit, or put pressure on the regulator to set more limitations to protect the river's aquatic and environmental health. Experience-based decision models are commonly used decision models in agent-based model applications. They are effective real-world strategies and can be easily derived from data, observations, or histories from the field. The method is simple and straightforward. This study demonstrates that the agent-based model is a useful tool to manage conflicts in complex water resources systems. It provides a clear description of humans/organizations' interactions and a better understanding of complex interactive systems comparing with traditional numerical models.

Becu et al (2003) developed a multi-agent system, CATCHSCAPE to help manage water resource conflicts of the Mae Uam catchment in northern Thailand. Due to mounting human pressure, irrigation water competition is increasing between farmers upstream and downstream in the region. CATCHSCAPE is combined with a distributed water balance model and an agent-based model. The study uses the hydrological model to simulate the biophysical dynamics of the catchment and the agent-based model to simulate stakeholders' decisions. In the agent-based model, individual farmers are defined as active agents characterized by their family size and labor force. Each farmer is assigned the ability to memorize resource allocation information and update their expectations based on the experience from the previous year. The model used a simplified Linear Programming model to simulate farmers' crop choice decision making, and the method belongs to the microeconomic models in the behavior-theory group. The crop choice decision is determined based on the optimization functions of farmers' income according to seasonal farming costs, water, and labor requirements. The agent-based model also implements the preference model to simulate farmers' crop choice decisions. Paddy rice is set as a dominant crop in the region, and crop cultivation choice is motivated by socio-cultural preferences.

Yang et al. (2011) build a multiple agent system to explore the socioeconomic and environmental consequences of the current water allocation regulation and test a water market-based water allocation management plan to improve water allocation management in the Yellow River Basin in China. In this model, three types of agents are defined, off-stream water users, in-stream water users, and in-stream ecosystem water users. Several water users in one sub-basin are lumped as a single water use agent. The model allows agents to approach an optimal decision using a decentralized optimization algorithm. It assumes that maximizing water use benefit is a common behavior rule for all water use agents. Each agent optimizes its objective with different priorities for collaboration. The agents' behavior theory used in the study is a modification of the microeconomic model.

Zhao et al. (2013) compared the performance of administered and market-based water allocation systems through agent-based modeling. An agent-based model is developed to analyze water users' behaviors under the administered and the market-based water allocation systems. Water users are considered as agents. This agent-based model uses microeconomic models for the agent's decision-making process. The model is composed of several water user agents that are set to optimize their benefits associated with water transactions. The agents' behavior is formulated following a penalty-based decentralized optimization framework. The model uses utility functions in place of income. These utility functions take a form of a weighted linear combination of many criteria under consideration and local constraints. Then it calculates the probability of an agent's choosing one specific option in the decision-making process.

Xiao et al. (2018) constructed an agent-based model to assess water users' behavior for water demand management at the South Saskatchewan river basin in southern Alberta, Canada. The specific behavior of water users to be investigated is how to decide whether to conserve or consume more water to achieve a better economic return based on the initial allocation scheme. In the study, all water users in a basin are categorized into two main types of agents. Consumptive water use includes agricultural, municipal, and industrial water uses, which are defined as general agents, and non-consumptive water use includes reservoirs and instream flow requirements, which are defined as ecosystem agents. The model uses microeconomic models to simulate each agent's behavior. Different net benefit functions are assigned to different types of agents, and they describe the relationships between water use and its output (economic net benefit). For example, the net benefit functions for agricultural agents use the quadratic form, in which the coefficients are derived from a regression analysis model. Each agent is trying to maximize their economic returns by updating their water consumption.

Hu and Beattie (2019) developed an agent-based model and coupled it with a groundwater model to address the issue of unsustainable groundwater use in the High Plains Aquifer Hydrologic Observatory Area. The purpose of the study is to evaluate the performance of this optimization strategy compared with observations. The agents of the model are individual farmers who are grouped into two types. Type 1 farmer agents place more value on their past average experiences, while type 2 farmer agents place more value on recent observations. The model uses microeconomic models to simulate farmers' decisions on crop choice and groundwater irrigation. Farmers' utility is defined by the estimation of crop water demand and prices for different crops. Through maximization of their utility, the farmer decides the types of crops to plant, the upper bound of the irrigated area, and the lower bound of the dryland area for the crops. The model also uses an optimization method to simulate farmers' daily decisions on actual water use for irrigated crop areas based on the observed daily precipitation. The model results show that the optimization strategy leads to either higher crop profits or a slower rate of groundwater depletion compared with observations. The agent-based model is described in terms of the ODD protocols (Grimm et al., 2010), which make the model description more standardized and easier to understand.

Agent-based models can describe the feedback between human and natural systems and incorporate the effects of institutional and physical constraints at various levels. The ability to describe complex system dynamics at different spatial scales makes ABMs an ideal candidate for socio-hydrological issues such as the management of sustainable water resource management practices. Through applying ABM in water resource planning and management, people understand more about complex human and water systems. Using an ABM to model coupled human and water systems, research can also gain a better understanding of the water systems and test new water management policies and regulations. Agent-based models are commonly combined with hydrological models in simulating water systems. In the above ABM studies reviewed, both reactive and active agents are used to represent water users. In simulating agents' decision-making behavior, several different behavior theories can be combined based on different conditions.

However, from these ABM applications in water resource management, we can observe that the microeconomic model or its modifications are frequently used to simulate water user agents' behaviors allowing agents to maximize their benefit. These microeconomic models are characterized by a common feature: computing a certain utility value for available options and then choosing the one with the maximum or satisfactory value. The agents are assumed to make rational choices. However, it is believed that in the real world, such choices or decisions are usually affected, or bounded by imperfect resources including knowledge and information or limited ability to make use of such resources (Simon, 1997). Bounded rationality also posits that agents should be limited in their environmental knowledge. Microeconomic models and their modifications may be cautious to use because of these caveats. Other decision-making theories could be applied and explored for water resource management and planning in the future. Our study aims at fulfilling the bounded rationality in agent-based model development for water resource management by exploring different agent-based model behaviors.

3. MATERIALS AND METHODS

3.1. Study Area

Our study area in western North Dakota includes 16 North Dakota counties underlain by the Bakken and the underlying Three Forks Formations. The name "Bakken" originates from a North Dakota farmer, Henry Bakken, who owned the land where the first oil well was drilled in the Bakken formation (i.e., Bakken Shale Play, https://bakkenshale.com/). The Bakken Shale Play is located in eastern Montana and western North Dakota, as well as parts of Saskatchewan and Manitoba in the Williston Basin (46.5°N-49.0°N, 99.5°W-107.2°W). The extent of the Bakken Formation is shown in Figure 3.1 and the underlying Three Forks Formation extends further south into South Dakota. The maximum thicknesses for the Bakken and the Three Forks Formations are approximately 160 ft (49 m) and 270 ft (82 m), respectively, both occurring at the depocenters adjacent to the Nesson anticline in North Dakota. The Bakken Shale is a rock formation that was deposited in the late Devonian and early Mississippian ages. The formation consists of three layers: an upper shale layer, middle dolomite, and a lower layer of the shale. The shale layers are petroleum source rocks as well as seals for the layer known as the Three Forks (dolomite) or Sanish (sands) formations. Oil was initially discovered in the Bakken Play in 1951 but was not commercial on a large scale until the past ten years. The advent of modern horizontal drilling and hydraulic fracturing helps make Bakken oil production economic. The U.S. Geological Survey has estimated that the Bakken Shale Formation could yield 4.3 billion barrels of oil and estimates from Continental Resources stretch as high as 40 billion barrels (USGS, 2008).

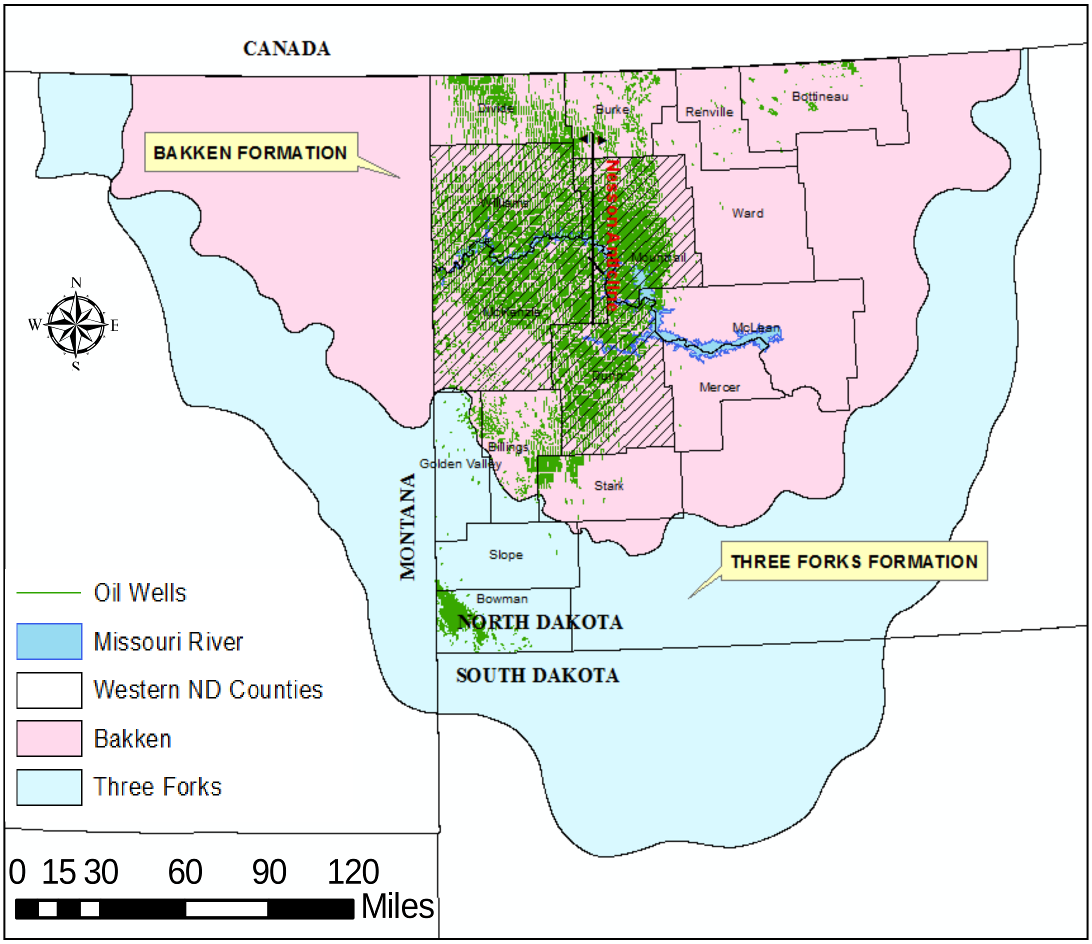

Figure 3.1. Western North Dakota with oil wells and regional features.

3.2. Data and Preprocessing

3.2.1. Hydraulic Fracturing Water Use

Hydraulic fracturing water use data were provided by the ND Department of Mineral Resources Oil and Gas Division (OGD). The database includes approximately 11,000 oil and gas well records with well completion (also known as geo-stimulation or hydraulic fracturing) water volumes, completion dates, and other well attributes. A summary of oil and gas wells in western ND that received geo-stimulation during 2004-2014 is provided in Table 3.1 It should be mentioned that the Bakken region in western ND is predominantly an oilfield with less than 1% gas wells (Freyman, 2014). Oil production in the Bakken region is primarily concentrated in a

13,500 mi^2 area (Scanlon et al, 2014) with more than 85% of the horizontal wells drilled in a core area of four ND counties, namely, Dunn, McKenzie, Mountrail, and Williams, as shown in Table 3.1. Table 3.1 also shows that more than 90% of the oil and gas wells developed in the Bakken and Three Forks Formations during 2004-2014 are Bakken horizontal wells, whose approximate locations are shown in Figure 3.1.

Table 3.1. Oil and gas wells (2004-2014) receiving geo-stimulation (GS) in 16 western North Dakota counties.

County	Bakken horizontal wells	Other wells	Total
Billings	164	104	268
Bottineau	0	190	190
Bowman	0	23	23
Burke	279	92	371
Divide	657	49	706
Dunn	1751	34	1785
Golden Valley	18	53	71
McKenzie	2902	205	3107
McLean	47	1	48
Mercer	2	0	2
Mountrail	2402	12	2414
Renville	1	98	99
Slope	0	7	7
Stark	200	26	226
Ward	1	3	4
Williams	1674	135	1809
Total	10098	1032	11130
Four-county core area total [a]	8729	386	9115

[a] Four counties include Dunn, McKenzie, Mountrail, and Williams.

The OGD oil and gas wells data were processed to obtain the historic water use for hydraulic fracturing in the Bakken region. It should mention that incorrect units were used for 10 Bakken horizontal wells in the database, and they were manually corrected (Mike Hove, personal communication). A summary of hydraulic fracturing water use for oil and gas wells in western ND is provided in Table 3.2. It is shown that 99-100% of hydraulic fracturing water use was associated with Bakken horizontal wells. Table 3.2 also shows that the total HF water use in western ND increased from ~316 million gallons in 2008 when the recent oil boom started to more than 9 billion gallons in 2014. The average HF water use per Bakken horizontal wells increased from ~0.5 million gallons in 2008 to ~4.0 million gallons in 2014.

Table 3.2. Hydraulic fracturing (HF) water use for oil and gas wells in western North Dakota.

Year	Bakken horizontal wells		Other wells		Total HF water use (gallon)	Total HF water use (gallon)	Percentage of HF water use by Bakken horizontal wells (%)
	Average HF water use (gallon)	Subtotal HF water use (gallon)	Average HF water use (gallon)	Subtotal HF water use (gallon)			
2004	156,598	977,553	4,205	228,096	1,170,873	1,303,404	80
2005	107,265	4,236,063	3,346	358,436	4,662,058	4,561,914	92
2006	325,492	23,135,421	4,479	553,947	23,669,818	23,787,123	98
2007	498,976	97,429,449	8,576	1,205,649	98,509,564	98,407,002	99
2008	506,684	314,120,364	20,986	2,411,297	316,557,350	316,401,321	99
2009	757,976	454,887,996	33,575	1,922,521	456,699,129	456,843,102	100
2010	1,475,526	1,316,112,189	7,224	651,702	1,316,811,902	1,316,763,891	100
2011	1,890,892	2,581,065,771	88,876	5,083,276	2,586,133,762	2,586,279,387	100
2012	2,255,465	4,217,815,344	246,571	23,656,783	4,241,389,604	4,241,276,616	99
2013	2,623,760	5,567,490,186	104,933	10,720,498	5,578,321,695	5,578,243,269	100
2014	3,923,608	9,090,917,049	216,468	18,182,486	9,109,182,523	9,109,164,705	100

3.2.2. Water Depots

As mentioned earlier, water used for hydraulic fracturing and other shale oil production-related activities such as well drilling, cementing, and brine dilution in western ND is almost exclusively supplied by hundreds of water depots. Water depot shapefile and the permitted water use data were obtained from NDOSE. The water use database contains annual water uses for all water permits issued by the NDOSE, water use types, locations of the point of diversion, as well as water sources (i.e., aquifers for groundwater and river basins for surface water), etc. The water depot shapefile was merged with the ND water use dataset through the unique water permit numbers to estimate annual water volumes sold by these water depots. Between 1980 and 2007, the state issued just 10 water permits for water depots. From the year 2007 to 2014, the number of water depots has increased from 16 to 588 (Table 3.3). As shown in Figure 3.2 and Table 3.4, most water depots are located in the oil production counties.

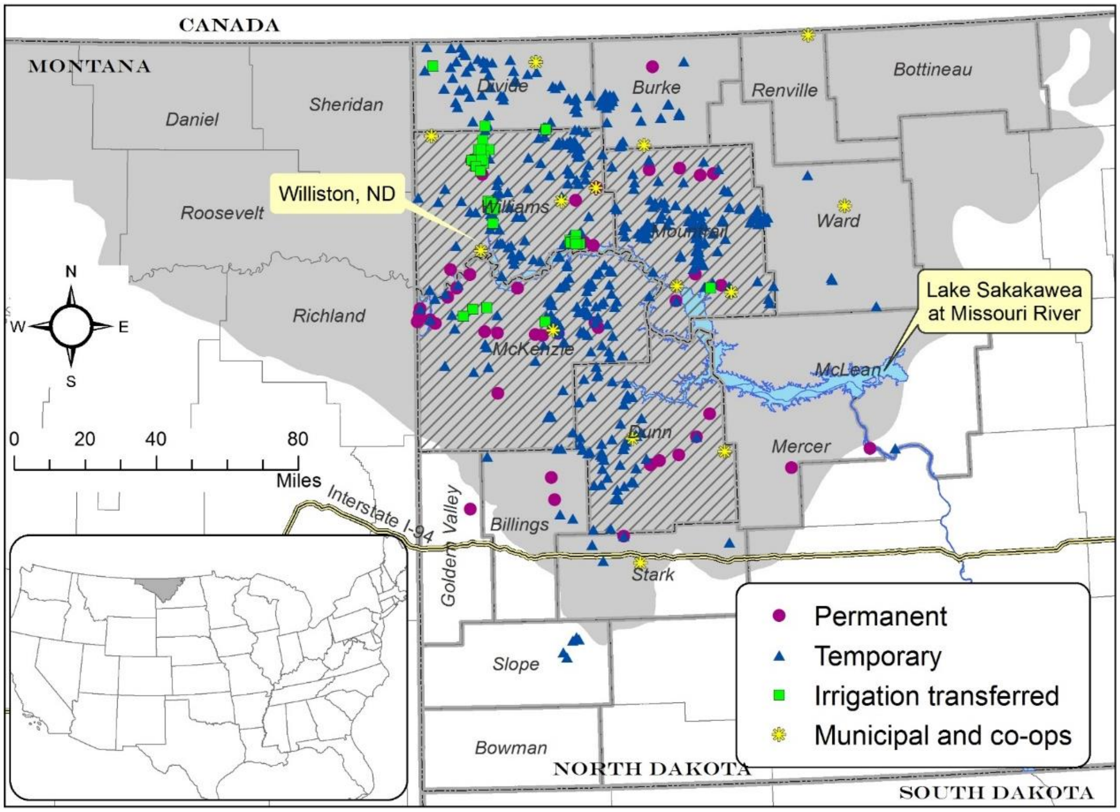

Figure 3.2. Water depots in Western North Dakota (2014).

Table 3.3. The number of water depots in western North Dakota (2007-2014).

Year	Permanent	Temporary	Irrigation Transferred	Municipal Co-ops	Total
2007	14	0	0	2	16
2008	19	2	0	4	25
2009	22	1	0	6	29
2010	30	10	5	10	55
2011	40	23	17	13	93
2012	46	94	32	13	185
2013	56	152	37	12	257
2014	63	479	32	14	588

Table 3.4. The number of water depots in western North Dakota counties in 2014.

Year	Permanent	Temporary	Irrigation Transferred	Co-ops	Total
Billings	2	4	0	0	6
Bottineau	0	0	0	0	0
Bowman	0	0	0	0	0
Burke	1	31	0	1	33
Divide	0	58	3	1	62
Dunn	10	54	0	2	66
Golden Valley	1	0	0	0	1
McKenzie	21	93	4	1	119
McLean	1	1	0	0	2
Mercer	1	0	0	0	1
Mountrail	14	110	1	2	127
Renville	0	0	0	1	1
Slope	0	6	0	0	6
Stark	1	5	0	1	7
Ward	0	9	0	1	10
Williams	11	108	24	4	147
Total	63	479	32	14	588

Based on their major characteristics, we categorized these water depots into four types – permanent, temporary, irrigation transferred, and municipal co-ops. The permanent water depots (see Figure 3.3) are those owned by individuals who have successfully obtained permanent (or perfected) water permit to sell water to the oil industry. These individuals have normally been in the water business for some time. The temporary water depots are those owned by individuals who have obtained temporary water permit to sell water to the oil industry. A temporary water permit only approves the permit holder to use a certain amount of water for a period of no more than one year, without granting the permit holder a water right. As shown in Table 3.3, NDOSE started to issue considerably more temporary water permits beginning in 2012. It should be noted that an individual may own both permanent and temporary water depots.

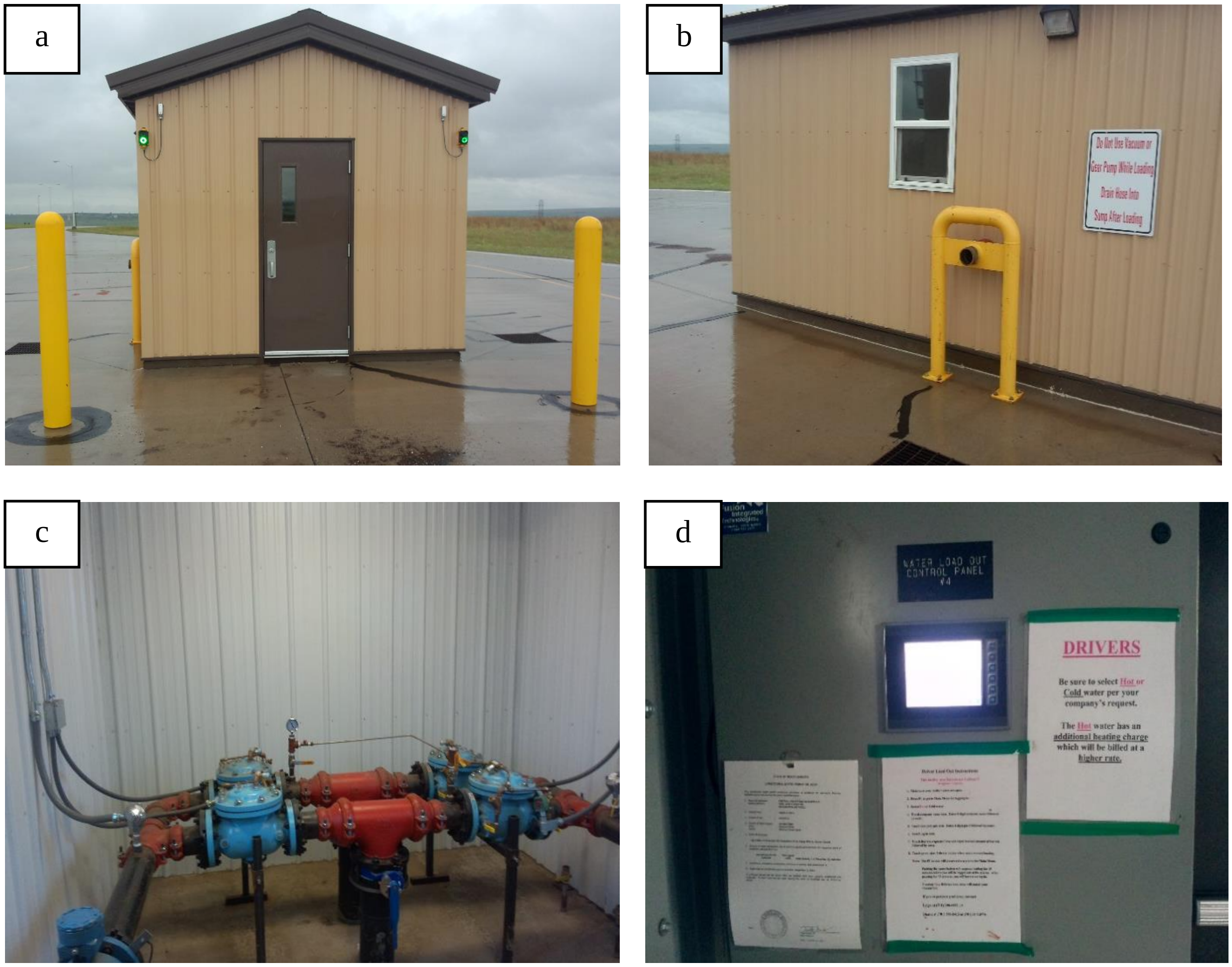

Figure 3.3. Pictures of Central Dakota waterworks in western North Dakota.
Note: taken by the author in 2015): (a) exterior, (b) loading side, (c) valves, (d) control panel.

The irrigation transferred water depots are owned by the farmers who have permanent water permits for irrigation. During 2008-2014, an emergency measure, called the "In Lieu of Irrigation" program (ILOP), was undertaken by NDOSE to allow the temporary (one year and renewable) use of water permits for irrigation for oilfield water use. In other words, if irrigation permit holders (usually farmers) forgo part of their permanent water permits in a calendar year (usually after a wetter than normal winter), they may apply for a temporary water permit yearly to sell the forgone portion of the water to the oil industry. The existence and emergence of this type of water depots are highly dynamic and dependent upon climatic conditions. At the heights of the Bakken oil boom, the ILOP accounted for about one-fourth of the total water delivered by water depots. The program was discontinued in 2015.

As mentioned earlier, several local towns have also built water depots to sell excess municipal water to increase the city's revenue (Kusnetz, 2012). Furthermore, the newly constructed WAWS project, which was authorized and funded by the 2011 legislature and now serves communities and industries in the northwest region of the state, also plans to sell 20% of its water to the oil industry. In 2014, approximately 20% of the total water depot use was supplied from the Missouri River through the WAWS project. The water depots that sell excess municipal water and the water from the WAWS project are called the co-ops water depots in our study.

3.2.3. Water Sources

The four types of water depots draw freshwater from the four major sources shown in Figure 3.4. "Surface waters" consist of streams and lakes, excluding the Missouri River and Lake Sakakawea, which are denoted as "Lake Sakakawea and Missouri River". "Shallow aquifers" include shallow glaciofluvial aquifers in the region. The "FH-HC aquifer" is a bedrock aquifer covering almost the entire region (Figure 3.4). As shown in Table 3.5, before 2012 Bakken shale oil production used more groundwater than surface water, while after 2012 the trend was reversed with about two-thirds of fracking water coming from surface water. The main reason for this shift is that the NDOSE started to issue considerably more temporary water permits beginning in 2012 and the sources of water for these temporary water permits were primarily surface water, including the Missouri River and Lake Sakakawea. The spatial extents of surface and groundwater sources were obtained from NDSWC (Figure 3.4).

As mentioned earlier, the surface waters and the shallow aquifers have been fully or nearly fully appropriated. The water availability from shallow aquifers and surface waters is also dependent on climate conditions. Water diversion from Lake Sakakawea or Missouri River requires permits from the U.S. Army Corps of Engineers. The Missouri River accounts for 96% of the state's surface streamflow and is the only large source of unallocated water in the state and particularly in the water-limited Bakken region. In May 2010, the U.S. Army Corps of Engineers placed restrictions on access to the Missouri River from Lake Sakakawea, which comprises most of the length of the Missouri River in the Bakken region. The surplus water restrictions, while still in place, have been relaxed somewhat and, in December 2010, 32.5 billion gallons of annual surplus water from Lake Sakakawea were made available for temporary permits (Horner et al., 2016).

As aquifers become fully appropriated the State Engineer has been authorized by the legislature to put entire aquifers or portions of aquifers on deferred status, with no further allocations. Under the prior appropriation system, if harmful conditions become apparent, water uses are retired in the order of beneficial use date, within the area of effect. For example, the FH-HC aquifer, the only regional high-capacity groundwater source, is restricted from substantial oil development use and should not be further depleted by oil development as long as the current restrictive policy remains in place. As early as 1984 a state policy known as the "Lindvig Memorandum" was adopted allowing for use of the FH-HC water for the oil industry only in highly restricted conditions (Schuh, 2010, Fischer, 2013). A more restrictive policy for use of FH-HC water for industrial use was formalized in 2013. If this restrictive policy is lifted or a severe drought further limits water supply from other water sources, the FH-HC aquifer may be affected by oil development.

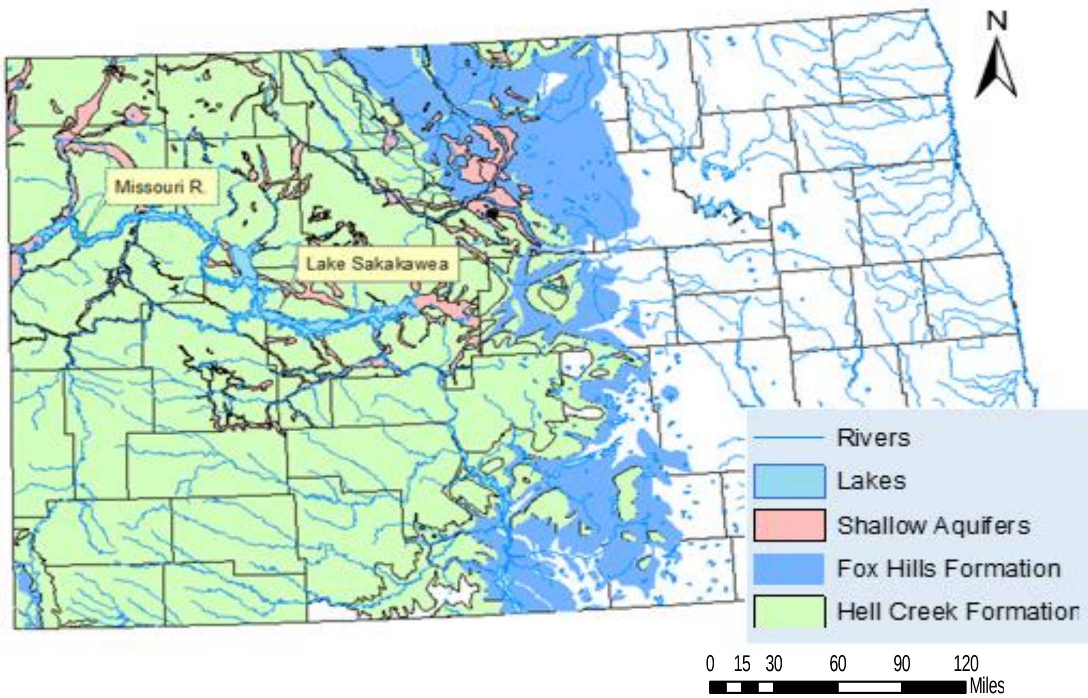

Figure 3.4. Water sources in western North Dakota.

Table 3.5. Water sources for unconventional oil development in western North Dakota.

Year	Surface water						Groundwater						Water depot water use (MG)
	Missouri River/ Lake Sakakawea		Other surface waters		Subtotal		Fox Hills-Hell Creek aquifer		Other aquifers		Subtotal		
	(MG) [a]	(%)	(MG)	%	(MG)	(%)	(MG)	(%)	(MG)	(%)	(MG)	(%)	
2007	152	58.8	2	0.9	154	59.7	38	14.9	65	25.4	104	40.3	258
2008	249	45.4	18	3.3	267	48.7	39	7.2	242	44.2	282	51.3	548
2009	231	39.7	18	3.1	249	42.8	35	6.0	298	51.2	333	57.2	582
2010	673	42.3	21	1.3	694	43.6	40	2.5	858	53.9	898	56.4	1,592
2011	924	32.9	102	3.7	1,026	36.6	48	1.7	1,731	61.7	1,778	63.4	2,805
2012	1,564	31.0	828	16.4	2,391	47.4	53	1.1	2,603	51.6	2,657	52.6	5,048
2013	2,342	37.0	1,762	27.9	4,103	64.9	26	0.4	2,191	34.7	2,217	35.1	6,320
2014	3,711	36.4	3,656	35.9	7,367	72.3	21	0.2	2,800	27.5	2,822	27.7	10,189
Average	1,458	38.3	999	15.6	2,457	53.9	35	2.4	1,411	43.7	1,614	46.1	4,359

[a] MG = million gallons.

3.2.4. Precipitation

Precipitation information in western ND may be used by farmers in their decisions on whether to forego part of their irrigation water permits to sell water for industrial use yearly. Annual county-level precipitation data were retrieved from the PRISM Spatial Climate Datasets (PRISM Climate Group, http://prism.oregonstate.edu/, accessed June 2016) for the 16 western ND counties (Table 3.6). It should be noted that the average annual precipitation in the 16 western ND counties during 2007-2014 was 20+% greater than the 30-year normal of these counties (Lin et al., 2017).

Table 3.6. Annual county-level precipitation of western North Dakota (unit: mm unless specified).

Counties	2007	2008	2009	2010	2011	2012	2013	2014	30-yr normal
Billings	339	306	430	487	535	322	626	539	385
Bottineau	393	483	458	668	523	376	638	550	458
Bowman	401	353	429	458	525	307	719	549	387
Burke	370	459	408	607	570	376	605	508	422
Divide	369	415	366	557	590	349	537	444	380
Dunn	357	387	477	575	628	386	719	575	410
Golden Valley	345	297	374	469	502	304	570	518	365
McKenzie	331	352	406	537	594	358	609	450	385
McLean	415	459	491	663	596	406	681	563	432
Mercer	410	436	514	640	621	385	715	605	428
Mountrail	359	425	435	587	604	400	638	509	415
Renville	379	469	449	642	544	369	628	554	441
Slope	397	287	442	425	466	265	679	521	373
Stark	368	351	491	490	561	332	714	614	414
Ward	404	485	459	637	587	390	660	543	435
Williams	363	383	384	523	543	353	551	396	380

3.2.5. Roads and Bridges

Hart et al. (2013) estimated that it requires about 1,340 one-way truck trips to establish one unconventional oil or gas well. Most of these truck trips are hauling HF water (Figure 3.5). An empty water truck weighs 30,000 lbs and one truckload can hold up to 5,465 gallons of water (weighing ~45,000 lbs). It is important to consider road and bridge access for such heavy truck loads. For example, a temporary water depot is likely to be built at an existing road while a permanent water depot does not have this requirement because the water depot owner may build an access road to the water depot as part of the investment. The road and bridge data for western ND were obtained from the North Dakota Department of Transportation (NDDOT). The centerlines of the roads were mapped with GPS equipment. The transportation network can also be used to calculate the travel distance between a water depot and a Bakken horizontal well. The major highway network in western ND is shown in Figure 3.6 and an example of the local road system in McKenzie County is shown in Figure 3.7.

Figure 3.5. Water trucks filling at water depots in western North Dakota.
(Source: The Bakken, http://thebakken.com/articles/710/the-state-of-water).

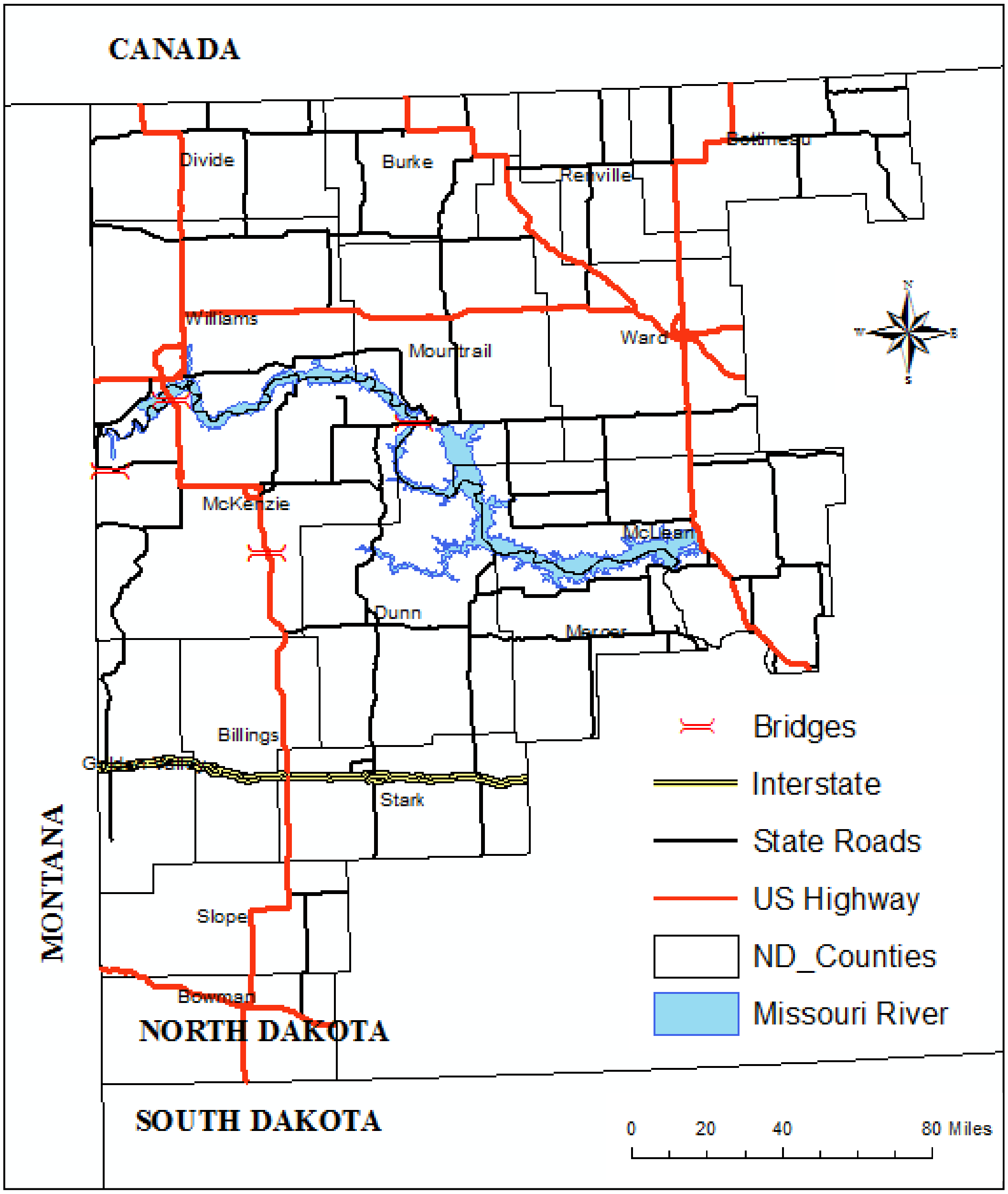

Figure 3.6. Main roads and bridges in western North Dakota.

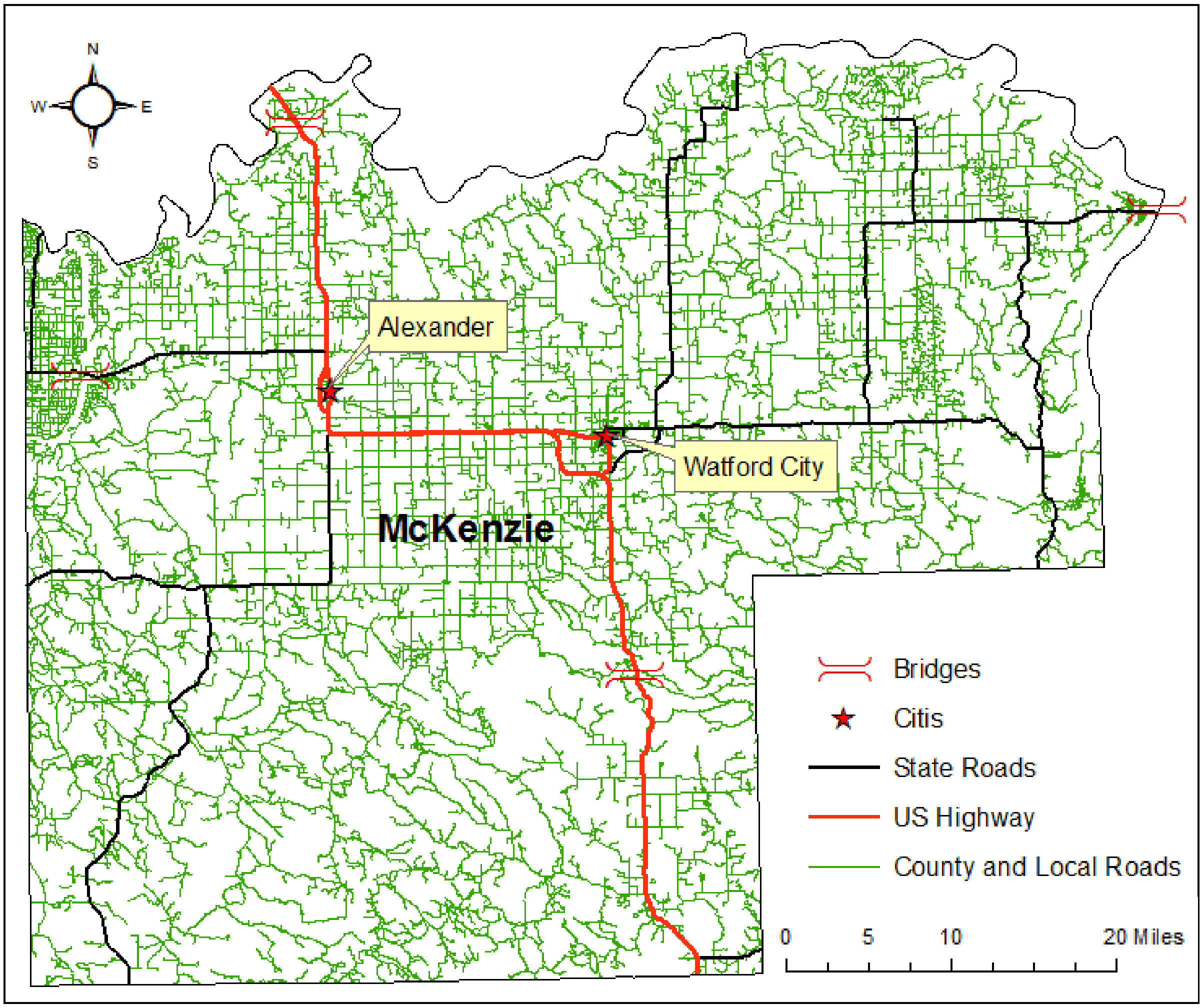

Figure 3.7. Road and bridges in McKenzie County, North Dakota.

3.3. Knowledge Engineering

To better understand the Bakken shale oil development and the water depot-based water allocation and management system in western ND, we conducted two rounds of structured interviews (phone and in-person) with the field experts and water depot owners in the summers of 2015 and 2016. Besides these formal interviews, we also visited with several staff members in the Water Appropriations Division of NDSWC several times during 2015-2016 and visited 5 private and cooperated water depots in western ND in June 2015.

The first round of structured interviews was conducted on July 27-29, 2015, when we attended the Bakken Conference and Expo at Grand Forks, ND. We interviewed five experts from water solution companies and research institutions. The interview questions and answers are summarized in Tables 3.7 and 3.8. The original questionnaire sheets are provided in Appendix A.

Table 3.7. A summary of the 2015 Bakken Shale oil development interview.

Question	Answer Summary
What type of fracking fluid and proppant does your company use? Where does your company buy proppant from?	Companies use slickwater or gel-based fluid where slickwater is more commonly used with slickwater using about 250,000 barrels of water per frack/well and gel using 50-60,000 barrels of water per frack/well. Proppant used is either ceramic, ceramic/sand mixture, or sand with about 90% of the volume of proppant used globally is sand alone. There are a few kinds of ceramic proppant that withstand higher psi in ascending order: economy lightweight, to tier 1 bauxite based, and most resistant at tier 2 bauxite based. There are a few kinds of sand as well that withstand different psi in ascending order: Fit for the purpose (FFP), to Brady Type, and most resistant northern white which is common from Wisconsin. The bauxite for bauxite based ceramic proppant is mined in Arkansas for Saint-Gobain and white sand can come from Wisconsin where other sands can come from China
On average, how much water is used during the well drilling process (including drilling and cementing, not including stimulation)?	This process only takes about 2-3% of total water
On average, how much water is used for brine dilution? What percentage of wells need brine dilution?	Average 50-60 barrels/day/well, 0.5 to 1 gal/min. Also, some may take up to 100 barrels/day.
In general, in what geographical region do the wells need brine dilution?	Mostly areas around Williston and south of Williston
If any, how much water is used during the secondary and tertiary recovering process? [The secondary recovery is also called waterflooding and the tertiary recovery is also called enhanced oil recovery.	An unknown amount of water. Denbury is a company that is experimenting with these techniques in unconventional wells
On average, what is the percentage of flowback water (the fracking water returned to the surface during initial production)?	For every barrel of oil recovered often there will be three barrels of water. This would be 75% water
Does your company reuse/recycle flowback water and/or produced water?	Very few companies are reusing or recycling. Technology is available but not widely used. One company is Sand X
If yes, in what processes is the flowback/produced water being reused (e.g., stimulation, recovery, etc.)? And, what percentage of the total water used for well drilling/stimulation/recovery is reused/recycled water?	Drilling may use more saline water as well as some recycled water for recovery
What percentage of the oil wells require refracking? What are the main reasons these wells require refracking	Refracking is not common as well because companies would rather drill a new well rather than refrack. Also, there is a lack of economic viability and difficulty when wells are too close to each other; however, with lower crude oil prices and increases in technology, there might be more use in 5-10 years
For the wells that require refracking, on average how many refracking jobs do they require?	Unknown.

Table 3.7. A summary of the 2015 Bakken Shale oil development interview (continued).

Question	Answer Summary
In your opinion, what are the main factors that affect the volume of water used for fracking (e.g., geology, type of HF fluid, pressure, number of stages, lengths of laterals, etc)?	The type of HF fluid makes a high impact. Slick water uses about 250,000 barrels of water per frack/well and gel uses 50-60,000 barrels of water per frack/well
What is the average concentration of total dissolved solids in the produced water? How does your company dispose of produced water?	Concentration is often at or above 250,000 TDS. Most companies can dispose of produced water in saltwater disposal (SWD) wells
How do you heat up fracking water? To what temperature you need to heat up the fracking water? What is the estimated cost of fracking water heating?	Most heat water on the well site using propane. Water typically needs to be heated to the 75-90o F range. The EERC reported water should be in the 85-90o F range. We would estimate the cost of heating water at a well site around $1.50/barrel but need more confirmation. Water depots charge between $.50-.75/barrel to heat the water to 1400 F. Water depots also use natural gas to heat the water, where onsite heating uses propane which is about three times as expensive
How far do oil companies normally transport water from water depots to well fracking sites? What are the main factors that affect your company's decision to buy what from certain water depots?	Normally transport water from water depots 0-40 miles. Location is a larger factor due to transportation costs, but water price is another factor
Has your company applied for industrial water permits from the North Dakota Office of Engineer?	Some oil companies apply for industrial permits for their water
What is the definition of the initial production of oil, water, and gases?	Normally there is a benchmark like 24 hours, 30 days, 60 days, 90 days, 1 year. 30 days is often used if not specified
What is the definition of the cumulative production of oil, water, and gases?	Total production at the current date.
How to estimate well life-long cumulative oil/water production from initial production?	Unknown. Oil and gas companies may know more.

Table 3.8. A summary of the 2015 water depot-based water allocation and management interview.

Question	Answer Summary
What is the average distance between your water depots to the points of diversion?	The water depots have between 1-50 miles for surface water sources and a few hundred feet to a few thousand miles for groundwater sources
On average, how many oil companies do you serve? What do you think is the main reason for the oil companies to buy water from your water depots?	An unknown number of oil companies. The main reason appears to be the price of water and location
Do you sell hot or cold water or both? What percentage of the water you sell is hot water?	Few water depots sell hot water, and most just sell cold water
What are the challenges facing your company?	Unknown.
How much does it cost to build a water depot?	Ranges from $100,000-2,000,000
What constitutes a significant share of the start-up cost?	All construction, pipeline, and various costs account for start-up cost
What is the approximate yearly (or monthly) cost of operation?	Ranges from less than $.05/barrel to less than $.20/barrel
What is the largest share of your operating cost?	If the water depot provides service on-site, labor will probably be the largest operating cost; otherwise, very little operating cost
On average, what was the price per 1000 gallons of water at your water depots in the past 3 months?	The average is about $20 per 1,000 gallons but could be as high as $25 per 1,000 gallons
Would you say the price of water at the Bakken changes frequently? Yes/No	Unknown. Additionally, the range can vary from $.20/barrel to $1/barrel. WAWS set the price at $.84/barrel
What are the main determinants of water price?	Infrastructure at the area and the location of the water depot
If you sell both cold and hot water, how much more do you charge for hot water?	Can range from $.50 to $.75 per barrel to heat the water to 140° F

The second round of structured interviews was designed to gain a better understanding of the decision-making processes and business behaviors of various types of water depots. In July 2016, we interviewed eight water depot owners/operators in Watford City, ND, and Williston, ND, through phone calls or face-to-face interviews. Among these eight water depots, two are permanent water depots, three are temporary water depots, one is irrigation transferred water depot, and two are municipal/co-op water depots. One of the water depot owners we interviewed has more than one water depot. The 2016 interview questions and answers are summarized in Tables 3.9, 3.10, and 3.11. The original questionnaires are provided in Appendix A.

Table 3.9. A summary of the 2016 permanent water depot interviews.

Question	Answer Summary
What information do you consider before applying for a water permit? (e.g. Water Demand, Water Sources, Road Condition) Which factors are most important?	Most people check with the ND SWC before applying for a water permit to check how much water they should apply for. Little information other than the presence of oil wells or companies in the area is considered by an individual (Water Demand).
Do you build your water depot after talking with oil companies or potential water consumers, or do you build with an expectation of being able to sell water?	N/A
How do you decide if you want to apply for a conditional or temporary water permit?	Apply for a temporary water permit only if plans are to sell water for less than a year; otherwise, apply for a conditional permit for a longer period. A conditional permit will also take more time to get approved, so to have faster access to water people apply for temporary permits.
How do you estimate the water demand nearby? Where do you get the water demand information?	Depends on how many oil companies will be fracking at well sites nearby; Potential water depot owners only estimate water demand by looking at the number of oil wells near a potential water depot site.
How do you decide which water sources you want to use?	Most people use an available water source on their own land
How do you determine the length of time you plan on using the water requested when applying for a water permit?	It depends on how much time others nearby have applied for with their water permits.
How do you decide the depot location and point of diversion location? (What are the acceptable distance between the depot and the existing road?)	Depot locations are determined by examining where busy areas are for oil operations and where few water depots are already located. The point of diversion location is preferred to be close to the depot location. Locating a depot closer to an existing road is preferable as well. Typically, depot location is within 1-2 miles from an existing road;
How do you estimate the amount of water to apply for?	Based on what the ND SWC suggests based on their models. Also, it depends on how long a person is willing to wait for the review of the application; more water takes longer to review;
How do you estimate the water withdrawal rate?	Based on what the ND SWC suggests based on their models. Surface water and groundwater have very different water withdrawal rates. Lake Sakakawea and the Missouri River allow very high pumping rates. Average groundwater withdrawal at 300-400 gallons per minute (GPM).
How many points of diversion do you have? Why do you have different POD for the same water sources?	For groundwater, different PODs might exist to find a good location to withdraw water from. Different PODs also come from applying several times for the same water source.
How much time do you spend planning before actually applying for a water permit?	N/A
Is water price an important factor in the competition for water sales with other water depots?	It was especially important during the high oil demand period. Prices varied from $1/barrel when oil production was booming to $0.20/barrel now at depots near the oil well sites.
What would you estimate the capital cost to build your water depot to be? (construction, pipeline cost, pump)	Average $200,000 -250,000; cheaper water depots are under $100, 000; a water depot with 6 truck lanes would be $1,500,000.
What is the approximate operating cost for your water depot? (electricity and labor)	N/A
How many permits are typically approved and rejected by the NDSWC each year or what is the average approval rate?	From Jan 2, 2013 – Jun 20, 2016, there were 236 denied out of 1,540 total permits applied for. This is about a 15% rejection rate (15.32%). On average, the rejection rate is 20%. This only applied to temporary water permits since conditional water permits are never denied; rather, they have a deferred status.

Table 3.10. A summary of the 2016 temporary water depot interviews.

Question	Answer Summary
What information do you consider before applying for a water permit? (e.g. Water Demand, Water Sources, Road Condition) Which factors are most important?	Look at drilling permits and make sure that trucks would not have to cross a bridge to access the water depot site. For the water source, he sometimes pumps out of surface water sources.
Do you build your water depot after talking with oil companies or potential water consumers, or do you build with an expectation of being able to sell water?	The water depot is built based on the factors mentioned earlier about the drilling permits and bridges. He may talk with an oil company for feedback as well.
How do you decide if you want to apply for a conditional or temporary water permit?	The surface water sources he uses are creeks, so they can’t be used in the winter. Temporary permits have worked well, and he would apply for a conditional permit if he had access to larger bodies of water such as a lake or something larger.
How do you estimate the water demand nearby? Where do you get the water demand information?	Look at the drilling permit nearby
How do you decide which water sources you want to use?	Based on relationships and money. He has good relationships with landowners, so he can access the water sources that are a part of these landowners’ property.
How do you determine the length of time you plan on using the water requested when applying for a water permit?	N/A
How do you decide the depot location and point of diversion location? (What are the acceptable distance between the depot and the existing road?)	Consults with landowners and only decides on locations based on what the landowners are comfortable with.
How do you estimate the amount of water to apply for? How do you estimate the water withdrawal rate?	The ND SWC helps and decides the amount for him. He mentioned positive experiences where the ND SWC seems to have his best interest in mind when applying for permits to maximize the amount he could get approved.
How many points of diversion do you have? Why do you have different POD for the same water sources?	N/A
How much time do you spend planning before actually applying for a water permit?	No specific amount of time was mentioned, but it takes longer now with drought conditions.
Is water price an important factor in the competition for water sales with other water depots?	The water price is very competitive.
What would you estimate the capital cost to build your water depot to be? (construction, pipeline cost, pump)	A minimal cost system in place at a creek costs $500. (Only a pump essentially)
What is the approximate operating cost for your water depot? (electricity and labor)	$1,800 per day.

Table 3.11. A summary of the 2016 irrigation transferred and municipal co-op water depot interviews.

Question	Answer Summary
What information do you consider before applying to transfer your water permit for selling water?	Nearby water demand. (Oil company contacted him to get water)
If you consider precipitation, and what kind of forecast precipitation information will you use?	he asks the NDSWC how much he could transfer
How do you make a decision based on forecast precipitation data?	N/A
Do you apply for a change in the use of water permits after talking with oil companies or potential water consumers, or do you apply with an expectation of being able to sell water?	Talks with oil companies beforehand
How do you estimate the water demand nearby? Where do you get the water demand information?	He gets information directly from nearby oil companies
How do you decide the water amount for transferring? Is water demand or surplus water a larger factor?	Based on information suggested by the NDSWC
What information is considered for Coop depot before applying for a water permit to sell water? (extra water, population growth, water demand)	WAWS: The government has set a policy where a maximum of 20 percent of total water withdrawals can be sold to oil companies, but the full 20 percent is not always sold. Now because of lower oil production water demand, approximately 5 percent of water withdrawal is being sold.
For WAWS, how do you decide on water depot locations?	The WAWS considers water demand and the locations of independent water depots in the area to avoid competition as well as building water depots in locations far enough away from cities.
What are the main water depot companies operating now?	Ames Water Solutions (Savage Water Solutions) West Dakota Water
What is the water price charged per barrel from WAWS?	It is always \$0.84/Barrel, and it is fixed by the government. Independent depots' water price is in the range of \$0.20-0.40/barrel now, but all the water from the WAWS is treated through the Williston water treatment plant and can be used for drinking. Note: Some farmers still come to nearby water depots for irrigation water use.

3.4. Software

The spatial agent-based model of water depots in western ND was developed in programming language C# and ArcObject SDK 10.2 (Esri, Redlands, CA). The development platform is Visual Studio 2012 (Microsoft, Redmond, Washington). The executable must be run in the environment of ArcMap 10.2 or higher version.

3.5. Coupling ABM with Groundwater Model

As mentioned in Chapter 1, NDSWC has developed and calibrated a MODFLOW-2005 groundwater model for the FH-HC aquifer (Fisher, 2013). MODFLOW-2005 is a three-dimensional (3D) finite-difference groundwater model first published in 1984 and now is maintained by the U.S. Geological Survey (USGS). MODFLOW-2005 solves the three-dimensional groundwater flow equations to simulate groundwater flow through a porous medium using a block center finite difference method (Harbaugh et al., 2005).

The FH-HC MODFLOW groundwater model covers an area of approximately 35,000 square miles (Fig. 3.8). The area is divided into 345 rows by 303 columns, oriented north-south, with cells of 3,650ft by 3,650ft. The grid was generated in the State Plane coordinate system (NAD83, units ft, Zone is ND South). The grid origin is located in the north-western corner of the modeled area at easting 849,530.25ft and northing 1,247,491.55ft. Vertically, the aquifer is represented as one confined layer. The aquifer in Montana was delineated based on information from Montana’s Ground Water Information Center. The bottom of the aquifer was defined as the transition to the top of the Pierre Formation, primarily from the increase in gamma-ray detections and decrease in electrical resistivity indicating a higher clay or shale content. The entire aquifer thickness includes both Fox Hills and Hell Creek Formations. The FH-HC groundwater model extent is shown in Figure 3.8.

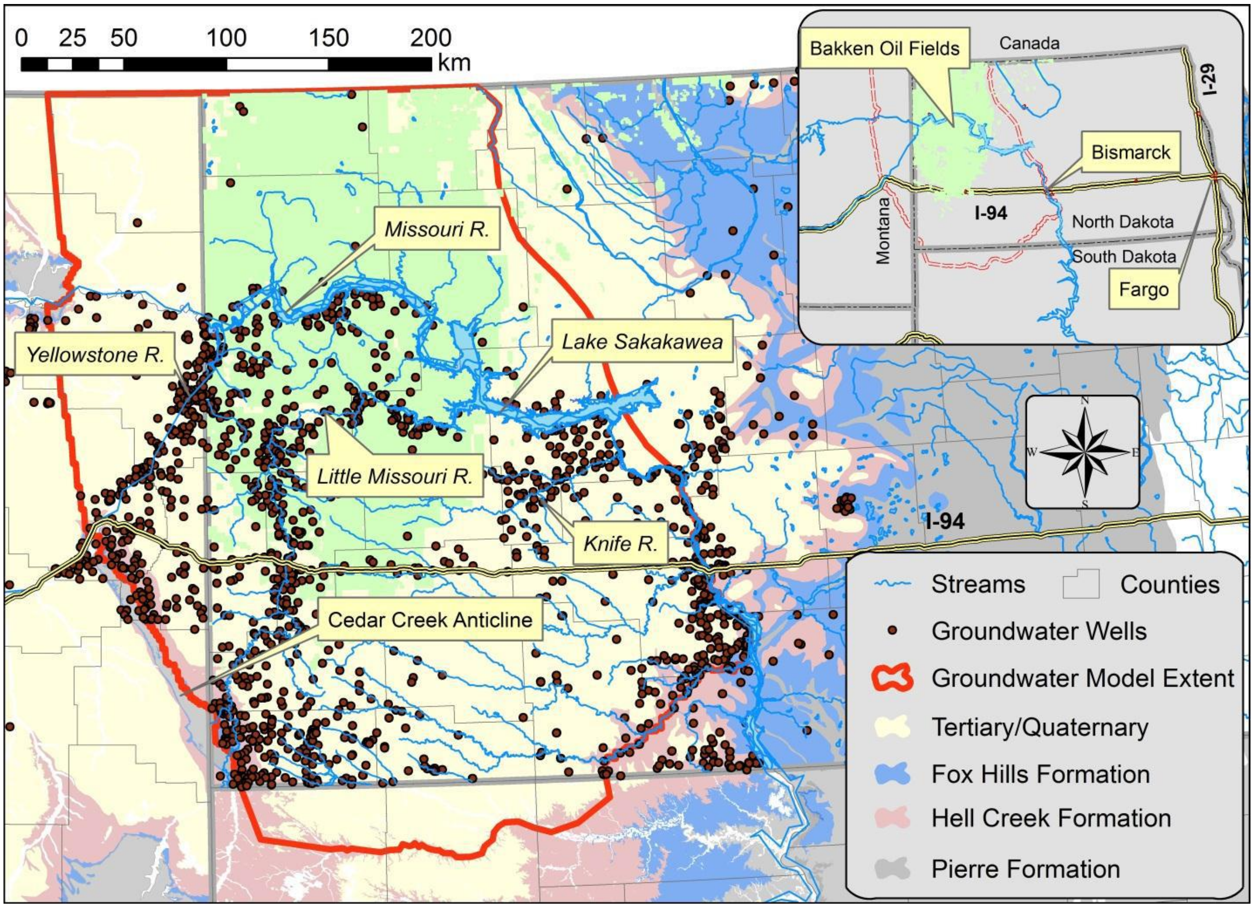

Figure 3.8. The Fox-Hills-Hell Creek aquifer in relation to the regional features of western North Dakota.
Note: This figure was produced by Z. Lin, from the proposal "A water depot-based decentralized optimization model for groundwater allocation and management at the Bakken Shale in western North Dakota".

The model was discretized into a steady-state stress period followed by transient yearly stress periods. The yearly transient stress periods were further divided into 15-time steps. The steady-state stress period, representing conditions in 1942, was to allow the simulated water levels to come into equilibrium with the boundary conditions. Hydrologic stresses and groundwater flow rates are assumed to have been constant or steady-state before 1942. The calibrated transient model runs from January 1, 1943, through December 31, 2009 (Fisher, 2013). The model will be coupled with the water depot agent-based model to simulate future water levels under different water supply and demand scenarios. The water depot agent-based model will provide yearly hypothetical pumping rates and locations from the FH-HC groundwater system to the FH-HC groundwater model, which will be used to predict the groundwater level changes in the FH-HC aquifer caused by the impacts of Bakken shale development, water management policies, and climate in western ND.

3.6. Coupling ABM with Surface Water Model

From the dataset obtained from NDSWC, the Missouri River and Lake Sakakawea are the most frequently used surface water sources in the region. However, they are not potentially affected by HF water use compared to other surface water sources because of their massive annual water flow and are not heavily appropriated. Little Muddy River is the most frequently used surface water source except the Missouri River and Lake Sakakawea in the region. During the year 2007 to 2014, 26 industrial water permits were issued on Little Muddy River and accumulated industrial water use was 1,639 acre-feet. Both the number of permits and total HF water use from the Little Muddy River is ranked second only behind the Missouri River. The average annual 7-day low flows from the Little Muddy River increased about 88 percent during 2008-2014, however, this increase is the least among other surface water sources in the region due to the tremendous HF water use (Lin et al., 2017). The Little Muddy River is a significant surface water source to address HF water stress.

The Soil and Water Assessment Tool (SWAT) model will be coupled with the developed ABM to simulate the potential impact of water demand and supply scenarios on streamflows in the Little Muddy River watershed. DEM, land use, and soil GIS data of the Little Muddy River watershed will be obtained from USGS websites. The precipitation data for the SWAT model will be obtained from the Climate Forecast System. The simulation time of the SWAT model will be from 2004 to 2014.

We will first run the agent-based model under different precipitation conditions. From the outputs of the agent-based model, HF water use from the Little Muddy River will be selected and imported to the SWAT model. The SWAT model with updated inputs will be run to predict the streamflow changes in the Little Muddy River.

3.7. Scenario Analysis

The coupled simulation models are capable of evaluating the influence of implementing new regulation policies for managing groundwater and surface water resources in western North Dakota under different future scenarios. The matrix of the future scenarios of water demand and supply is listed in Table 3.12.

Table 3.12. Future scenarios of water demand and supply in western North Dakota.

Supply	No change in demand (0%)	Small increase in water demand (50%)	Big increase in water demand (100%)
Wet year (122% of a normal year, current)	Scenario I-1	Scenario I-1	Scenario I-1
Normal year	Scenario II-1	Scenario II-2	Scenario II-3
Dry year (78% of normal)	Scenario III-1	Scenario III-2	Scenario III-3
No access to the Missouri River system	Scenario IV-1	Scenario IV-2	Scenario IV-3
Unlimited access to the Missouri River system	Scenario V-1	Scenario V-2	Scenario V-3

4. THE AGENT-BASED MODEL DEVELOPMENT

The agent-based model for the water depots in western North Dakota is described following the ODD+D protocol (Müler et al., 2013). The following ODD+D description provides an overview, design concepts, and details of our agent-based model that includes human decision-making processes.

4.1. Overview

4.1.1. Purpose

The purpose of the model is to simulate the water depot-based water allocation system in western North Dakota that distributes freshwater for Bakken shale oil development. The model was designed for regulators to make scientifically sound policies to manage regional water resources for long-term sustainable use.

4.1.2. Entities, State Variables, and Scales

The model includes four types of water-depot agents and one regulator agent such as state water management authority (i.e., North Dakota Office of the State Engineer). The four types of water depot agents are (1) water depots with conditional or perfected industrial water permits (denoted as permanent agents), (2) water depots with temporary industrial water permits (denoted as temporary agents), (3) water depots with a portion of their permanent irrigation water permits temporarily transferred for industrial water use (denoted as irrigation transferred agents), and (4) water depots owned by local cities/towns or the newly constructed Western Area Water Supply (WAWS) project (denoted as municipal/co-ops agents). Each water-depot group is defined as all water depots that have the same type of water permit. The regulator agent is a system-level administrator interacting with the other four types of water depot agents.

The state variables that represent the attributes of the water-depot agents are approved water amount, water permit type, water depot location, water source, water quality, passion, effort, network, operation time, total investment, operational fee, water price, water use, profit, historical water price, historical profit, and historical water use. In this model, the primary exogenous driver is the annual HF water demand in western North Dakota. The simulation area is the 16 western North Dakota counties where the Bakken shale oil development is occurring. All the water-depot agents are in discrete units, with the longitude and latitude being used to represent the agents' locations. The simulation period is 2007-2014 with a yearly simulation time step.

4.1.3. Process Overview and Scheduling

The main objective of the agent-based model is to maintain the water supply and demand balance for hydraulic fracturing in the Bakken region of western North Dakota. In the initialization process, the model is loaded with the area's GIS data, and the initial state is set to be the 2007 observed water depots. At each yearly time step, the 16 counties' HF water demands are calculated against the current water supply. The total HF water demand in each county is the sum of the HF water uses for all horizontal wells located in that county. On the other hand, the current total supply for industrial water use in each county is the total amount of water sold by all water depots located in that county. If the annual HF water demand is greater than the current water supply, the application, regulation, and competition sub-models will be called in order to generate more water depots (Fig. 4.1). Otherwise, the model will go to next year.

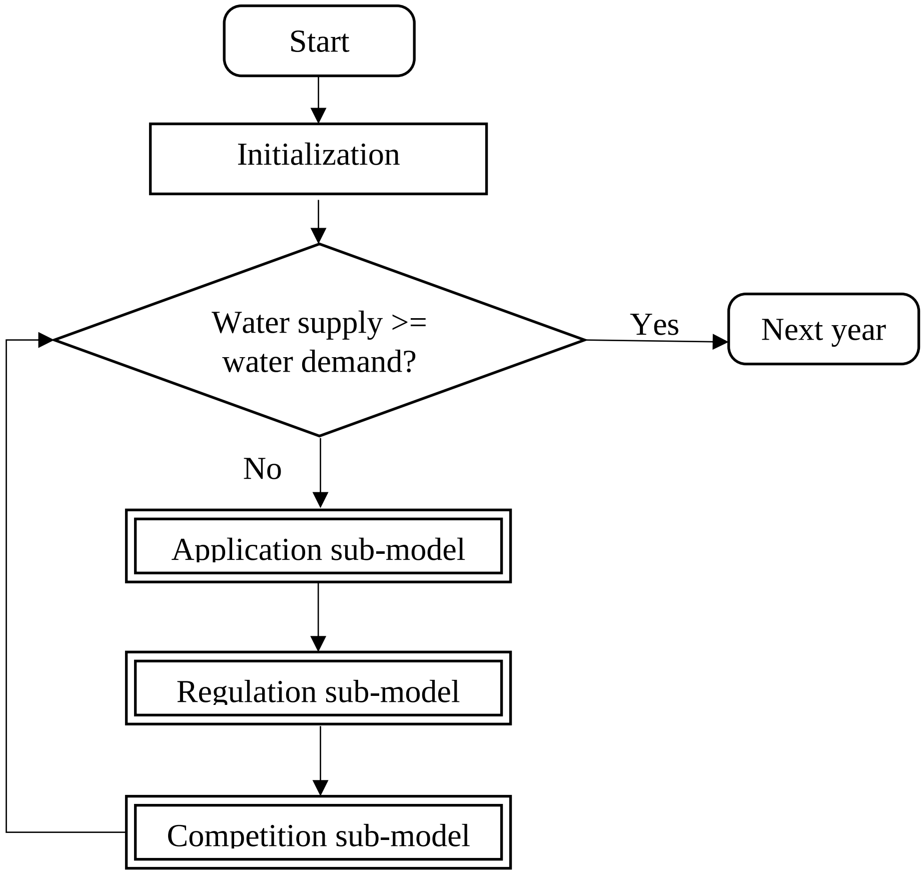

Figure 4.1. Overall flow chart of the agent-based model for water depots in western North Dakota.

4.2. Design Concepts

4.2.1. Theoretical and Empirical Background

Figure 4.2 shows the conceptual design of the agent-based model of the water allocation system in western North Dakota, where four types of water depots supply fresh water for Bakken shale oil development while being regulated by the North Dakota Office of State Engineer (NDOSE). The fundamental assumption for the model is that the amount of water supplied by the water depots should meet the amount of water used by the oil companies for hydraulic fracturing.

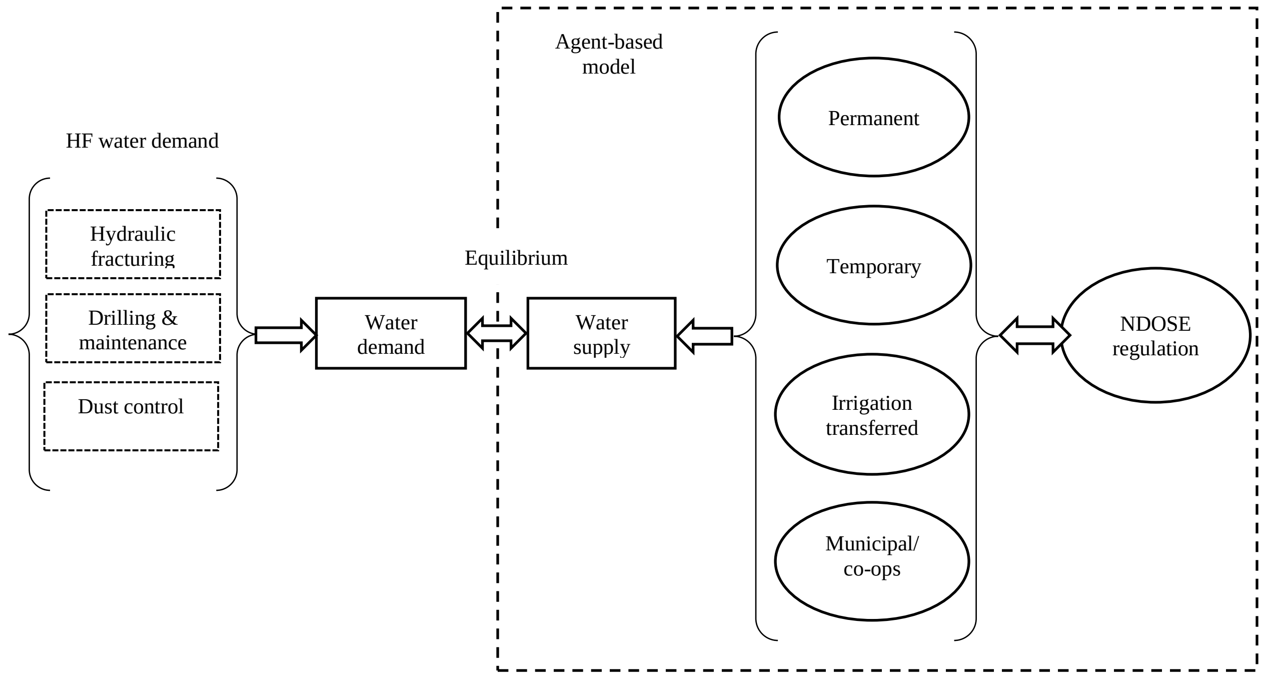

Figure 4.2. Conceptual design of the agent-based model of the water allocation system in western North Dakota.
Note: HF – hydraulic fracturing, NDOSE – North Dakota Office of State Engineer.

In the development of the agent-based model, institution theory is used to model the regulations of the state water management agencies, while evolutionary programming allows water-depot agents to select appropriate strategies when applying for industrial water use permits. Cognitive maps endow the water-depot agents' ability and willingness to compete for more water sales. All water-depot agents have their influence boundaries that restrict their competitive behavior toward their neighbors but not to non-neighboring agents. The water-depot agents' decision model is based on the assumption that their information processing capacity is limited and that they have only partial information within their cognitive boundaries; hence, they are boundedly rational. The decision-making process is constructed and parameterized with both qualitative and quantitative information, i.e., the knowledge gained from surveys/interviews with stakeholders and empirical water use data. By linking institution theory, evolutionary programming, and cognitive maps, our approach addresses a higher complexity of the real human decision-making process.

Water rights and permits in North Dakota are regulated by the North Dakota Office of State Engineer (Schuh, 2010), so the water allocation system that existed in western North Dakota is an administered market system. Based on our interviews with the regulator and water depot owners, the regulation of water permits from the state government significantly affects agents' behaviors. An (2012) stated that institution theory is commonly used for simulating the agents' behaviors guided by governmental regulations. In the regulation sub-model, institution theory is applied to model the interactions between water depots and the North Dakota Office of State Engineer.

In the water depot-based water allocation system in western North Dakota, each water depot owner selects a location to build a water depot. To simulate this location selection behavior, evolutionary programming and genetic algorithms are a good choice. Manson et. al (2005) applied evolutionary programming and genetic algorithms to simulate household agents' behaviors of searching for a suitable location for activities such as clearing forests and planting crops. Their location selection output is found to be consistent with the actual location obtained from local interviews (Manson and Evans, 2007). This consistency proved the reliability of the evolutionary programming and genetic algorithm methods in simulating agent's location selection behaviors. Evolutionary programming and genetic algorithms are applied in the permit application sub-model.

The cognitive map is a descriptive decision theory that describes how people make decisions. The method involves the individual's intention, experience, memory, learning ability, beliefs, knowledge, and relationship with neighbors to reach its conclusions about some issues

(Kolkman, 2005). From our interviews with the water depot owners, their intention, relationship, and knowledge affected their decision-making process during water depot operations. So, the cognitive map is applied in the competition sub-model to simulate the agent's ability and level of desire to compete for more water sales.

In the permit application sub-model, individual oil well HF water use data provided by the North Dakota Department of Mineral Resources' Oil and Gas Division (NDOGD) are used to determine the shortage in the water supply. The water depot data obtained from NDOSE are used to determine water depot types. Historical water permit data are also obtained from NDOSE to determine how much water amount to apply by a water-depot agent when starting a new water depot. The oil well HF water use, water depot, and water permit data are available from 2004 to 2014.

Various GIS spatial data are used by water depot agents through evolutionary programming to search for a suitable location when building a new water depot. These GIS data include land uses, road conditions, water sources, and oil well locations. Land use and road condition spatial data are obtained from the North Dakota GIS Hub (https://gishubdata.nd.gov/). Water sources are obtained from NDOSE, and oil well locations are obtained from NDOGD. All GIS spatial data used in the model are up to date and they covered the entire study area, the 16 counties in western North Dakota.

In the regulation sub-model, historically observed streamflow and groundwater level data obtained from USGS gauge stations (https://waterdata.usgs.gov/nd/nwis/rt) and NDSWC observation wells (https://www.swc.nd.gov/info_edu/map_data_resources/) are used to determine the difficulty level of applying for industrial water permits from a certain water source. Historical water permit data are used to determine the approved water amount for industrial use. The county-level precipitation data obtained from PRISM (http://www.prism.oregonstate.edu/) are used to determine whether it is necessary to hold certain industrial water permits in abeyance. In the competition sub-model, interviews with water depot owners are used to determine the goals, water price range, and other main concepts related to water-depot agents' competition behaviors. Other GIS data including road conditions, oil well locations, and water source locations are also used to formulate water-depot agents' competition behaviors.

4.2.2. Individual Decision-Making

Decision-making is modeled at the individual water-depot agent level. Water-depot agents make decisions in two different aspects. First, water-depot agents need to select a location to build a new water depot, and subsequently decide which water source to withdraw water from and how much water to be specified in their water permit applications. Second, water-depot agents need to adopt certain strategies for water sale competition.

To start a business, the water-depot agents need to find a suitable location with unknown water demand and a limited budget. They also try to find the best strategies to compete for more water sales by adjusting the water prices and expanding their networks with the nearby oil wells.

To find a suitable location, the water-depot agents use a form of multicriteria evaluation to assess the suitability (S) of any location for building a water depot. The agents treat the multicriteria evaluation as a symbolic regression problem. The symbolic regression approximates the suitability function as:

$$S = \sum_{i=1}^{5} \beta_i X_i \tag{4.1}$$

in which, X stands for different spatial factors: X_1 for land use, X_2 for distance to a local road, X_3 for distance to a certain water source, X_4 for nearby oil well density, X_5 for nearby water depot density. β's are the weights for the spatial factors and are determined through evolutionary programming (To be described in the permit application sub-model).

Cognitive map theory is applied to structure the water-depot agents' mental models in the decision-making process of water sale competition. The goal of a water-depot agent is to make the business profitable. Water price and network are two major concepts related to the water-depot agent's competition behavior. To find the best strategies for water sale competition, the water-depot agents compare their water sales with their neighbors' within their cognitive boundaries, then copy the strategies from their neighbors through adjusting water price, developing additional network links. The water-depot agents also try to develop the best strategies based on their own past performance.

Social norms or cultural values do not play a direct role in the water-depot agents' decision-making process. However, the regulation of water permits from state government significantly affects the water-depot agents' behaviors. Land use, road condition, distance to local roads, and distance to water sources also influence the outcome of the water depot's location selection. Except for the temporary water-depot agents, other water-depot agents are assigned with memory attributes. The agent's competition decision-making is influenced by the memory of the past water prices, HF water demands, and water sales. The water-depot agents may have different levels of memory strength, i.e., they weigh their experiences in the past more or less differently.

The water-depot agents try to address the uncertainty associated with obtaining a water permit from NDOSE by considering the previous applications that propose to withdraw water from the same water source. The water-depot agents also try to address the uncertainty associated with the HF water demand by treating the past water demands as a predictor of the future ones.

4.2.3. Learning

In this model, individual learning is included in the competition sub-model that simulates the behaviors of the water-depot agents' competition for more water sales. The permanent and the irrigation transferred agents have learning abilities since these two types of agents run their business for more than one year and have more flexibility in adjusting their strategies. A permanent agent or an irrigation transferred agent changes its competition behavior by learning from its neighbors and its own experience in the past. The details can be found in the competition sub-model. The water-depot agents are capable of exchanging water price information within their cognitive boundaries but no collective learning is implemented in the model.

4.2.4. Individual Sensing

The regulator agent can sense the observed streamflows of the rivers/streams and the observed water levels of groundwater aquifers within the study area. It can also sense all approved water amounts and precipitations. The regulator agent also knows the information about water permit applications, water permit types, permit application and approval dates, year of operation, and annual water-depot water uses.

The individual irrigation transferred agents know about the county-level water demand, precipitation, approved water amount of the irrigation water permits, water depot locations, water sources, water uses, water prices, operation time, budget, road information, nearby oil wells, and network links. The municipal/co-op agents know about city or town populations, approved water amount of the municipal water permits, water depot locations, water sources, actual water uses, water prices, operation time, road information, nearby oil wells, and network links. The permanent and the temporary agents know about historical water permits for a certain water source, approved water amounts, water depot locations, land use, water sources, water uses, water prices, operation time, budget, distance to road, nearby oil wells, and network links.

The regulator agent's sensing process is modeled without errors, and the spatial scale of its sensing is global. The water-depot agents are also assumed to receive water price information without errors, and the spatial scale of their sensing is local. In the model implementation, the agents are assumed to simply know the values of the relevant variables, i.e., they do not carry out any activities to receive this information. The costs for cognition or for gathering information are also not explicitly included.

4.2.5. Individual Prediction

The permanent and the temporary agents use historical water permit data associated with a certain water source to decide how much water to apply in their water permit application for a new water depot. This prediction process is simulated with no error, and there are no internal models used by the agents to estimate future conditions.

4.2.6. Interaction

Two types of interaction behaviors are modeled in the study: one is the interactions between the regulator agent (i.e., NDOSE) and the water-depot agents, and the other is the interactions among the water-depot agents. All water-depot agents have to follow the NDOSE's regulations, so the interactions between the regulator and the water-depot agents are direct. Their interactions are also dependent upon specific water sources because some water sources (e.g., the FH-HC aquifers) are regulated more strictly than others. The regulator agent also coordinates the water uses, which may affect the water extraction decisions for individual water-depot agents, who implement the regulator agent's decisions without errors.

The water-depot agents compete for more water sales with each other. The interactions between the water-depot agents are indirect because the HF water demands fulfilled by one agent are no longer available for the other agents. Since a water-depot agent only competes with the other agents within its cognitive boundary, so this type of interaction depends on the locations of the water-depot agents. The communications between the water-depot agents mainly include exchanging water price information.

4.2.7. Collectives

Individual water-depot agents belong to four different groups of agents: permanent, temporary, irrigation-transferred, municipal/co-op agents. These four groups are defined by the modeler based on the differences in their water permits. Permanent water depots hold conditional or perfected industrial water permits, which are associated with water rights and last for more than one year. Temporary water depots hold temporary industrial water permits, which are not associated with water rights and expire within a year. Irrigation transferred water depots temporarily transfer irrigation water permits into industrial water permits for one year. Municipal/co-op water depots are owned by local towns or the newly constructed WAWS project, and their water permits are temporarily transferred from municipal into industrial water use.

4.2.8. Heterogeneity

The water-depot agents are heterogeneous. They are different in the state variables such as approved water amount, water permit type, water depot location, water source, passion, effort, network, operation time, total investment, operational fee, profit, water price, water use, historical water price, historical profit, and historical water use. The decision-making processes of the four types of water-depot agents are also different in three aspects. First, the depot location selection process is different. The permanent and the temporary agents use evolutionary programming and genetic methods to select a suitable location within a county, while the locations of the irrigation transferred and the municipal/co-op agents are determined by the existing depot locations. Second, the process of determining the total industrial water amount to apply for is also different, the irrigation transferred and the municipal agents have a process that estimates how much water to transfer from their original water permits based on precipitation or population data. However, the permanent and the temporary agents estimate the water amount based on the historically approved water permits for a certain water source. Third, the competition behaviors of the four types of water-depot agents are also simulated differently. The permanent and the irrigation transferred agents are assigned with learning ability so that they can make some adjustments to water prices or expand the network by learning from their neighbors and their own past experience. The permanent, irrigation transferred, and municipal/co-op agents can set annual water sale objectives at the beginning of each year and review their objectives at the end of that year. The temporary agents are not capable of changing their water prices and do not set annual water sale objectives.

4.2.9. Stochasticity

In the permit application sub-model, all new permanent and temporary agents are assigned with an initial location randomly generated by assuming they may be uniformly distributed within the 16 counties in western North Dakota. For each new permanent or temporary agent, the total water amount to apply for in the water permit is also randomly generated based on the past water permits issued for the same water source. To simplify the actual water permit approval process, in the regulation sub-model a random value generated between 0 and 1 is compared with the difficulty level assigned to the water source. The detail is provided in the regulation sub-model.

In the competition sub-model, the permanent or the irrigation transferred agents set up the initial water prices randomly between $0.20/barrel and $1.00/barrel. Their passion attributes are randomly set to be “high”, “medium”, or “low”. Correspondingly, the permanent or the irrigation transferred agents set up their water sale objectives with the return on investment (ROI) ratio being randomly generated between 20 -100 %. Three different investment levels, $50,000 – $250,000, $250,000-$1,000,000, or $1,000,000 -$2,000,000, are randomly generated for the permanent or the irrigation transferred water depots. The municipal/co-op agents set up their water sale objectives with the expected water use ratio randomly generated between 0 to 5 %. The effort values corresponding to the three different passion attributes (low, medium, and high) are randomly generated between 0-40, 40-70, and 7-100%. The temporary agents set up their water prices and the effort values dependent upon how they perceive the competition level within the cognitive boundary. If the competition level is perceived to be high, the water prices are randomly generated between $0.20/barrel and $0.60/barrel, and the effort values are randomly generated between 50-100%. If the competition is perceived to be low, the water prices are randomly generated between $0.60/barrel and $1.00/barrel, and the effort values are randomly generated between 0-50%. In the water use calculation sub-sub-model, the order of selecting water depots is random, and for each water depot, the order of selecting oil wells is also random.

4.2.10. Observation

Water depot locations, water sources, points of diversion, water uses, and the number of water depots are collected at the end of each simulation year for model testing and analysis. The key outputs of this agent-based model include the spatial locations, points of diversion, water-depot types, and water uses of individual water-depot agents whose water use is greater than 0. The water uses are also aggregated at the county and the water source levels.

4.3. Details

4.3.1. Implementation Details

The model is implemented using C# and ArcObject SDK 10.2 (Esri, Redlands California US). The development platform is Visual Studio 2012 (Microsoft, Redmond Washington US). The model of the desktop version can be made available upon request, but the executable must be run in the environment of ArcMap 10.2 (Esri, Redlands California US) or a higher version.

4.3.2. Initialization

The model is initialized in the year 2007. In the initialization process, the map of the 16 counties in western North Dakota are prepared, and the spatial data of water sources, oil wells, county-level precipitation, and road are uploaded. Also, sixteen existing water-depot agents are populated with attributes for locations, water sources, permit types, approved water amounts, and water uses. The water price and network link attributes are initialized following the processes described in the competition sub-model. The initialization is always the same for different simulation scenarios.

4.3.3. Input Data

The spatial extent of the 16 western North Dakota counties, as well as the oil wells drilled during 2007-2014, populations, county-level precipitation, road networks, and water sources in western North Dakota, are provided as GIS layers. Irrigation and municipal permits are provided as Excel files. All the input data and their explanations are listed in table 4.1.

Table 4.1. Input data for the agent-based model of the water depot-based water allocation system for the Bakken shale oil development in western North Dakota.

Input data	Explanation
County extent	A layer includes 16 counties in western North Dakota. In the model, the information of the 16 counties are processed in the following order: Divide, Burke, Renville, Bottineau, Williams, Mountrail, Ward, McKenzie, Dunn, Mercer, Mclean, Golden Valley, Billings, Stark, Slope, Bowman
Oil wells	GIS layers include oil well locations and HF demand from 2007 to 2014
Population	An Excel table includes city or town populations in 16 western counties obtained from United States Census Bureau (website)
Annual precipitation	An Excel table includes annual county-level precipitation of the 16 western counties from 2007 to 2014
Roads	A GIS layer includes all different types of roads in the 16 western counties
Water resources	GIS layers include all surface water and groundwater resources located in the 16 western counties
Irrigation permits	An Excel table includes all irrigation permits inside the 16 western counties
Municipal permits	An Excel table includes all existing municipal and coop water depots locations and the related water source information

4.3.4. Sub-models

The agent-based model consists of three sub-models: permit application, regulation, and competition sub-models. The permit application sub-model describes the process of a water-depot agent applying for an industrial water permit. This sub-model used the evolutionary programming and genetic algorithm methods to simulates water-depot agents' decision-making on location selection, water source selection and applied water amount for their water permit applications.

The regulation sub-model implements the institution theory to simulate the process of water-depot agents' interactions with the regulator agent, NDOSE. In this sub-model, the regulator affects water-depot agents' states and behaviors in three areas. First, the regulator agent checks the water-depot agent's actual water use. The regulator agent may cancel the water-depot agent's conditional water permit if the cumulative water uses equal to zero after the water-depot agent has been holding a water permit for more than three years. Second, the regulator agent sets the accessibility and the difficulty levels of applying for a water permit from four different types of water sources in western North Dakota (i.e., Fox-Hills and Hell Creek, other groundwater, Missouri River, and Lake Sakakawea, and other surface water sources). The approval rate of a new water permit application will be determined by these two parameters. Third, the regulator agent holds a certain number of water permits in abeyance based on the permits' priority dates during dry years when precipitation is below 30-year normal.

The competition sub-model applies the cognitive theory to simulate the water-depot agents' competitions for more water sales by adopting the best marketing strategies through learning from their neighbors and their own past experience. Table 4.2 lists the parameters used in these three sub-models.

Table 4.2. Parameters used in the sub-models.

Parameter symbol	Explanation	Default value/ scenario range
N	Total number of newly generated water-depot agents	700-1000
R_{pt}	The ratio of newly generated N_t temporary agents divided by N_p permanent agents	1-500
Permit application sub-model		
M	Population size	10-500
G	Generation over which genetic programs evolve	10-100
P_c	Crossover probability	0.9
P_m	Mutation probability	0.001
P_r	Reproduction probability	$1 - (P_c + P_m)$
D_{mg}	Maximum depth of genetic programs when generated	5
D_{mc}	Maximum depth when genetic programs cross	17
F_s	Functions that can act as tree nodes	+ - × ÷
P_L	Maximum genetic program length	500
Regulation sub-model		
A_l	The accessibility of the Lake Sakakawea and Missouri River	Yes or No
A_f	The accessibility of the Fox-Hills Hell Creek	Yes or No
D_l	The difficulty level of obtaining water permits from the Lake Sakakawea and Missouri River	0-1
D_{osw}	The difficulty level of obtaining water permits from other surface water sources	0-1
D_f	The difficulty level of obtaining water permits from the Fox Hills-Hell Creek aquifer	0-1
D_{og}	The difficulty level of obtaining water permits from other groundwater sources	0-1
S_t	Streamflow threshold under which new water permits withdrawing water from other surface waters will not be approved	0.2
G_t	Water level threshold under which new water permits withdrawing water from other groundwaters will not be approved	0-100 m
A_b	Percentage of water permits hold in abeyance based on the permits priority dates during dry years	0-100
Competition sub-model		
P	Profit expectation	0-100%
I_t	Competition intensity threshold	1-10,000
P_a	Permits abeyance ratio	5%
α	Weight for water quality	1-100
β	Weight for water price	1-100
γ	Weight for road distance	1-100

4.3.4.1. Permit application sub-model

The permit application sub-model simulates the new water-depot agent's generation and industrial water permit application processes. This sub-model consists of three-generation sub-sub-models for the irrigation transferred agents, the municipal/co-op agents, as well as the permanent and the temporary agents, respectively, as shown in figure 4.3.

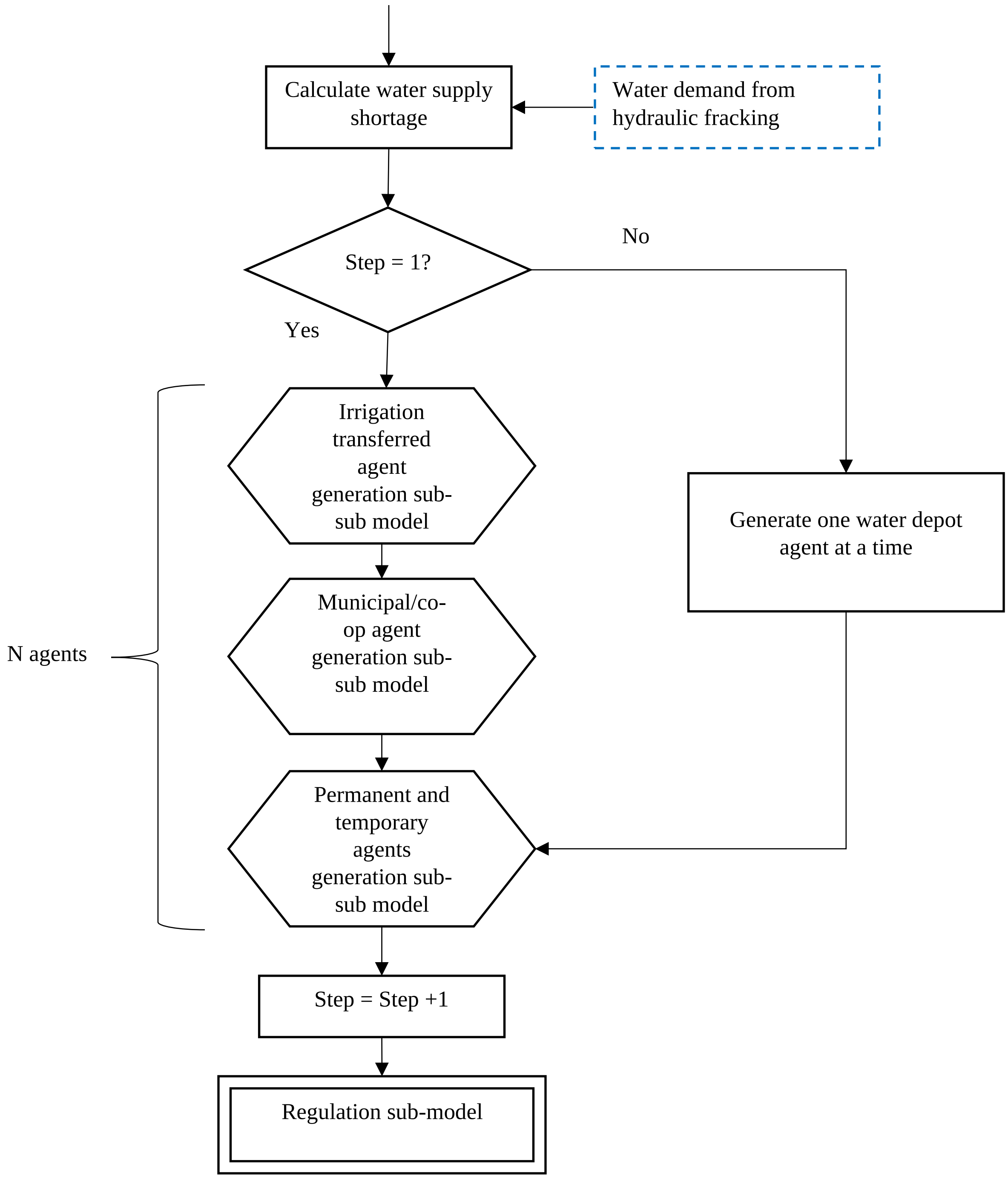

Figure 4.3. Permit application sub-model.

When the total water supply in the region is lower than the HF water demand, N water depot agents will be generated simultaneously. Among these N newly generated water depots, there will be N_i irrigation transferred water depots, N_{mc} municipal/co-op water depots, and N_{pt}

permanent and temporary water depots. In the water depot generation sub-sub-models, water depot location, water source, and water amount for each new water-depot agent will be determined. If the total water amount supplied by these newly generated *N* water depots still does not meet the HF water demand, the permit application sub-model will generate more temporary water-depot agents one at a time to fulfill the water demand.

In the irrigation transferred agent generation sub-sub-model shown in figure 4.4, all irrigation permit owners within the 16 western counties will make a decision whether to transfer a portion of their irrigation permits into industrial water use. The irrigation water permit owners will first compare the predicted precipitation in the current year with the 30-year normal. If the predicted county-level precipitation is greater than the 30-year normal, the irrigation permit owners will decide to transfer part of their water approved in irrigation permits for industrial water use for one year. These irrigation permit owners will become the irrigation transferred agents. Then, they will determine the water transfer rate T_{ir}:

$$T_{ir} = \beta_0 + \beta_1 W_d + \beta_2 P_i \tag{4.2}$$

in which, W_d stands for the county-level water demand in the current year; P_i stands for the difference between the current county-level precipitation and that received in the 30-year normal; β's are the weights for the predictor variables, and they are determined based on the observed data. The total irrigation water transfer amount W_{it} is determined by

$$W_{it} = T_{ir} \times W_i \tag{4.3}$$

in which, T_{ir} stands for the irrigation transfer rate and W_i for the total approved irrigation water amount in the irrigation water permits. The locations and the water sources of the irrigation transferred agents will be the same as the original irrigation water permits.

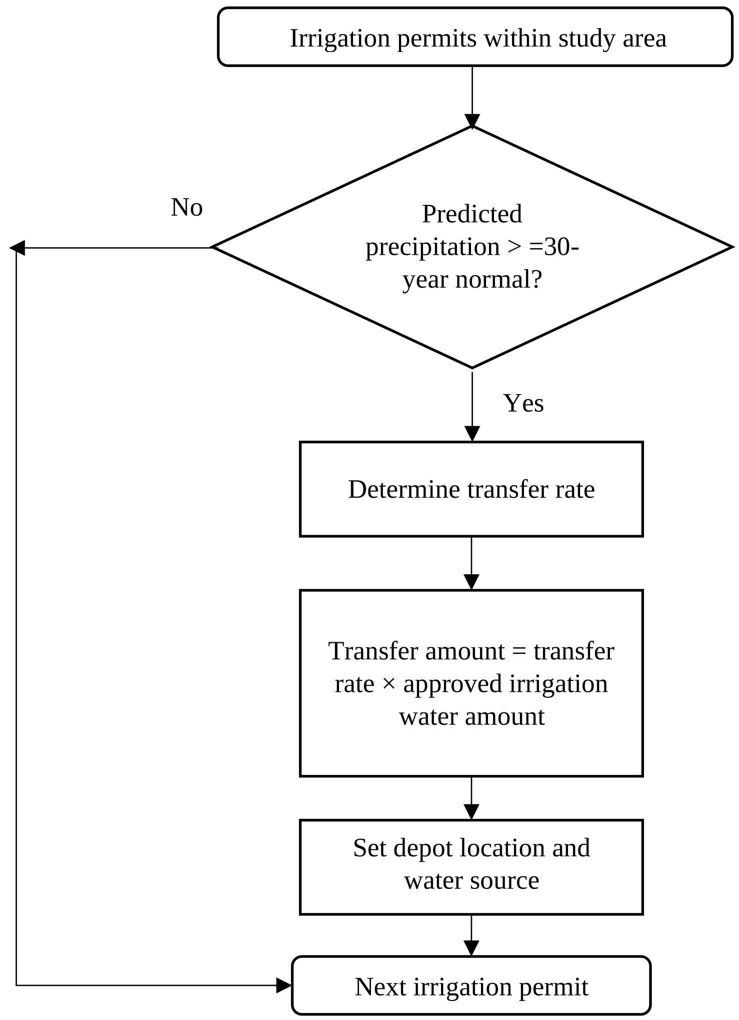

Figure 4.4. Irrigation transferred agent generation sub-sub-model.

The municipal/co-op agent generation sub-sub-model is shown in figure 4.5. All municipal water permits will be first checked whether they belong to the Western Area Water Supply Project (WAWSP). If a municipal water permit belongs to the WAWSP and the current simulation year is 2011, then this WAWSP municipal permit will be used to generate a co-op water depot agent. Nine co-op water-depot agents are generated in 2011 because the 2011 North Dakota state legislature authorized the construction of the WAWSP to serve the oil industry. The locations of these nine co-op water depot agents will be at the original WAWSP construction locations. All these nine co-op water-depot agents use the same water source, namely, Lake Sakakawea and the Missouri River. The North Dakota state legislature also authorized to sell up to 20% of the WAWSP's water to the oil industry, so 20% of the approved WAWSP permit is transferred for industrial water use. The approved water amount for each co-op water-depot agent is assigned to be one-ninth of the total municipal transferred water.

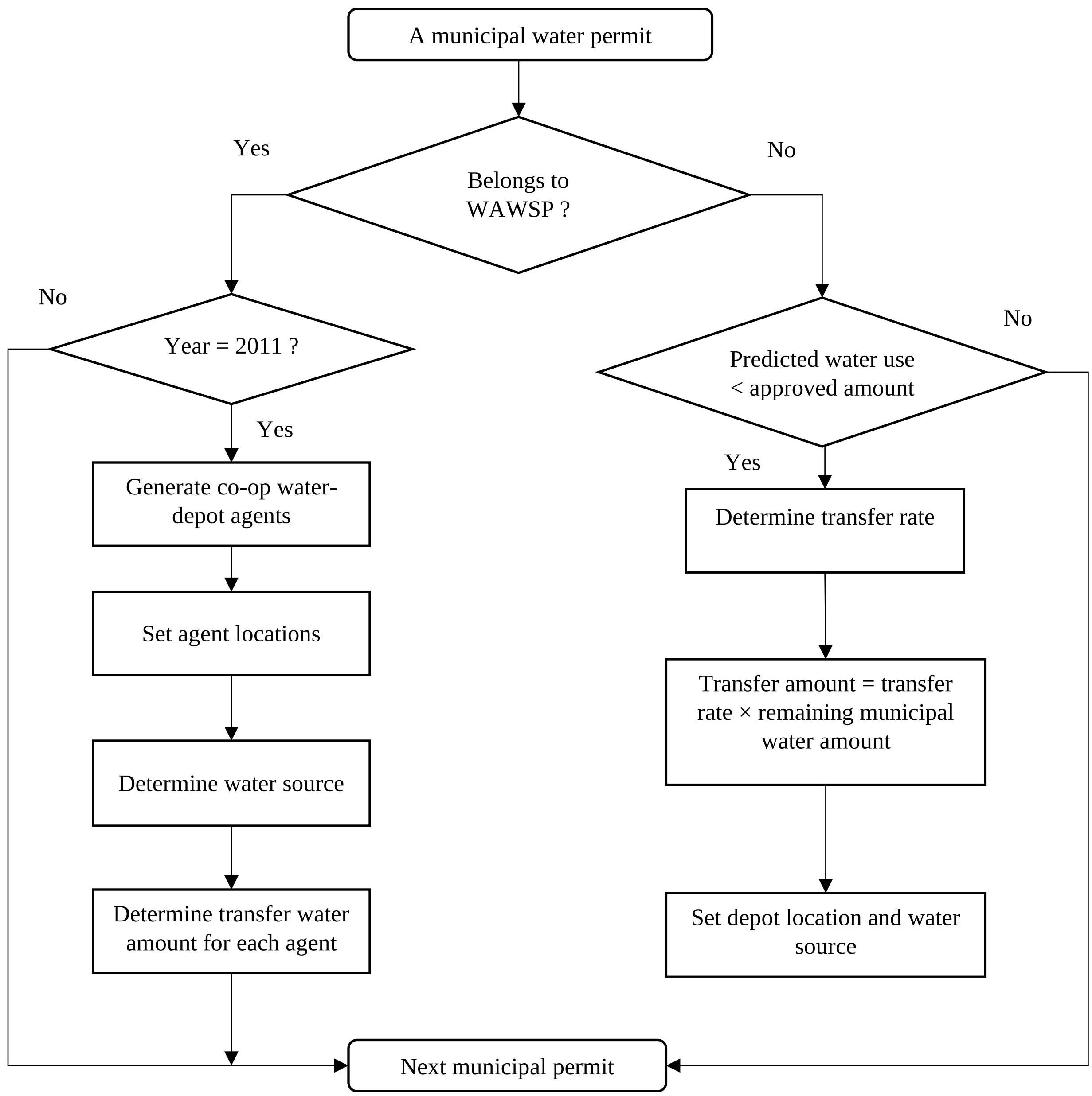

Figure 4.5. Municipal/co-op agent generation sub-sub-model.

If a municipal permit does not belong to the WAWSP, this municipal permit owner needs to make a decision on whether to transfer a portion of the municipal permit into industrial water use. The municipal water permit owner will first predict the municipal water use in the current year based on city or town population data:

$$W_{mp} = W_{ml} \times \frac{P_c}{P_l} \tag{4.4}$$

in which, W_{mp} stands for the predicted municipal water use amount in the current year; W_{ml} stands for the total municipal water use amount in the last year; P_c stands for the city or town population in the current year; P_l stands for the city or town population in the last year.

After calculating the predicted municipal water use in the current year, the municipal water permit owner compares the predicted municipal water use in the current year with the approved municipal water amount. If the predicted municipal water use is lower than the total approved municipal water amount, the municipal water permit owner will transfer a portion of the municipal permit into industrial water use. Then a municipal water-depot agent is generated, and the transfer rate T_{mr} is determined as

$$T_{mr} = \beta_0 + \beta_1 W_d + \beta_2 P \tag{4.5}$$

in which, W_d stands for the county-level water demand in the current year; P stands for the difference between the city or town's population in the current year and that in the last year; β's are the weights for the predictor variables and these weights are also determined based on the observed data. Then the total municipal water transfer amount W_{mt} is determined by:

$$W_{mt} = T_{mr} \times W_m \tag{4.6}$$

in which, T_{mr} stands for the municipal water transfer rate and W_m for the total approved municipal water amount in the municipal water permits. The depot location and the water source of the newly generated municipal transferred water depots will be the same as the original municipal water permit.

The permanent and temporary agent generation sub-sub-model is shown in figure 4.6. N_{pt} permanent and temporary water depot agents will be generated:

$$N_{pt} = N - N_i - N_{mc} \tag{4.7}$$

in which, N stands for the total number of newly generated water-depot agents; N_i stands for the total number of newly generated irrigation transferred agents; N_{mc} stands for the total number of newly generated municipal/co-op agents.

In these N_{pt} water-depot agents, there will be N_p permanent agents and N_t temporary agents. The numbers of these two different types of depot are calculated based on the ratio R_{pt}, which is defined as the ratio of N_t divided by N_p. Specifically,

$$N_p = \frac{1}{1+R_{pt}} \times N_{pt} \text{ and } N_t = N_{pt} - N_p \tag{4.8}$$

After the total numbers of the new permanent and temporary agents are determined, the sub-sub-model will determine how many new permanent and temporary water-depot agents will be generated for each county within the study area. To implement this procedure, a weight W is first calculated based on the county-level HF water demand in the current year. Then the number of the permanent and temporary agents generated for each county will be N_{pt} times W. The weights for the sixteen counties are W_1, W_2, ……, W_{16}. The sum of these weights equal to 1. For example, the weight W_1 for Divide county (the first county in the county list) is calculated:

$$W_1 = \frac{H_1}{H} \tag{4.9}$$

in which, H_1 stands for the HF water demand from Divide county in the current year, and H stands for total HF water demand from sixteen counties in the current year.

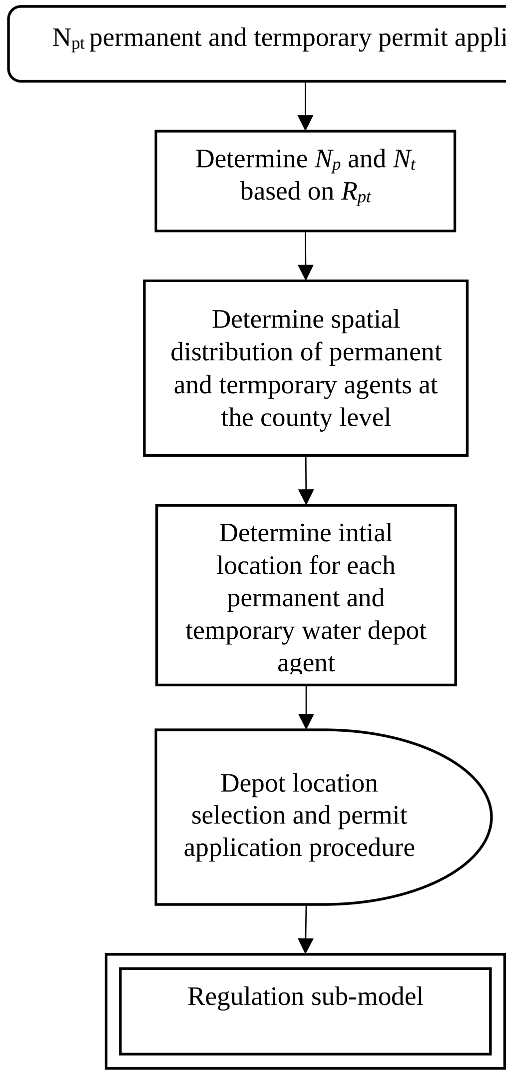

Figure 4.6. Permanent and temporary agent generation sub-sub-model.

After the numbers of permanent and temporary agents for each county are determined, the initial location of each permanent and temporary water depot will be determined. Within a county, all the permanent and temporary agents are assigned with an initial location randomly generated by assuming they are uniformly distributed within the county. Beginning with this initial location, the agent will search for a suitable location nearby to build a water depot facility and then select a water source and estimate the water amount to apply for their conditional permanent or temporary permit. The process is shown in figure 4.7.

To search for a suitable location to build a new water depot, a permanent or temporary agent will use the suitability estimation function to assesses the suitability of all nearby locations within a certain boundary. Then all the possible locations will be compared to find the most suitable location within the boundary. This most suitable location will be used to build a new water depot, and based on this location, the nearest water source will be selected by the water-depot agent to apply for a conditional or temporary water permit. Next, the water-depot agent will estimate the water amount to apply based on the water permits issued in the past for the same water source. As described earlier, suitability (S) is defined in Eq. (4.1).

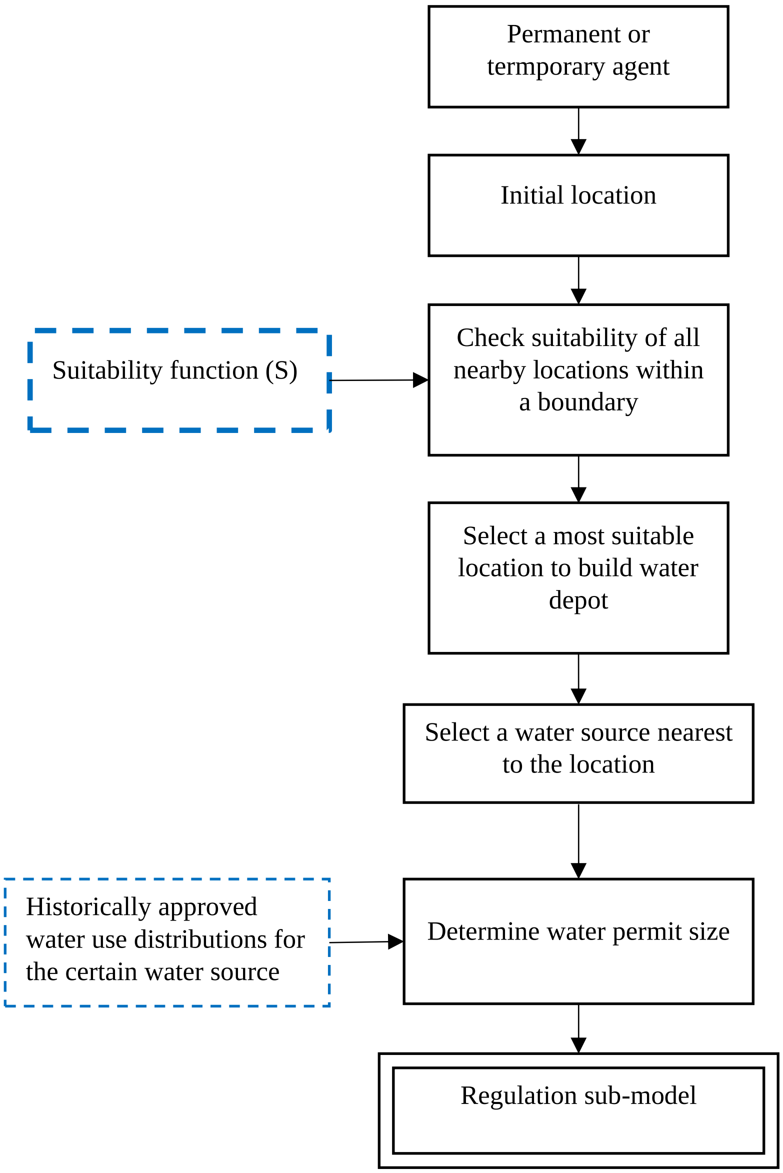

Figure 4.7. Water depot location selection and permit application procedures.

Eq. (4.1) is an instance of symbolic regression, where the observations of the response variable (suitability) are used to estimate the weights of the independent predictor variables. $C = \{C_1, ..., C_n\}$ are cells in the spatial layers corresponding to the response variable of suitability to build water depots. The genetic programs serve as symbolic regression solutions with a function set (F) composed of arithmetic operators (+ - × ÷) and a terminal set (T) defined by spatial factors X's. These genetic programs are trees composed of terminals and functions in a branching structure. Functions can range from simple arithmetic operators (×) to complex arithmetic operators (+ - × ÷). Terminals are defined by spatial factors *X* in Eq. (4.1) and include ephemeral random numbers used to solve the symbolic regression. The water-depot agent extracts values for each independent variable *X* in a certain sampled location and the weights β will be randomly generated initially.

The suitability function will be solved using evolutionary programming and genetic methods before being used for water depot location selection. The evolutionary programming process is shown in figure 4.8. The power of genetic programming lies in the computational analogs of natural selection. To begin the evolutionary programming process, a water-depot agent will be equipped with 500 genetic programs. Each member of the initial population of genetic programs has a tree structure randomly constructed from functions and terminals, and they compose the first generation (i.e., G = 1). The members of the first generation pass on their genetic materials to the next generation (i.e., G = 2). The initial generation consists of poor solutions because they are random agglomerations of functions and terminals, but each succeeding generation becomes better because the individuals create offspring via three operators – mutation, crossover, and reproduction – that are applied to the programs' tree structures over many generations to evolve into better programs. Crossover is equivalent to breeding because it involves trading portions of two-parent programs to create two offspring programs that contain random portions of parental tree structures (analogous to genes). Reproduction is like cloning because it involves placing a duplicate of a parent into the next generation as offspring. It is useful for maintaining the coherence of strategies across generations. The mutation is similar to genetic mutation because it randomly changes constituent nodes of a parent to create a new offspring program. In addition to ensuring that programs can jump into new parts of the search space, mutation protects terminals and functions from disappearing from the population.

Each generation serves as the ‘children’ of the preceding generation and the ‘parents’ for the next. In the evolutionary process, population size is fixed as 500 over time by replacing fewer fit programs in the parent generation with children of fitter parents according to their fitness value. The fitness value (F) is calculated through the fitness function defined as:

$$F = |S - O| \tag{4.10}$$

in which, *S* stands for the suitability values from genetic program output, *O* stands for the real suitability value for a sampled location in observation at a certain year. *O* takes a value of zero or one. If it takes a value of “0” for a given location (or cell), it indicates that there is no water depot built inside that cell. In contrast, a value of “1” means that there is at least one water depot built within that cell.

This evolution involves 500 times. After 500 generations of evolution (i.e., G = 500), a genetic program with the best fitness value computed through evolutionary programming will be the final symbolic regression solution. The suitability function is solved and can be used for water depot location selection. After a new permanent or temporary water depot selects its location and a water source, the point of diversion is then determined. The water depot will select a point in the water source nearest to the water depot location as the point of diversion.

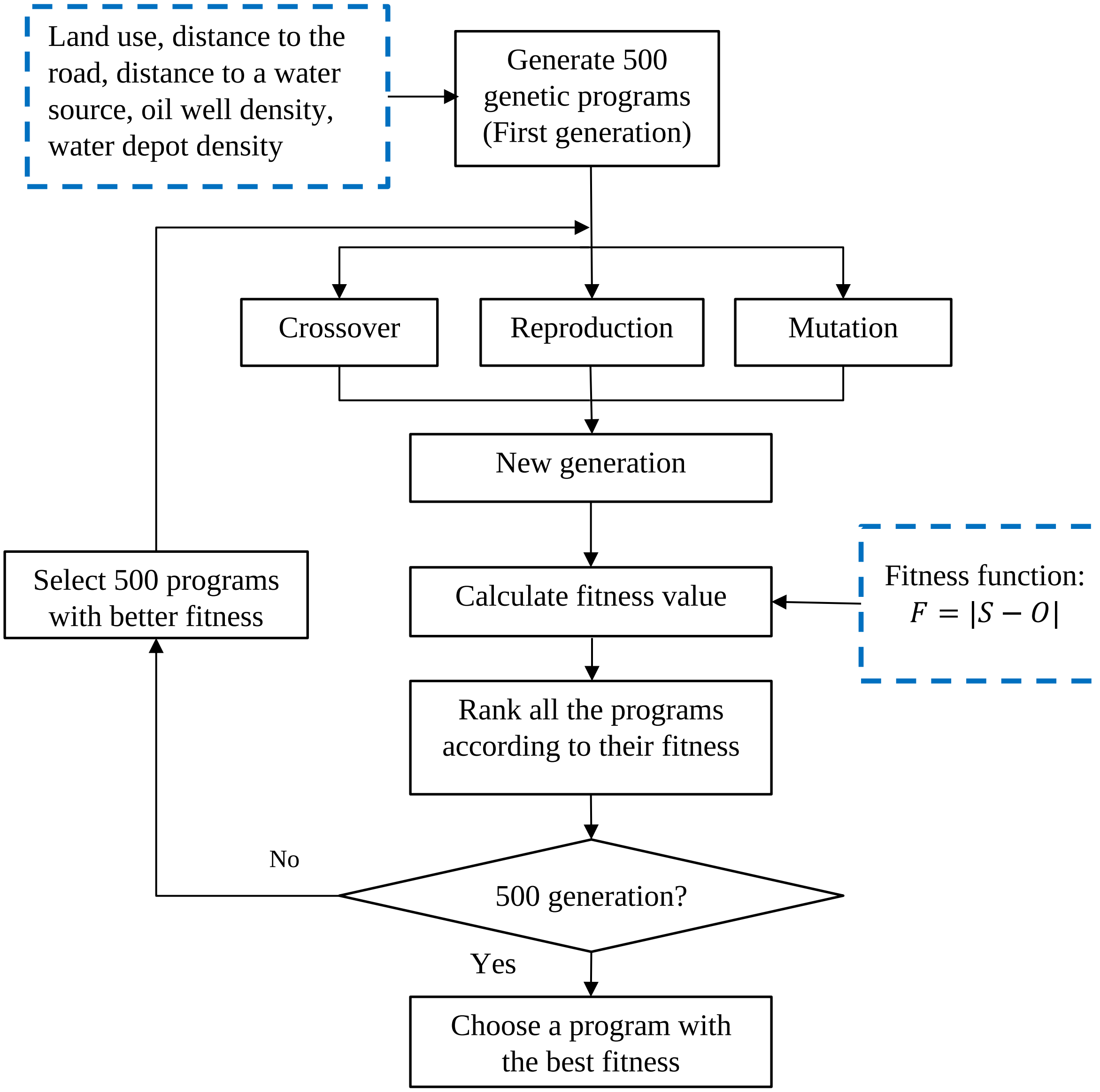

Figure 4.8. Evolutionary programming and genetic algorithm processes.

4.3.4.2. Regulation sub-model

The regulation sub-model is designed to model the water-depot agents' interactions with the regulator agent by applying institution theory. As shown in figure 4.9, the regulation sub-model consists of three sub-sub-models: existing water permit regulation, new permit application regulation, and dry year water permit regulation.

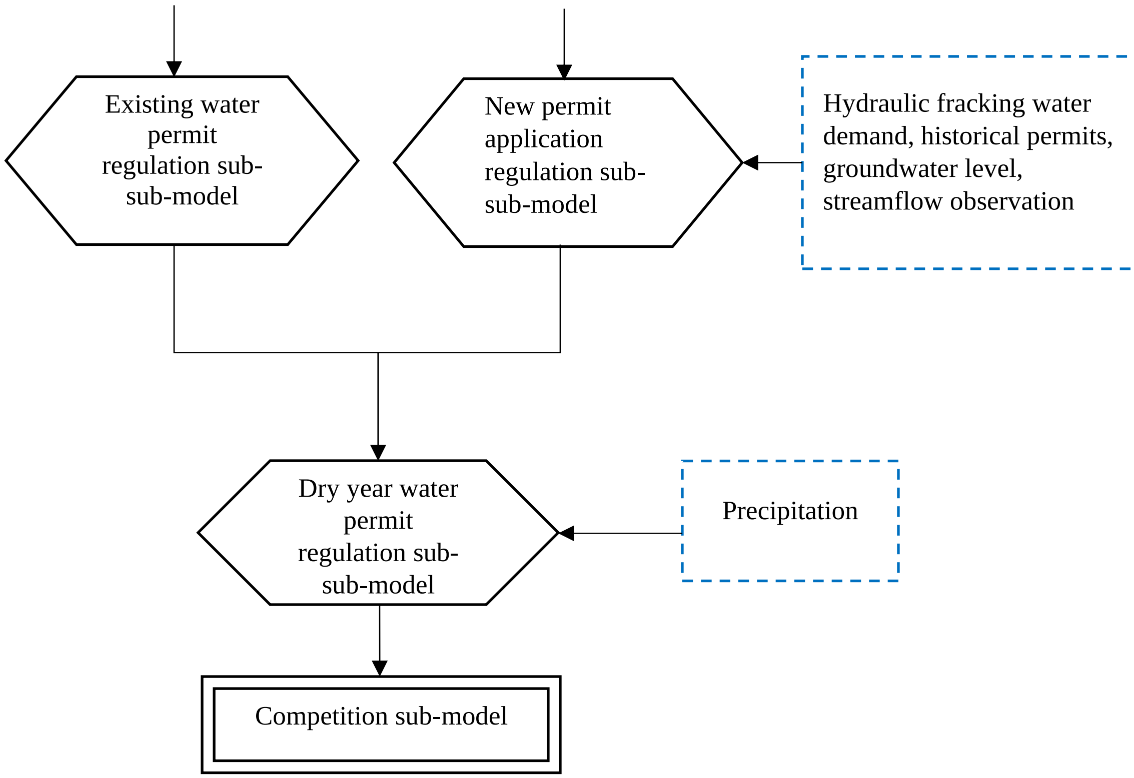

Figure 4.9. Regulation sub-model.

In the existing water permit regulation sub-sub-model (figure 4.10), all existing water-depot agents with conditional water permits will be audited by the regulator agent, who can obtain annual water use information from each water-depot agent. The regulator agent may cancel the water-depot agent's conditional water permit if the cumulative water use is still equal to zero after the water-depot agent holding the water permit for more than three years.

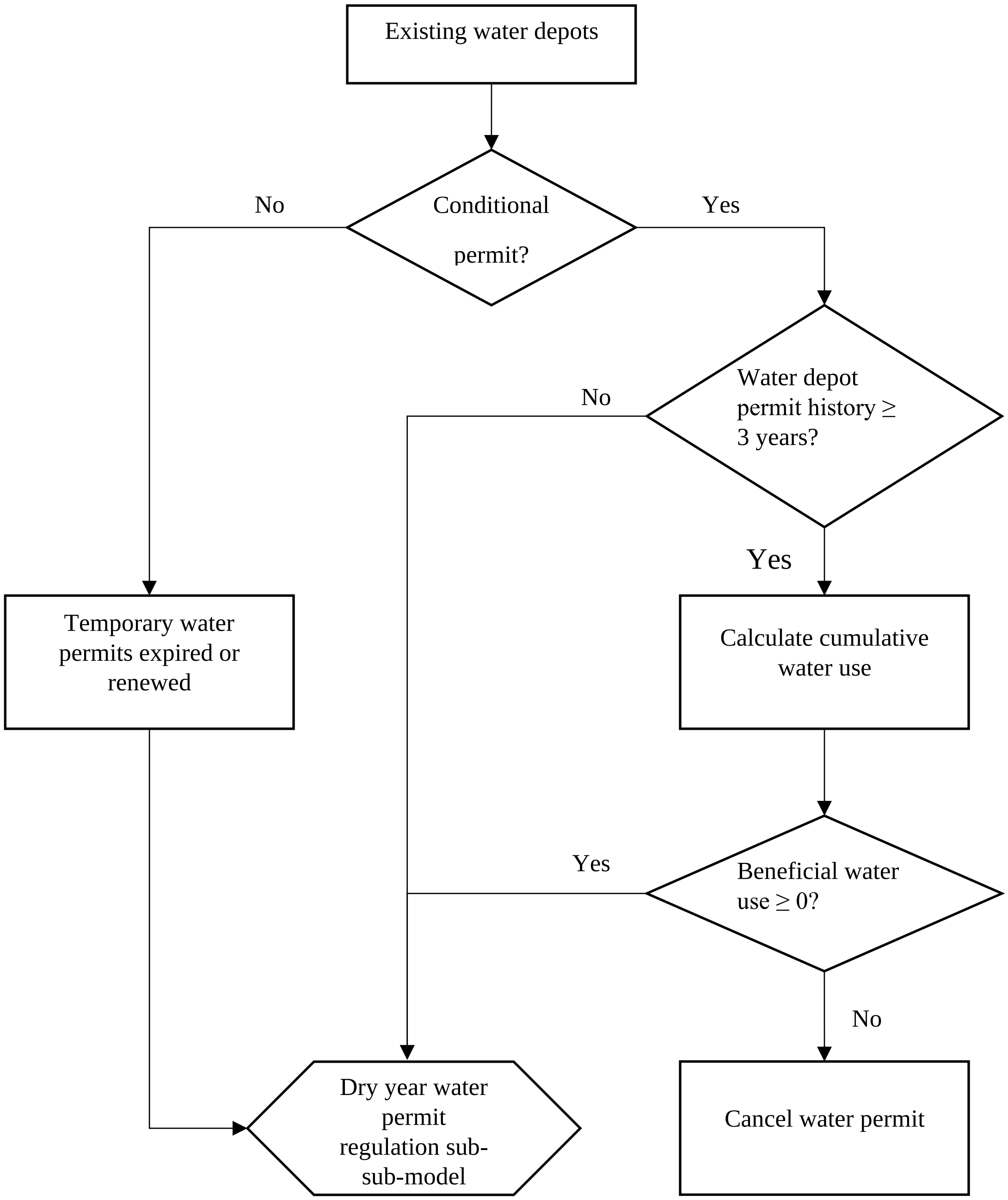

Figure 4.10. Existing water permits the regulation sub-sub-model.

As shown in figure 4.11, the new permit application regulation sub-sub-model consists of two procedures: the senior water right impact assessment procedure and the new permit approval procedure. If a water-depot agent is applying for a permanent water permit, the NDOSE will use the senior water right impact assessment procedure (see figure 4.12) to assess the new permit's impact on existing senior water permits. If the impact is deemed minimal, the new permit approval procedure will be called to simulate the regulator agent's decision on the new permit application. If the water-depot agent is not applying for a permanent water permit, only the new permit approval procedure will be called to model the regulator's approval decision.

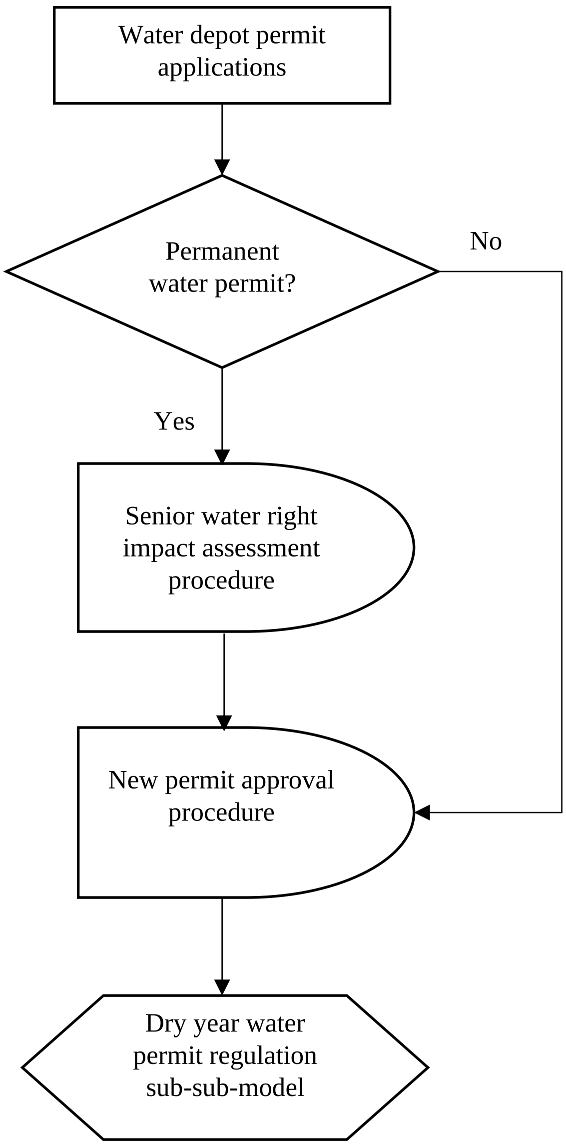

Figure 4.11. New permit application regulation sub-sub-model.

Figure 4.12 shows the procedures for assessing the senior water right impact of a new water permit application. The procedures are different based on the water source where the new permanent water permit application proposes to withdraw water from. If the water source is Lake

Sakakawea and the Missouri River, NDOSE will check if this water source is available. If it is available, the water permit will be approved directly due to its abundance; otherwise, the application is denied. If the water source is the other surface water except for Lake Sakakawea and Missouri River, NDOSE will check whether the new application will affect the streamflow of the river or stream where the new water permit will draw water from. A parameter S_t is used here to stand for the streamflow threshold under which the new water permit that will withdraw water from the other surface waters will not be approved. When a water-depot agent applies for a permanent water permit with water use from certain surface water, the regulator agent calculates a streamflow changing ratio C_1 (see Eq. 4.11) based on the observed streamflow data from that water source. If C_1 is smaller than S_t, the water permit application will be denied; otherwise, it will be approved.

$$C_1 = \frac{s_{cy-1}}{s_i} \tag{4.11}$$

in which, s_{cy-1} stands for the annual average streamflow in the year before the current year and s_i stands for the annual average streamflow flow in the initial year (2007).

If the water source is the Fox-Hills and Hell Creek aquifer, NDOSE will check if this water source is available. If it is not available, the water permit application will be denied directly due to the stricter policies placed by the state (https://www.swc.nd.gov/pdfs/ fox_hills_policy.pdf, see also Fischer, 2013); otherwise, NDOSE will check whether the new application will affect the senior water use of the Fox-Hills and Hell Creek aquifer. A parameter G_t is used to represent the groundwater-level threshold under which the new water permit withdrawing water from the Fox-Hills and Hell Creek aquifer will not be approved. The regulator NDOSE calculates the water level change ratio C_2 (Eq. 4.12) based on the observed groundwater level data from the Fox-Hills and Hell Creek aquifer. If C_2 is greater than G_t, the water permit application will be denied; otherwise, it will be approved.

$$C_2 = |G_{cy-1} - G_i| \tag{4.12}$$

in which, G_{cy-1} stands for the average groundwater level in the year before the current year, G_i stands for the average groundwater level in the initial year (2007).

If the water source is the other groundwater source except for the FHHC aquifer, NDOSE will only check whether the new application will affect the water level of the groundwater source where the new water permit will draw water from, following the same procedure described in the above.

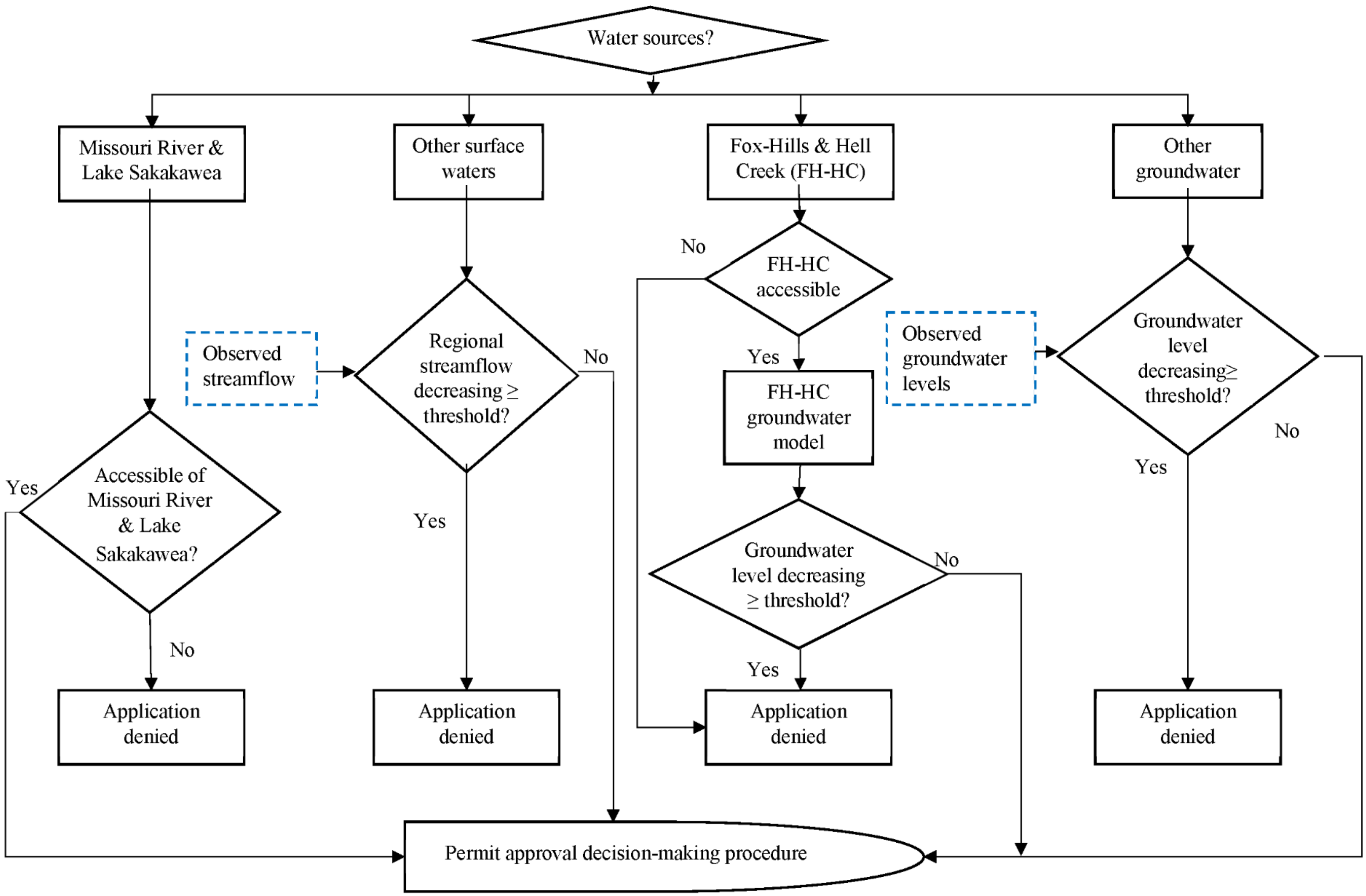

Figure 4.12. Senior water right impact assessment procedure.

Figure 4.13 describes the procedures of the new permit approval process. The procedures are different based on the types of water permits applied by the water-depot agents. If the water-depot agent is applying for a temporary, irrigation transferred, or municipal transferred permit, NDOSE will first check if this water source is available. If it is available, the water permit will be approved directly and the approved water amount will be the same as the applied water amount; otherwise, the application is denied.

If the water-depot agent is applying for a conditional water permit, which may grant the water-depot agent the conditional water right if the application is approved, it will take additional steps for the NDOSE to determine whether the permit application can be approved or not. The actual water permit approval process is complicated and taking a long time (https://www.swc.nd.gov/pdfs/water_permitting_process_chart.pdf). In our model, the process is simplified using a parameter representing the difficulty level at which a new conditional water permit application may be granted. Four different difficulty-level thresholds are set for the four types of water sources, and the order of the difficulty is Fox-Hills and Hell Creek > Other Groundwater > Other Surface Water sources > Missouri River and Lake Sakakawea. For a conditional water permit application, a random value between 0 and 1 will be generated and compared with the threshold of the difficulty level of the water source from which the new application is filed. If the random value is greater than the threshold value, the permit application will be approved, and the approved water amount will be the same as the applied water amount; otherwise, the application will be denied.

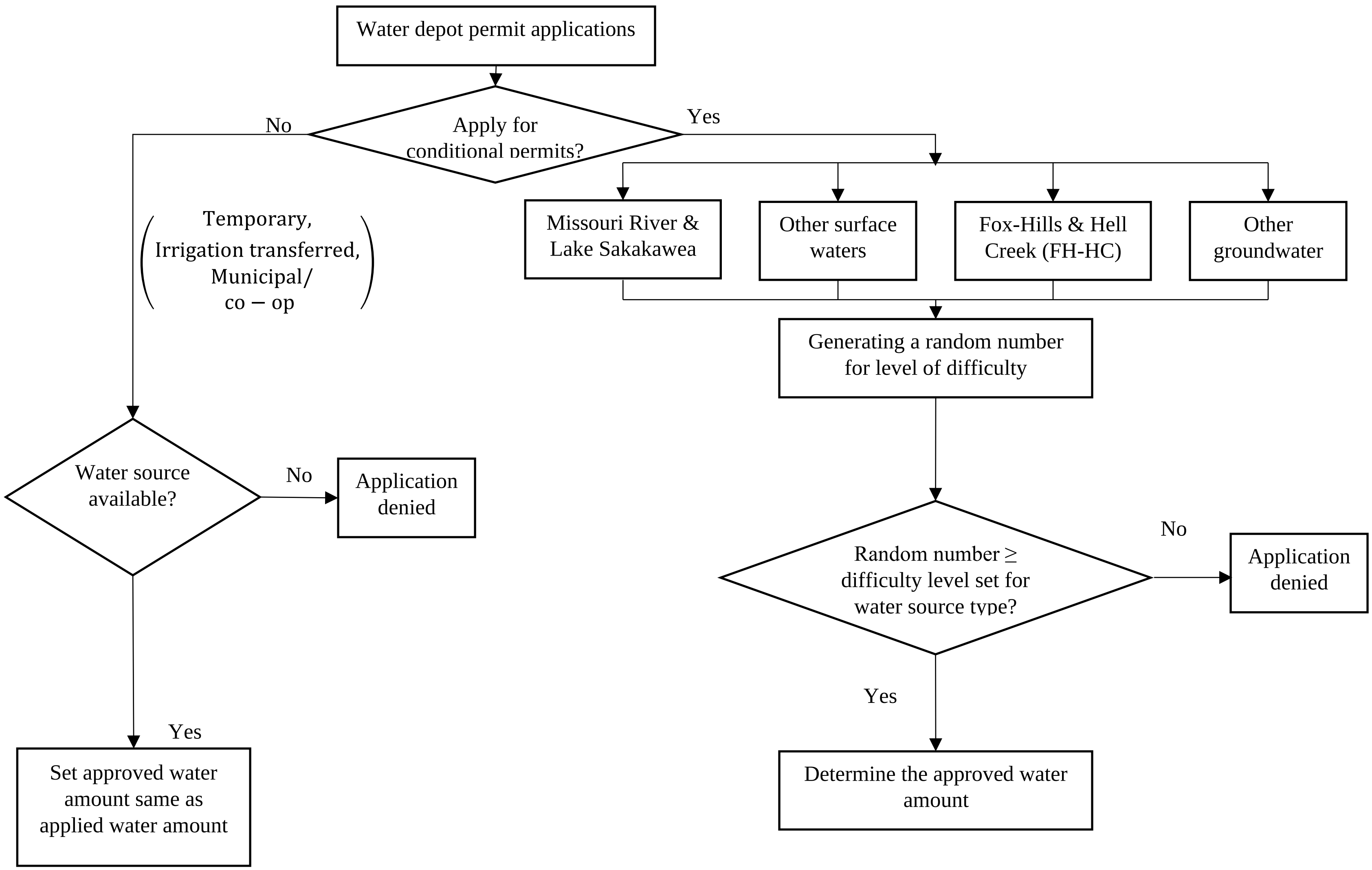

Figure 4.13. The new permit approval procedure.

Figure 4.14 shows the dry year water permit regulation sub-sub-model that simulates the interactions between the regulator agent and the existing water-depot agents during dry years. If the annual precipitation in the last year is below the 30-year normal, the regulator agent will rank all existing water permits by their priority dates. Then the regulator agent will hold A_b percent of recently issued permits into abeyance until next year.

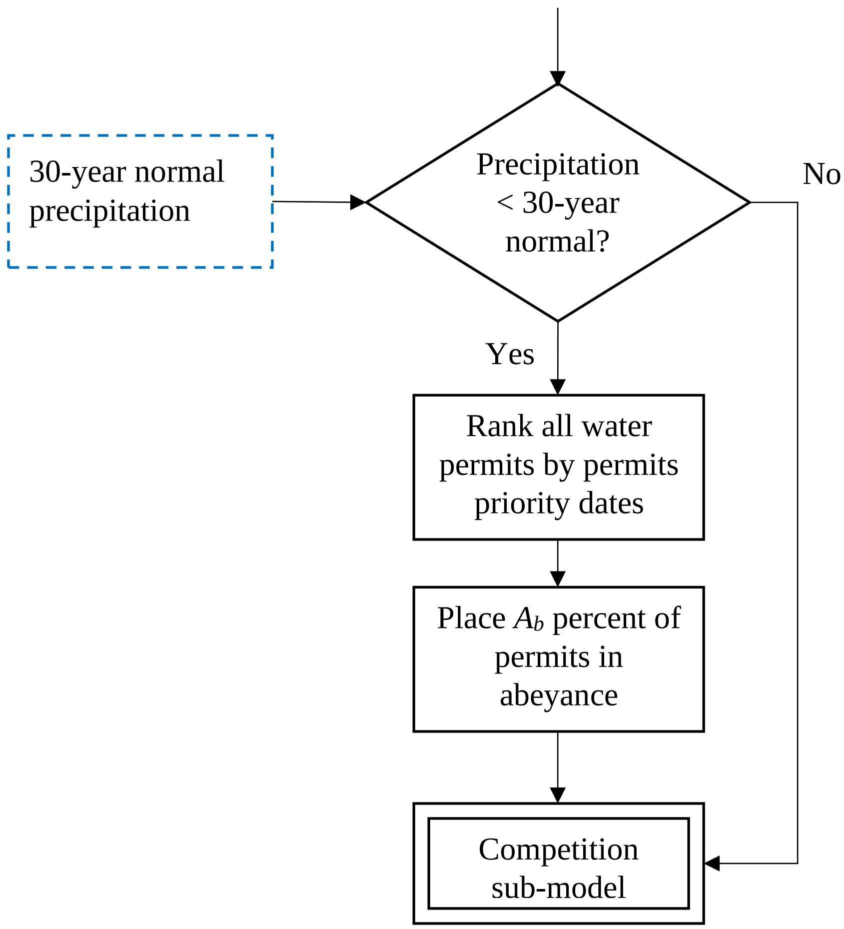

Figure 4.14. Dry year water permit regulation sub-sub-model.

4.3.4.3. Competition sub-model

Through the permit application and the regulation sub-models, water-depot agents are equipped with a location, a water source, water permit (agent) type, total approved water amount, and the associated permit expiration time. The competition sub-model simulates the water-depot agent's competition behavior for more water sales by applying the cognitive mapping method to model the agent's decision-making process. A stepwise method is used to realize the cognitive mapping theory into a formal agent-based simulation model as shown in figure 4.15. The key steps include interviews, individual cognitive mapping, collective mapping, UML (Unified Modeling Language), an all-encompassing framework, and the agent-based model.

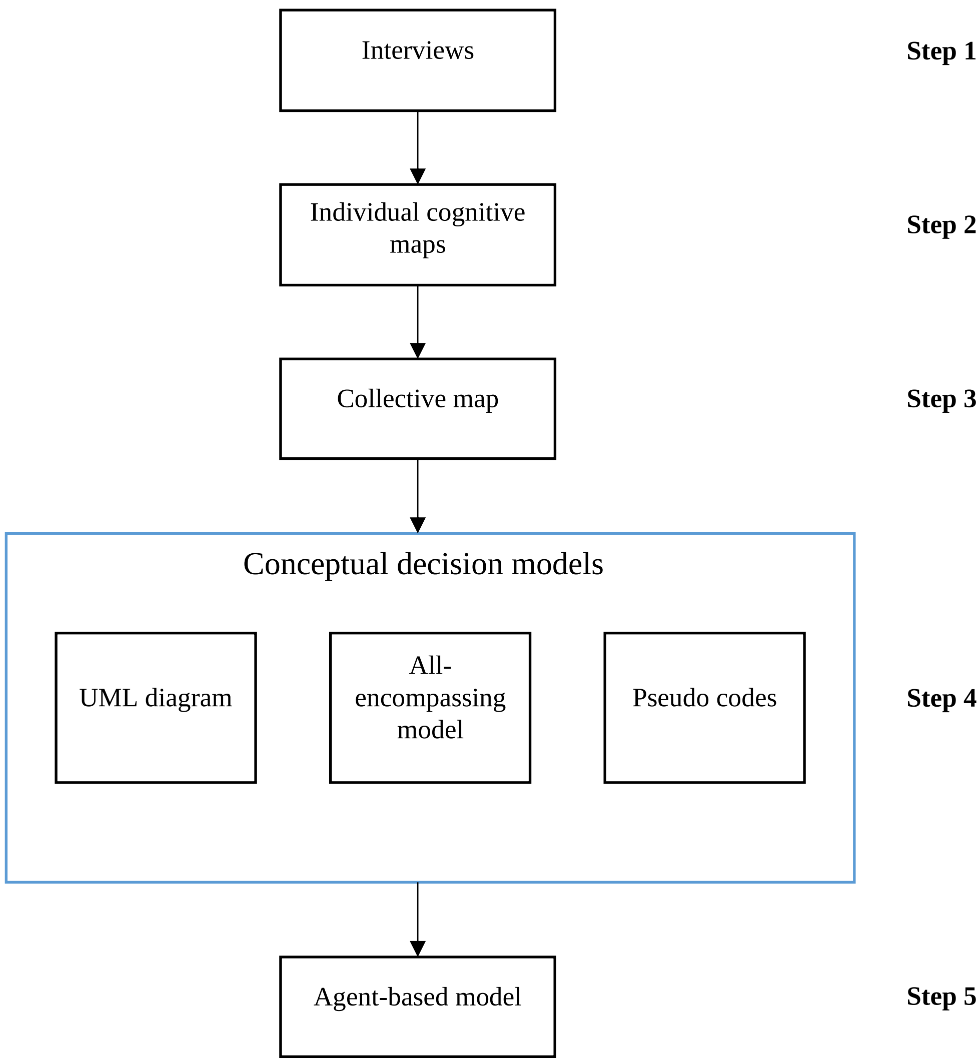

Figure 4.15. Implementation of the cognitive mapping in an agent-based model.

In step 1, we conducted three rounds of semi-structured interviews with the field experts, water depot owners, and the NDOSE regulators during 2015-2016. The first round of semi-structured interviews was conducted at the Bakken Conference and Expo in Grand Forks, North Dakota, on July 27-29. We interviewed five experts who worked in two water solution companies and research institutions. The second round of interviews was designed to gain a better understanding of the decision-making processes or competition behaviors of different types of water-depot agents. In July 2016, we interviewed eight water depot owners or operators in Watford City, North Dakota, and Williston, North Dakota, through phone calls or face-to-face meetings. Among these eight water depots, two were permanent water depots, three were temporary water depots, one was irrigation transferred water depots, and the remaining two were municipal and co-op water depots. One of the water depot owners we interviewed had more than one temporary water depot. The third round of interviews was conducted with the NDOSE regulators. We interviewed several staff members in the Water Appropriations Division of NDSWC several times between the years 2015 and 2016.

The interview scripts were structured into two parts aimed to elicit: (1) the broad views and perceptions of water management in the 16 counties of western North Dakota, and the regulatory policies for the water allocation system, and (2) the decisions made by water depot owners to apply for water permits and to compete for water sales. The cognitive mapping and analysis mainly focused on water-depot agents' competition behaviors based on the information received from the second part of the structured interview questions. The research team included two interviewers assigned with specific roles, one person ran the interviews and asked questions, the other took notes to provide interview transcripts. From the interviews, the water depot owners' actions and decision-making processes were identified. Also, the contents and meanings of personal constructs that interviewees used to reason when making decisions relevant to their actions were captured.

In step 2, individual cognitive mapping was used to represent the water-depot agent's decision-making by developing offline maps from the interview transcripts with water depot owners. Interview transcripts were analyzed through several themes: goals, activities/decisions, issues of concern, external drivers, perceived learning, and communication gaps. The aim was to get a quick sense of the data to conduct cognitive mapping. For each interviewee, we built a profile to summarize their responses along with quotes from the interviews. Table 4.3 is an extract of a temporary water depot owner's profile. The profile is considered to be a summary of how a water-depot agent thinks and can be used as a starting point for mapping. The individual cognitive map must include frame statements with more details in terms of who takes action, what action is taken, and when this action is triggered. In addition, the statements need to be framed to explicitly capture elements of decision making, such as perceiving information, forming judgments, and forming expectations. Figures 4.16-4.19 show the cognitive maps developed for individual permanent, temporary, irrigation transferred, and municipal/co-op water-depot agents, respectively. All the cognitive maps are developed using the Decision Explorer software (Banxia Software, Cumbria UK).

Table 4.3. An extract from a water depot owner's profile developed after the interview.

Participant	One temporary water depot owner
My PURPOSE is	Have more water sale in the market, and gain more
I am doing this ACTIVITY	Sell water to oil well operators Decisions to make as a part of this activity: 1. What water price to use? (scale: \$0.20/barrel to \$1/barrel) 2. Sign contracts with nearby oil wells? (Yes or no) 3. Heat the water or not? (scale: yes or no) 4. How much capital cost will be? (\$100,000 -250,000)
I am concerned about these ISSUES (along with causal links to purpose)	-The total amount of water use -Investment payback period -Capital and running costs
There are factors in the ENVIRONMENT, which shapes my activity	-Road condition -Climate condition during the year -HF industrial water market -Regulation policies
I need this KNOWLEDGE or INFORMATION to carry out my activity	-Water price nearby -Road distance to different oil wells -The density of water depots nearby

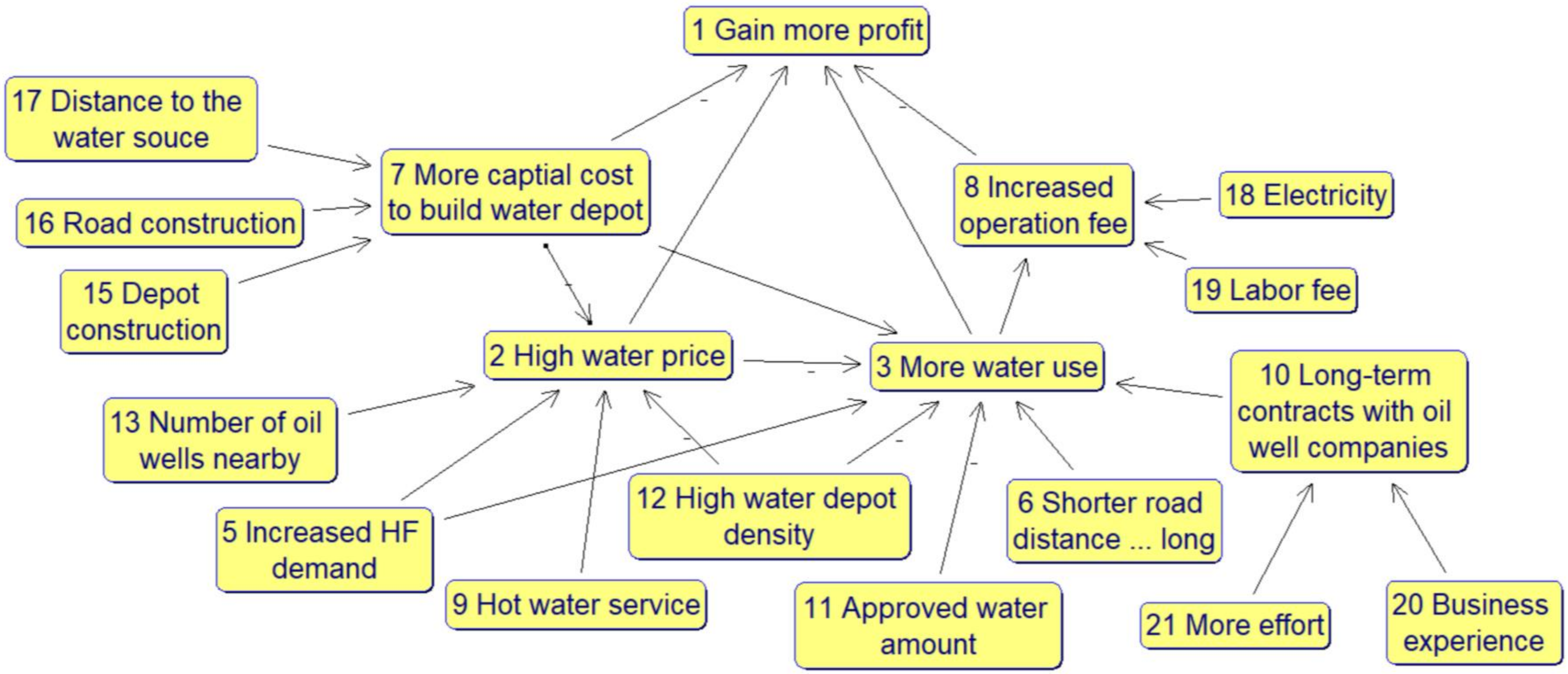

Figure 4.16. A cognitive map for an individual permanent water-depot agent.

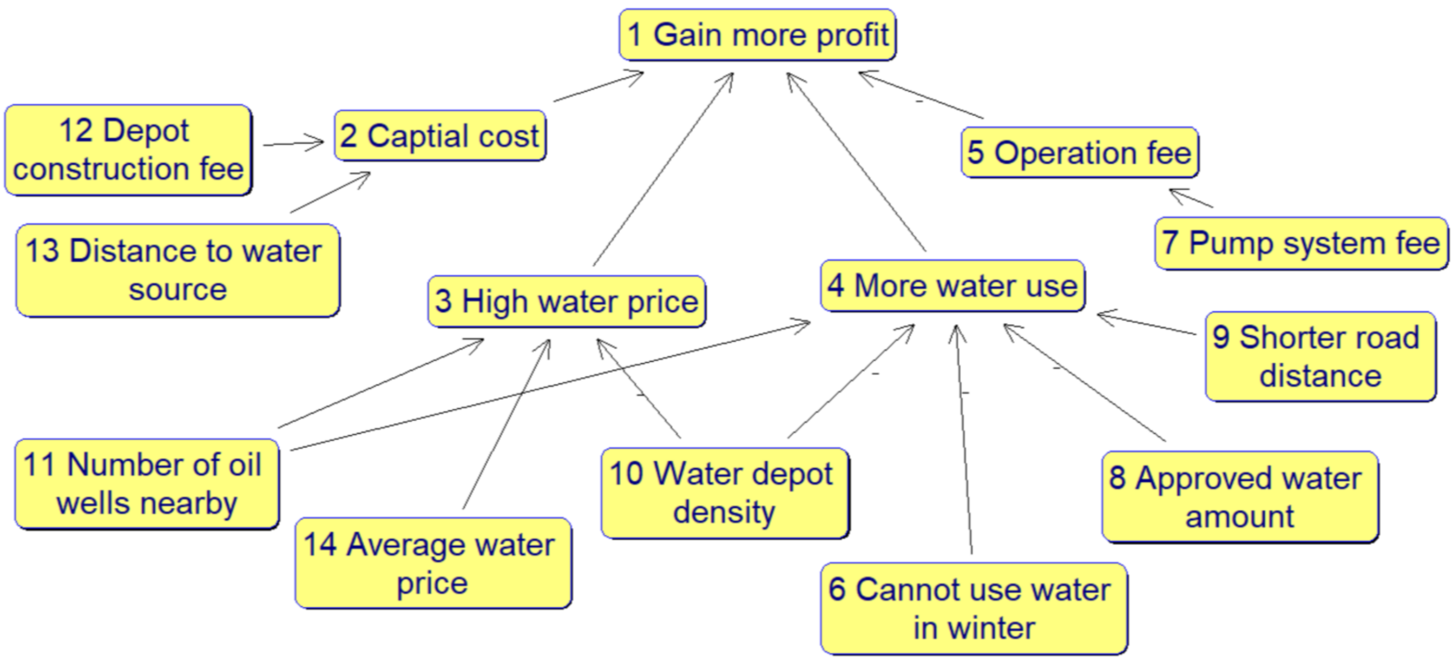

Figure 4.17. A cognitive map for an individual temporary water-depot agent.

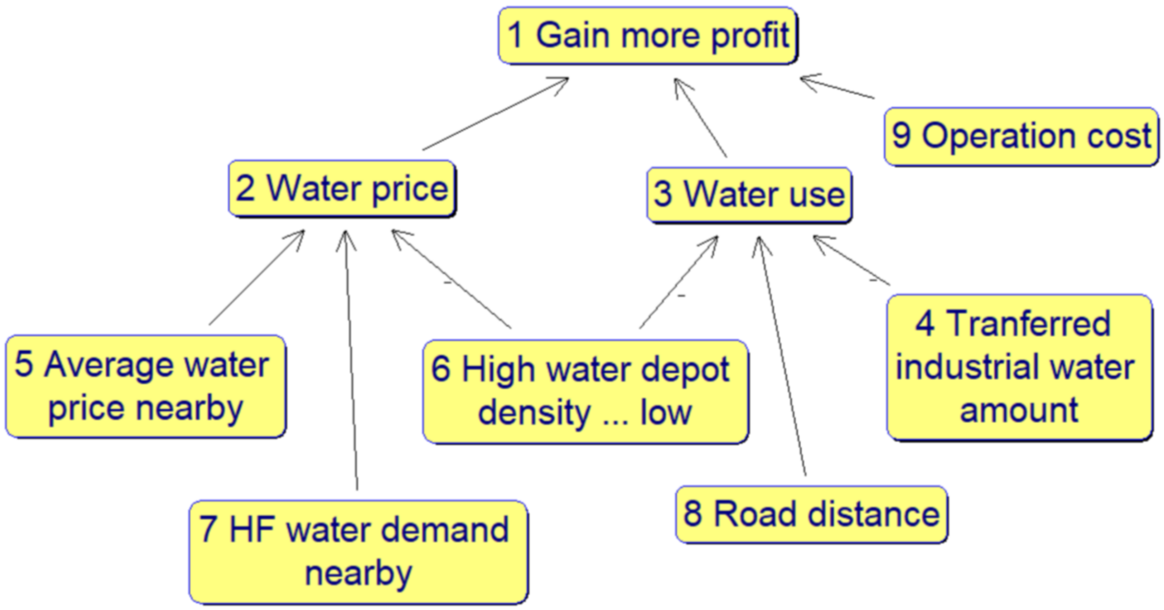

Figure 4.18. A cognitive map for an individual irrigation transferred water-depot agent.

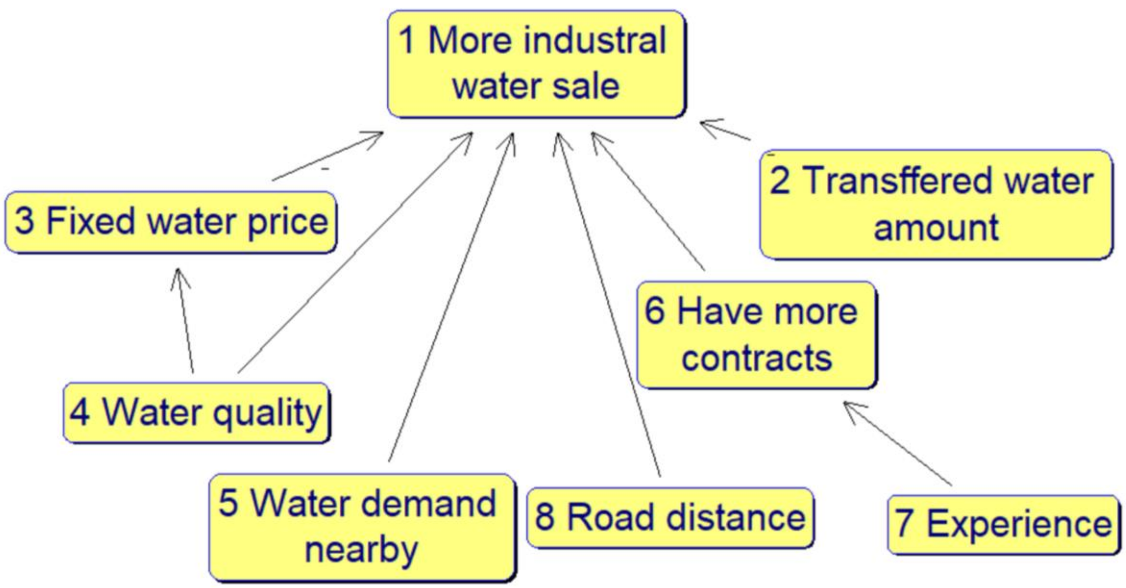

Figure 4.19. A cognitive map for an individual municipal/co-op water-depot agent.

In step 3, the collective map was developed by merging the individual cognitive maps. The purpose of this step is to merge individual cognitive maps into a collective map to develop a single unifying view that encompasses the individual views. To help structure the collective map and define the key issues that are important in the decision-making process, it is useful to start by identifying goals and core concepts, which are implemented using the Decision Explorer software (Banxia Software, Cumbria UK). Goals are head nodes that have no outgoing links and are placed at the top of the collective map. Core concepts link together a cluster of nodes, representing a sub-issue. There are two ways to identify core concepts: (1) content-based concepts because of their meaningful relevance to decision making, and (2) structure-based concepts because of their links to other concepts, as determined by the results from the domain, centrality analysis, and feedback (Eden, 2004).

Following the links from core concepts and feedback loops helps identify ‘triggering concepts’ or ‘source nodes’, which have no incoming arrows, or exogenous factors. Triggering concepts are important in decision-making in ABM as they represent the contextual (e.g. changes in climate conditions) and internal (e.g. personal interest and experience) drivers that affect the agent's decisions. The collective map needs to capture similarities among interviewees' mental models because the similarities provide the shared elements in the decision-making process. Calculating the frequency of occurrence of core concepts gives a good indication of how this issue is shared among interviewees. Comparing the chain of arguments linked to the core concepts generates insight into the different views surrounding the issue (Eden and Ackermann, 2004).

In the first attempt to develop a collective map, a strategic map was drawn as shown in figure 4.20. The strategic cognitive map represents the mental model underpinning water-depot agents' strategic decisions. Results from the structure analysis identified two key goals that the water-depot agents seek to achieve: (1) to gain more profit, and (2) to have more industrial water sales. Further insight into the data shows that this is highly influenced by the types of water-depot agents, whether it is a private or public business. Private business owners desire to obtain a higher profit. Results from the structure analysis also identified 10 core concepts, such as: “Road distance long … short”, “Water price from nearby water depots being high … low”, etc.

The concept of “Desire to sell water being high… low” was added as a core concept because of its content relevance. The researcher's knowledge gained through the interviews and data analysis provides useful inputs for unobvious concept identification. Water depot agents decided on the water price based on road distance to the nearby oil wells, HF water demand, regional water supply, average water price, and its own business experience. The water depot owners also made decisions to obtain more contracts with nearby oil well operators based on their motivations to sell more water, the road distance to oil wells, and the water use ratio.

Later, we developed an operational collective map shown in figure 4.21. The operational cognitive map represents the mental model underpinning annual operational decisions and actions taken by the water depot owners to manage their water business.

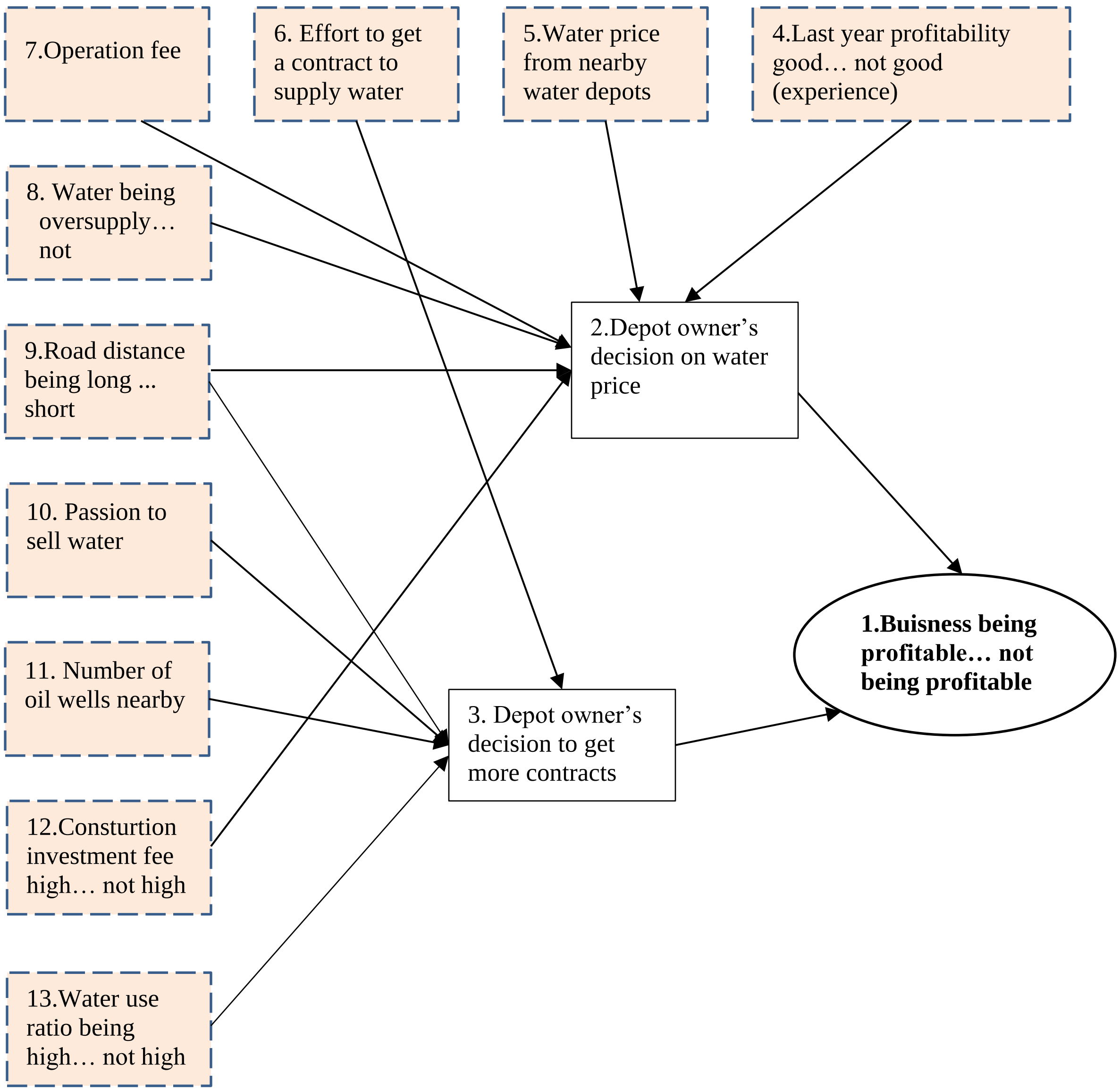

Figure 4.20. Strategic collective map of depot agents' competing decision-making.
Note: solid boxes represent decisions or actions, dashed boxes represent drivers or trigger nodes, oval nodes are objectives.

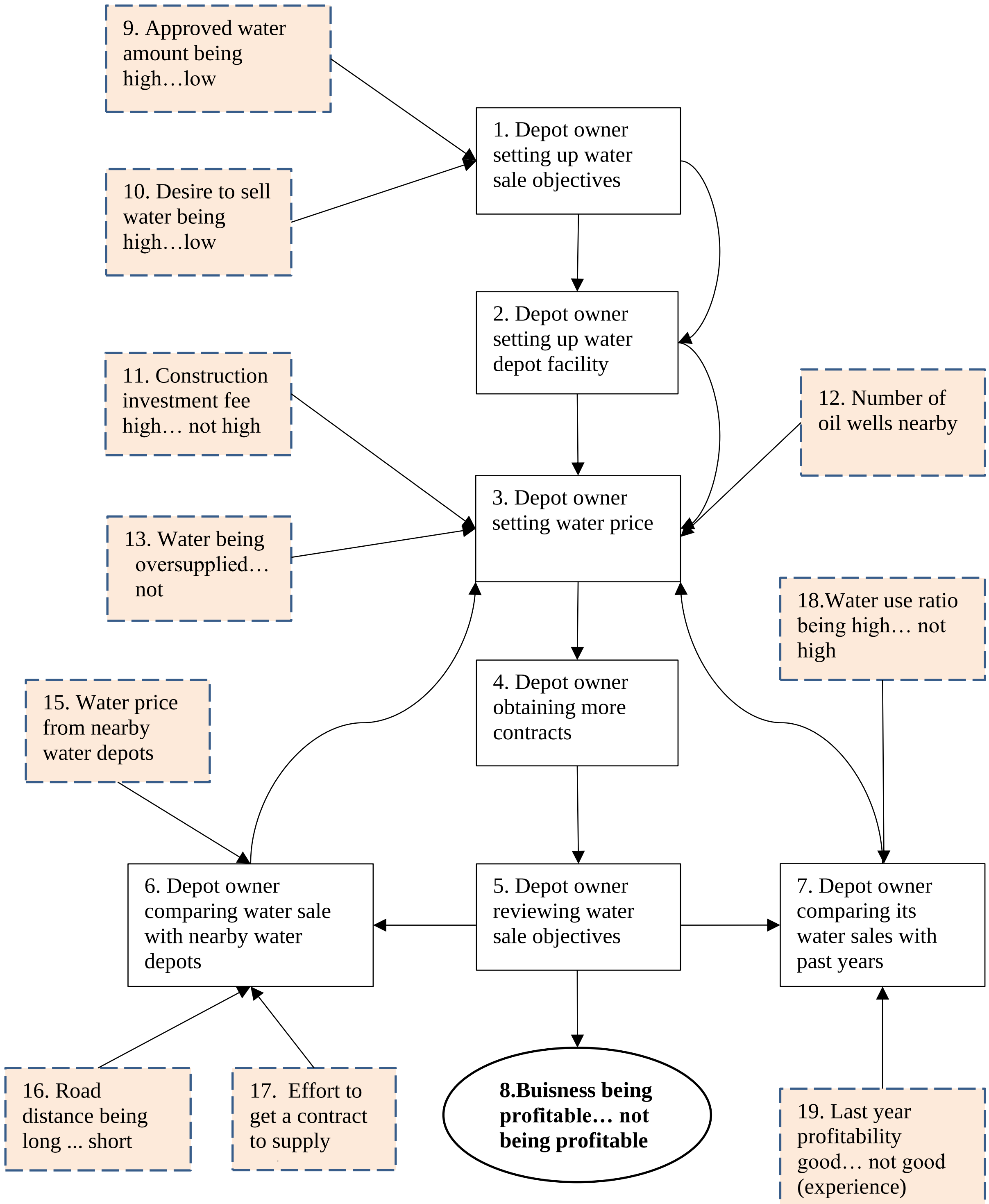

Figure 4.21. Operational collective map of depot agents' competing decision-making.
Note: solid boxes represent decisions or actions, dashed boxes represent drivers or trigger nodes, oval nodes are objectives.

In step 4 (referring to figure 4.15), we translated the information from the strategic and operational collective maps into a series of UML diagrams to describe water-depot agents' behaviors of competing for industrial water sales. The entire competition sub-model is composed of three different sub-sub-models which are long-term competition behaviors, short-term competition behaviors, and water use calculation sub-sub-models shown in figure 4.22.

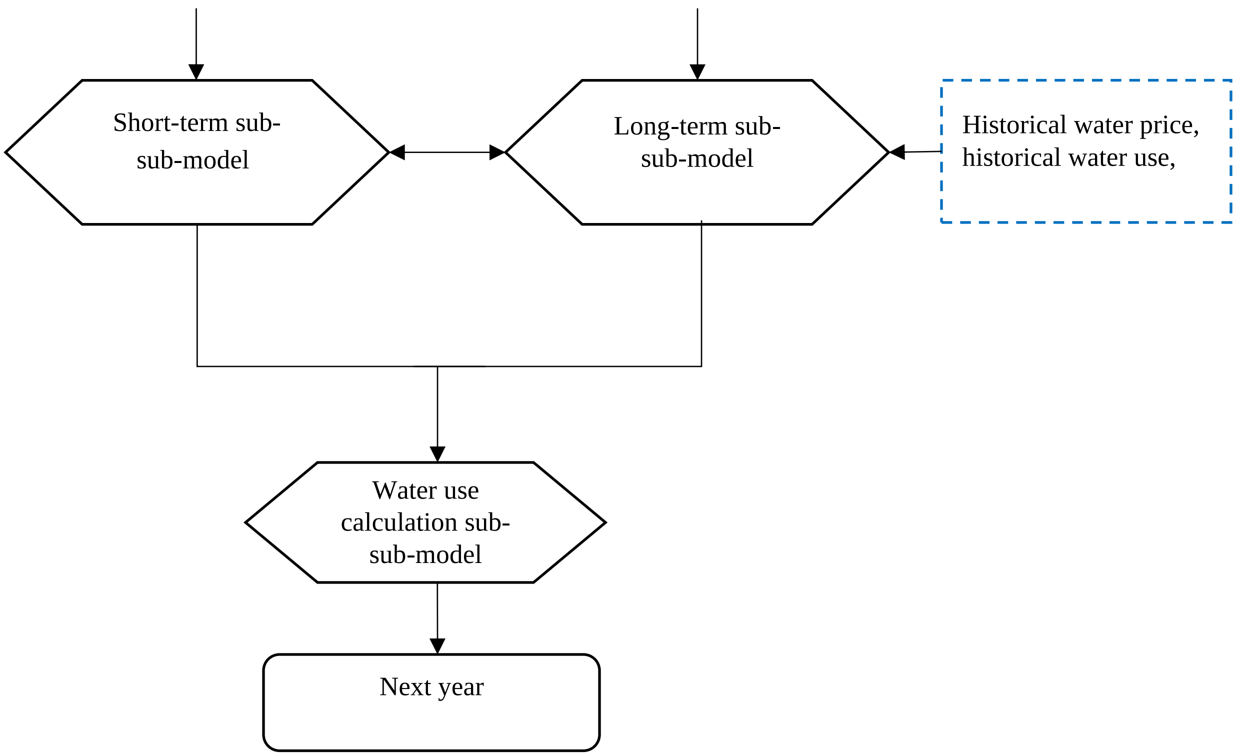

Figure 4.22. Competition sub-model.

The long-term sub-sub-model simulates the competition behaviors of the water-depot agents who hold water permits for more than one year. Holding a water permit for more than one year requires more sophistication. The competition behaviors of the permanent, irrigation transferred, and municipal/co-op agents are modeled with the long-term sub-sub-model shown in figure 4.20. On the other hand, the short-term sub-sub-model simulates the competing behaviors of the water-depot agents who hold a water permit for less than or equal to one year. The competition behaviors of the temporary agents are modeled with the short-term competition behaviors sub-sub-model.

In the long-term sub-sub-model, each permanent, irrigation transferred, or municipal/co-op agent will set its objectives at the beginning of the year (figure 4.23). Two quantitative objectives are set based on water sales and water use ratio. For a permanent or irrigation transferred agent, the objective is related to the profit value determined by the agent's passion attributes. The passion attribute of an agent is a simulation of the concept of "Desire to sell water being high… low" from the interview. In this model, passion attributes are assigned with three different levels: high, medium, and low. Correspondingly, the objectives of a water-depot agent are also set at three different levels. The high-level passion leads to a higher expectation or a higher objective, in which the total profit will be equal to or greater than 50 percent of the total investment. The medium-level passion leads to an objective that the water depot expects to have a profit ranging between 35-50 percent of the total investment. The low-level passion leads to an objective that the profit will range between 20-35 percent of the total investment. For the municipal/co-op agents, the objective is related to the water use ratio. The water use ratio is equal to actual industrial water use divided by the approved industrial water use amount. The municipal/co-op agents usually set an objective with an expected water use ratio between 0% to 5%. Not like the municipal water-depot agents, all the co-op water-depot agents share the same objective, and their water use ratio will be calculated together because they share the same water permit.

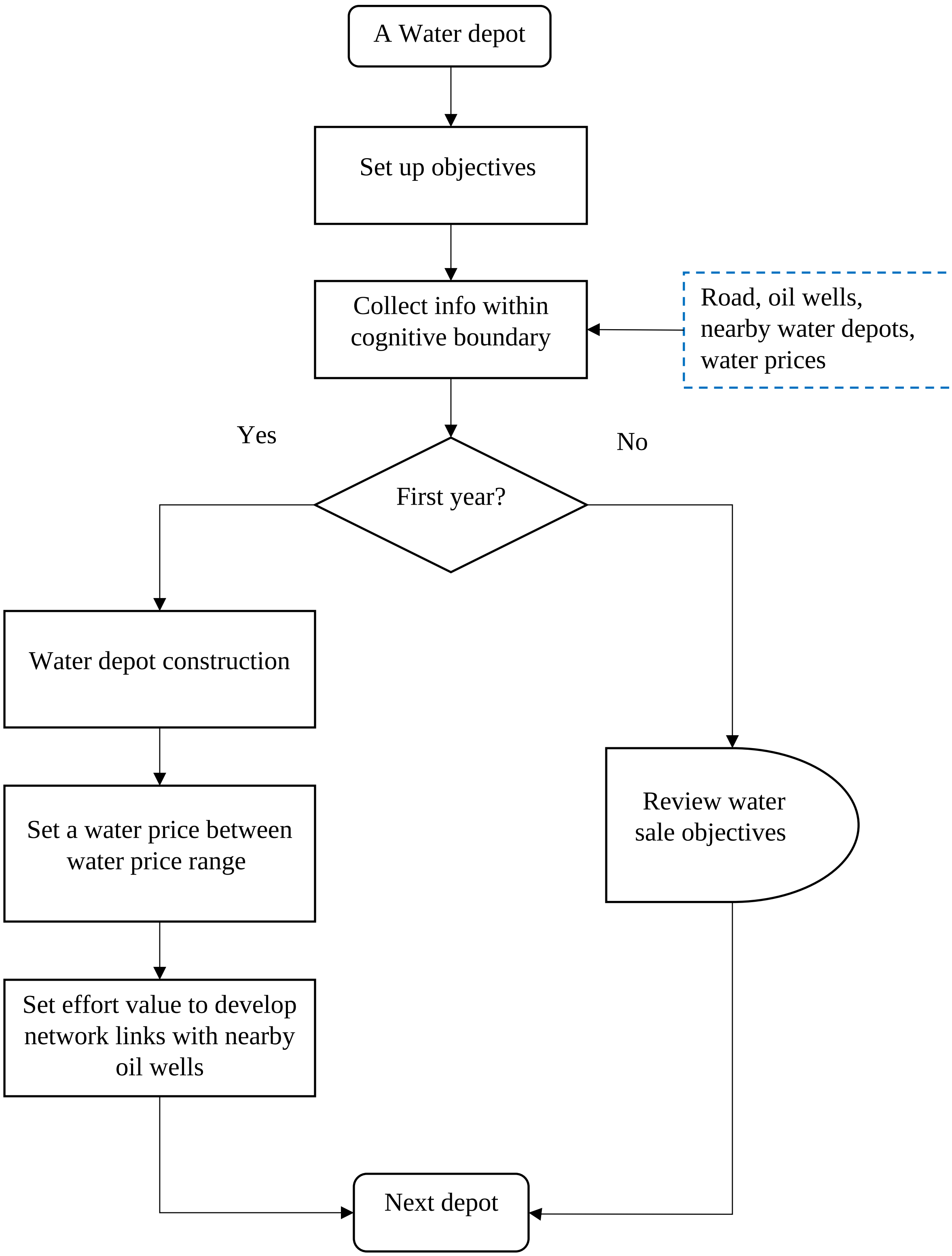

Figure 4.23. Long-term sub-sub-model.

After the water-depot agents set their objectives, they will begin to collect different types of information within their cognitive boundaries, such as road, oil wells, other water-depot agents, and water prices. The cognitive boundary is defined as a circle with a radius of 40 miles, which was determined based on the interviews with the water depot owners as the longest distance by which it would still be profitable to transport water from a water depot to an oil well. Due to limited time and knowledge, only the information within the cognitive boundary is important to the water-depot agents. This means that water-depot agents will not be able to access the same information outside of their cognitive boundaries.

When a permanent agent starts its business in the current year, it will begin to build the water depot at the selected location, and the investment will be estimated based on the approved water amount. According to the information collected from the interviews, the new water depot's investment may fall into one of the following three levels at \$50,000 – \$250,000, \$250,000-\$1,000,000, or \$1,000,000 -\$2,000,000. Based on the water permit data obtained from NDOSE, the total approved water amounts may be classified into three groups, 0-200, 200-3,000, and 3,000-20,000 ac-ft corresponding to the three different investment levels. A random value will be generated at the selected investment level.

The initial investment estimation for the irrigation transferred agents is the same as that for the permanent agents. For the municipal/co-op agents, the initial investment is assumed to be 0 because these water depots have already been constructed for other purposes before selling water for hydraulic fracturing.

Once the initial investment is estimated, the new permanent water depot or the irrigation-transferred water depot will determine the initial water price for the first business year. A random value generated between \$0.20/barrel and \$1.00/barrel is used as the initial water price. For the municipal/co-op agents, their water price is fixed at $0.84/barrel by the laws. The water-depot agents also need to determine the effort values based on their passion attributes. The effort value refers to how much effort a water-deport agent may put into developing the network with the nearby oil wells within its cognitive boundary. A water-depot agent can sell water to an oil well if and only if there is a network link between them. The network link between a water-depot agent and an oil well means that the oil well operator knows about the existence of the water depot because of the water-depot agent's efforts, such as making advertisements or making phone calls. If a water-depot agent's passion attribute is low, its effort value X will be randomly generated between 0-40%. If its passion attribute is medium, the effort value will be randomly generated between 40-70%. If its passion attribute is high, the effort value will be randomly generated between 70-100%.

The total number of network links owned by a water-depot agent is calculated as:

$$N_l = XN_o \tag{4.13}$$

where, N_l stands for the total number of network links owned by a water-depot agent in the current year; X stands for the effort value; and N_o stands for the total number of oil wells requiring hydraulic fracturing nearby the water depot in the current year.

If the current year is not the first business year for a water-depot agent, the agent directly begins to review its water sale objectives as shown in figure 4.24. When reviewing the water sale objectives, a permanent or irrigation transferred agent uses the investment and profit values to check whether the profit objective is achieved or not in the previous year. The investment value of the water depot is estimated in the long-term sub-sub-model and the annual profit value is calculated as:

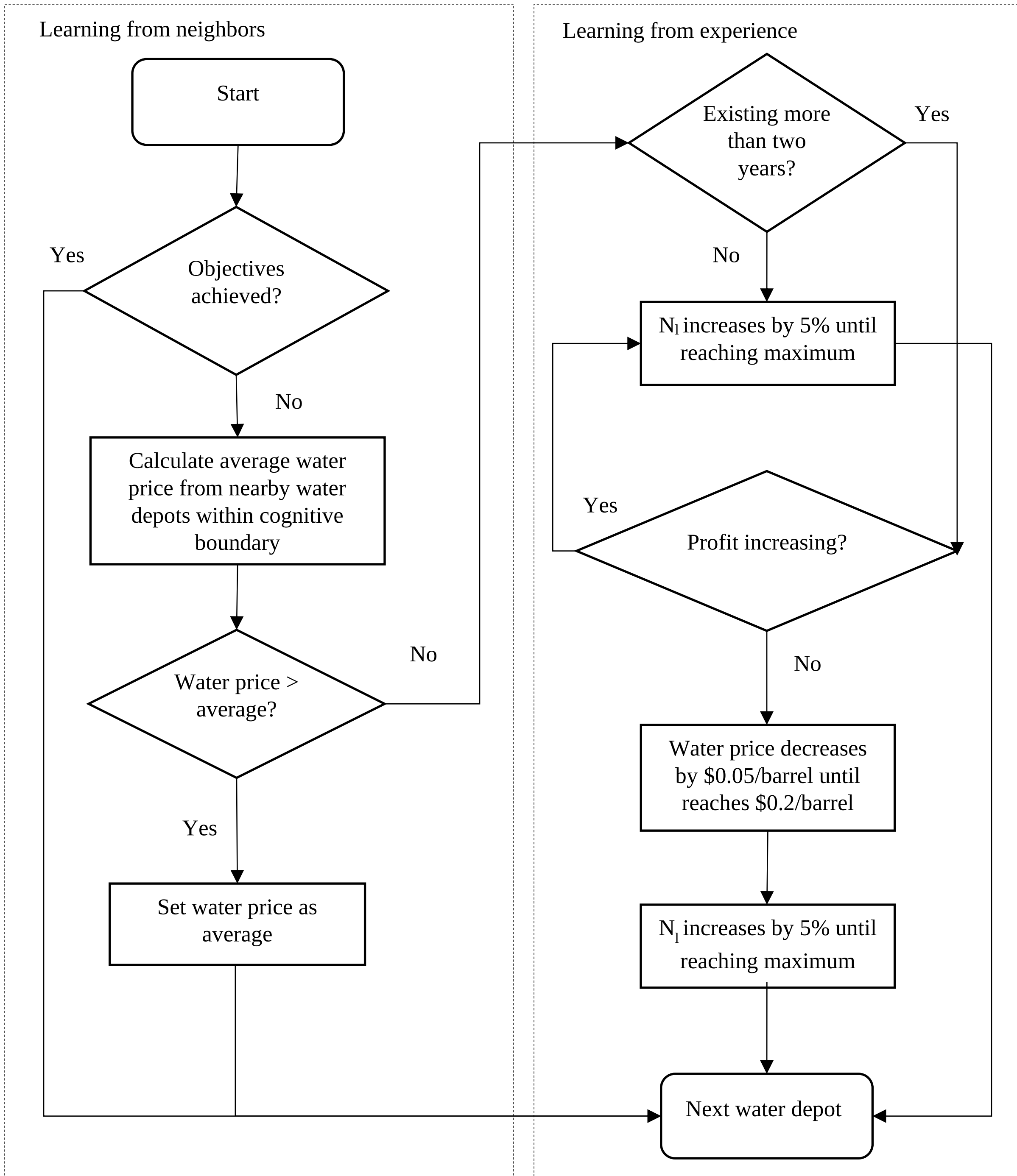

Figure 4.24. Agent's water sale objectives reviewing procedure.

$$P = (W_p - O_c) \times W_a \tag{4.14}$$

where, P stands for the profit achieved in the past year; W_p stands for the water price used in the last year; O_c stands for the operational cost which is assumed to be \$0.2/barrel; W_a is the water use amount in the last year.

If a water-depot agent's objectives are achieved, it does not need to make changes to its competition strategies used in the previous year. However, if the objectives are not achieved, the agent will make some adjustments by learning from its neighbors and its own experience in the past. To learn it from its neighbors, the agent collects the information about water prices from all other water-depot agents within its cognitive boundary. Then it compares its water price with the average water price. If its water price is higher than the average price, the agent will consider that the higher water price is the reason why its profit objective is not achieved, and subsequently set the water price to be the average water price.

If the water price is already less or equal to the average water price, the agent will make additional adjustments based on its own experience in the past. If the agent has existed for less than two years, the agent will expand its network links within its cognitive boundary. The total network links of the agent will be increased by 5% for the current year until all the oil wells within its cognitive boundary are covered in its network links. If this agent has existed for more than two years, it will compare its profit in the recent two years. If the profit is increasing, the water depot will continue to expand its network links with other oil wells. If the profit is not increasing, the agent will decrease the water price by \$0.05/barrel until the water price reaches the lowest value, \$0.2/barrel. At the same time, the agent will also try to expand its network links with oil wells in the current year until the oil wells within its boundary have already been exhausted.

When reviewing the water sale objective, a municipal/co-op agent will first check whether its water use ratio objective is achieved or not in the previous year. If the water use ratio objective is achieved, the agent does not need to make any changes to its competition strategies used in the previous year. If the water use ratio objective is not achieved, the agent will expand its network links by 5% until the oil wells within its boundary have already been exhausted. The municipal/co-op agent will not adjust its water prices since the price is fixed by the state laws.

In the short-term sub-sub-model shown in figure 4.25, a temporary agent will collect various types of information within its cognitive boundaries, such as road, oil wells, other water depots, and water prices before starting its business. The temporary agent will also estimate the market competition intensity:

$$I = \frac{N_o}{N_w} \tag{4.15}$$

where, I stands for the competition intensity in the current year; N_o stands for the number of fracking oil wells within its cognitive boundary; N_w stands for the number of water depots within the cognitive boundary.

The parameter I_t is used to represent the competition intensity threshold. If the estimated competition intensity is higher than the threshold, a random value generated between \$0.60/barrel and \$1.00/barrel is used as the water price and a random value generated between 0-50% will be set as the agent's effort value. If the estimated competition intensity is lower than the threshold, a random value generated between \$0.20/barrel and \$0.60/barrel is used as the water price and a random value generated between 50-100% will be set as the agent's effort value.

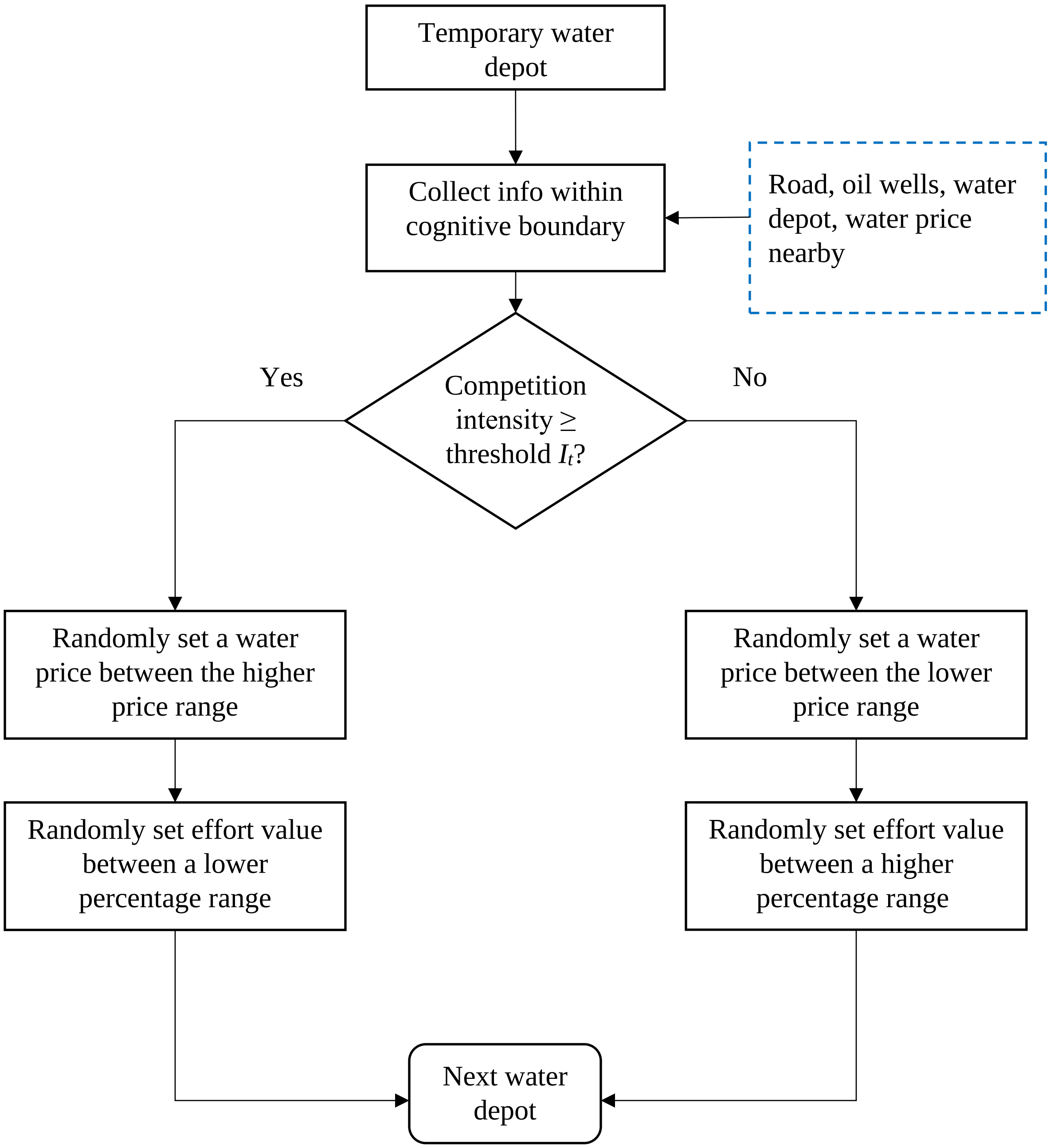

Figure 4.25. The short-term competition sub-sub-model.

The water use calculation sub-sub-model simulates the water selling process as shown in figure 4.26. Before calling the water use calculation sub-sub-model, each water-depot agent has already developed its network links with *N* oil wells in its cognitive boundary. If the water use by an agent has not reached the upper limit of its water permit, it will check all these *N* oil wells inside its network links to find other opportunities to sell more water.

If an oil well's HF water demand has not been fully fulfilled, a preference score will be given to each water-depot agent who has more water to sell and also holds a network link with the oil well. The agent with the highest score will have the privilege to sell water to this oil well. The preference score P_s is calculated as:

$$P_s = 10\alpha X_1 - \beta X_2 - \gamma X_3 \tag{4.16}$$

where P_s stands for the preference score for a certain water depot. X_1 stands for the normalized factor of water quality, which has two levels, treated and untreated. Treated or untreated water is represented with a value of 6 or 10 correspondingly. X_1 is the real water quality level value divided by 10, the maximum water quality value. X_2 represents the factor of water price. X_2 is calculated as the actual water price divided by the maximum water price of $1.00/barrel. X_3 stands for the distance between the water depot and the oil well. X_3 is calculated as the real distance divided by the maximum distance of 40 miles. α, β, and γ are the weights.

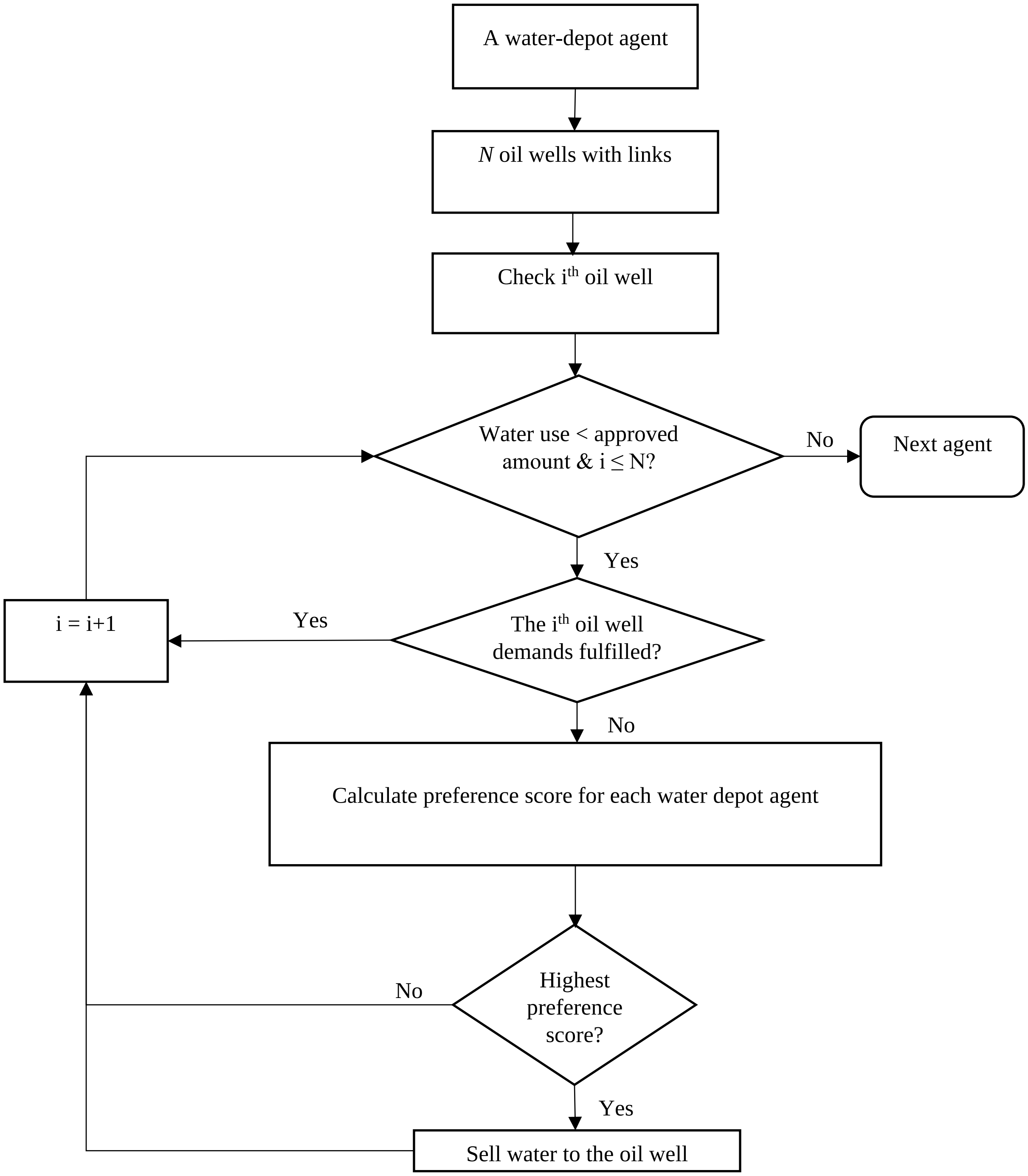

Figure 4.26. Water use calculation sub-sub-model.

5. MODEL CALIBRATION AND SENSITIVITY ANALYSIS

5.1. Model Calibration

The agent-based model described in Chapter 4 was manually (i.e., through trial and error) calibrated against the physical locations of individual water depots, the numbers of different types of water depots, and historical water uses by water depots. The calibrated model parameter values are shown in table 5.1.

Table 5.1. Calibrated values for parameters.

Parameter symbol	Explanation	Default value/ range	Calibrated values
Permit application sub-model			
M	Population size	10-500	500
G	Generation over which genetic programs evolve	10-100	50
D_{mg}	Maximum depth of genetic programs when generated	1-10	5
D_{mc}	Maximum depth when genetic programs cross	5-20	17
P_L	Maximum genetic program length	10-1000	500
Rd	Maximum distance for suitability estimation	5-15mile	10
Regulation sub-model			
A_l	The accessibility of the Lake Sakakawea and Missouri River	Yes or No	Yes
A_f	The accessibility of the Fox-Hills Hell Creek	Yes or No	Yes (2007-2010), No (2011-2014)
D_l	The difficulty level of obtaining water permits from the Lake Sakakawea and Missouri River	0-1	0
D_{osw}	The difficulty level of obtaining water permits from other surface water sources	0-1	0.12
D_f	The difficulty level of obtaining water permits from the Fox Hills-Hell Creek aquifer	0-1	0.85
D_{og}	The difficulty level of obtaining water permits from other groundwater sources	0-1	0.42
S_t	Streamflow threshold under which new water permits withdrawing water from other surface waters will not be approved	0-1	0.2
G_t	Water level threshold under which new water permits withdrawing water from other groundwaters will not be approved	0-10	4 m
A_b	Percentage of water permits hold in abeyance based on the permit's priority dates during dry years	0-20%	5%
Competition sub-model			
I_t	Competition intensity threshold	1-100	28
P_a	Permits abeyance ratio	0-20%	5%
α	Weight for water quality	1-100	11
β	Weight for water price	1-100	15
γ	Weight for road distance	1-100	14

5.1.1. Comparison of Water Depot Locations

Figure 5.1 shows the spatial distributions of the actual and model-simulated locations of all water depots. It appears that the model was able to place most of the model-simulated water depots in the vicinity of the actual water depot locations, especially in the center of the Bakken oil development such as in Williams, Mountrail, McKenzie, and Dunn counties. But in the outskirt of the region such as in the Slope and Ward counties, the model prediction was less precise. For instance, there were actually five temporary water depots in the Slope County (south of the region), but our model did not place any simulated water depots inside this county. Similarly, the model did not simulate any water depots in Ward County (east of the region).

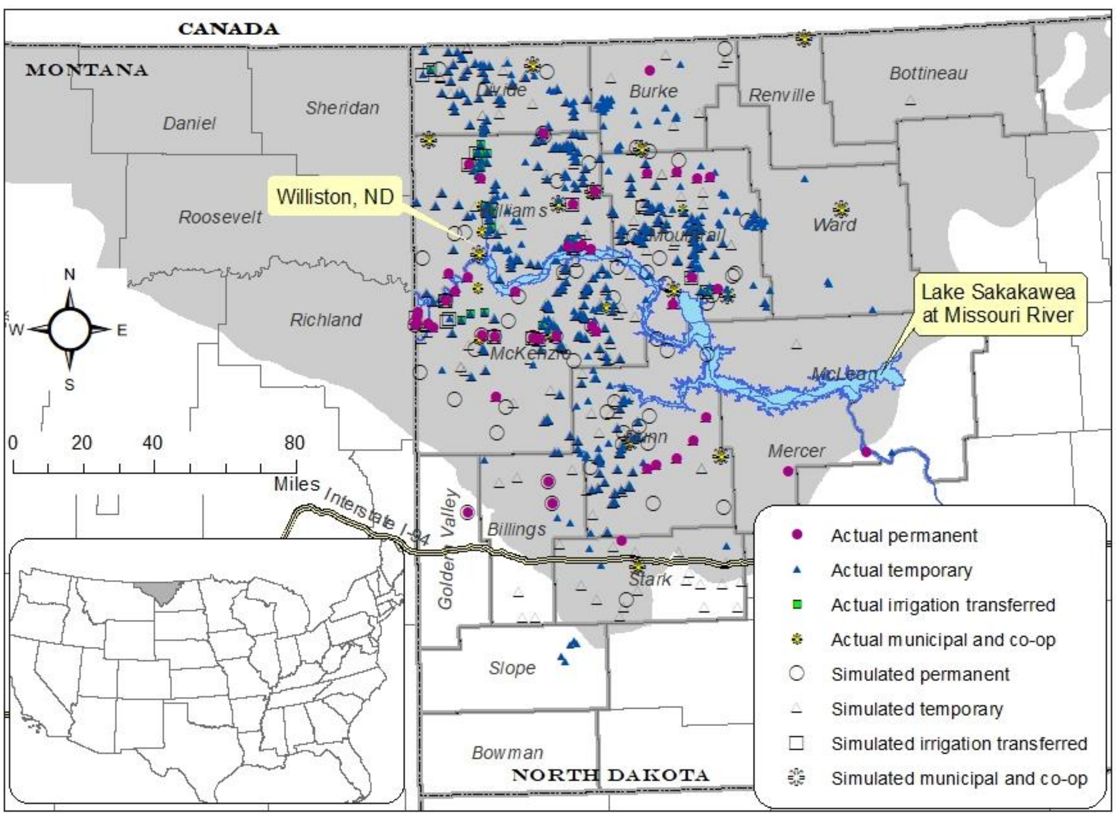

Figure 5.1. Comparison of the actual and the model-simulated locations of *all* water depots.

Besides visual comparison, we also used the Cohen's Kappa coefficient (κ) to measure the agreement between the actual and the model-simulated locations of water depots. Cohen's

Kappa coefficient (Cohen, 1960) is a statistic that is used to measure inter-rater reliability for qualitative (categorical) items. It is generally thought to be a more robust measure than simple percent agreement calculation, as κ takes into account the possibility of the agreement occurring by chance. Cohen's Kappa coefficient is calculated using the formula (Ahmed et al., 2013):

$$\kappa = \frac{(TP+TN)-(\widehat{TP}+\widehat{TN})}{m-(\widehat{TP}+\widehat{TN})} \tag{5.1}$$

where, $(TP + TN)$ is the actual agreement, $\left(\widehat{TP} + \widehat{TN}\right)$ is the expected agreement, TP is the true positive, TN is the true negative and *m* is the total number of cells. The value of Cohen's Kappa ranges between less than zero to 1. A negative value indicates no agreement and a value of 1 indicates perfect agreement.

The study area was divided into 1094 cells of 5 × 5 miles. Each cell may have zero, one, or multiple water depots. Table 5.2 compares the cells with different numbers of actual and model-simulated water depots inside them. It shows that about 73% of the cells with more than one water depot were simulated correctly, and about 66% of the cells with no water depot were simulated correctly. However, only about 28% of the cells with one water depot were correctly simulated by the model. Overall, about 62% of the cells were stimulated correctly, with κ=0.402.

Table 5.2. The cells with different numbers of the actual and the model simulated *all* water depots (κ=0.402).

Number of the actual water depots	Number of the model-simulated water depots			Total
	0	1	>1	
0	266	73	63	402
1	84	54	56	194
>1	62	73	363	498

We also compared the spatial distributions of the actual and the model-simulated locations for the four different types of water depots (see Fig. 5.2-5.5 and Tables 5.3-5.6). Figure 5.2 shows the spatial distributions of the actual and model-simulated locations of the *permanent* water depots. The figure shows that the model was able to place most of the simulated permanent water depots in the vicinity of the actual water depot locations. However, the model is less precise in Mercer County (east of the region) which has two permanent water depots, but our model did not place any simulated water depots inside this county. It should be noted that more than a dozen of the model-simulated locations coincided with the actual locations of the permanent water depots. This is because these permanent water-depot agents existed for the entire simulation period (2007-2014) and the model used the actual water depot locations specified in the initial year (i.e., 2007).

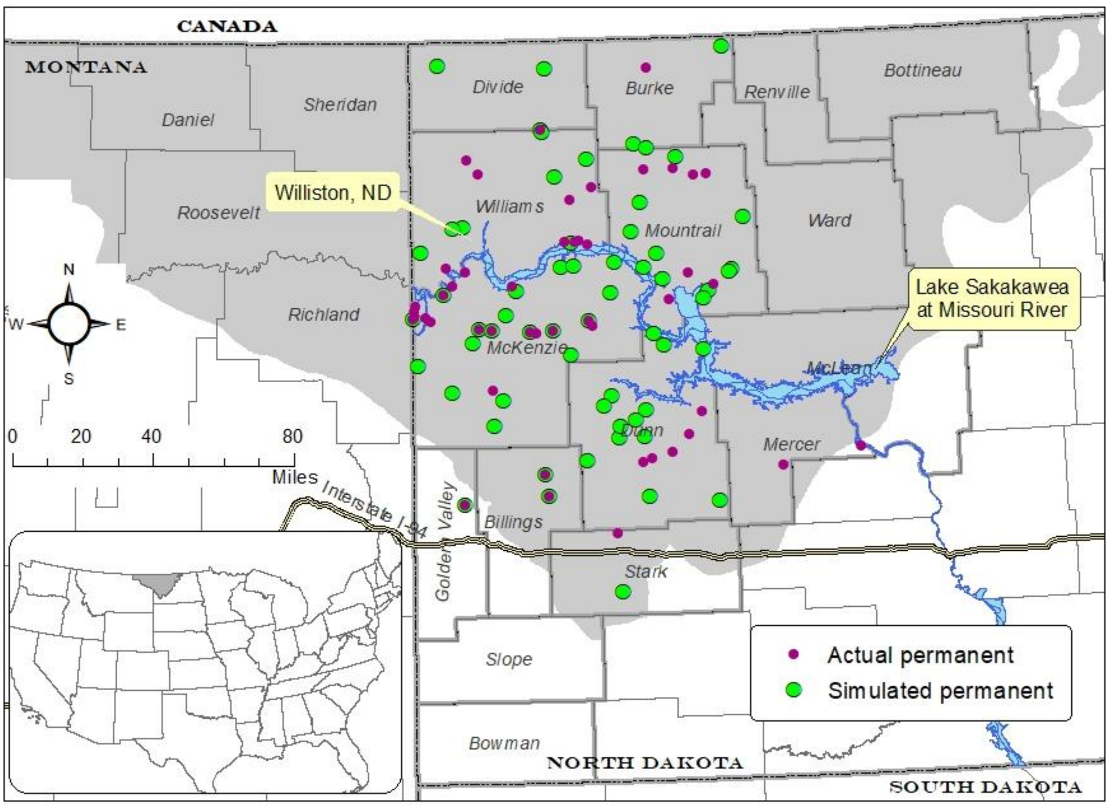

Figure 5.2. Comparison of the actual and the model-simulated locations of the *permanent* water depots.

Table 5.3 compares the cells with different numbers of actual and model-simulated permanent water depots inside them. It shows that about 39% and 48% of the cells with one or more than one water depot were simulated correctly by the model, respectively, although about

95% of the cells with no water depot were simulated correctly. Overall, about 89% of the cells were stimulated correctly, and the value of Cohen's Kappa coefficient (κ) for the permanent water depots is 0.482.

Table 5.3. The cells with the different numbers of the actual and the model-simulated *permanent* water depots (κ=0.482).

Number of the actual water depots	Number of the model-simulated water depots			Total
	0	1	>1	
0	925	38	9	972
1	32	27	11	70
>1	12	15	25	52

Figure 5.3 shows the spatial distributions of the actual and model-simulated locations of the *temporary* water depots. It appears that the model was also able to place most of the model-simulated temporary water depots in the vicinity of the actual water depot locations, especially in the four counties with the most oil development (Williams, Mountrail, McKenzie, and Dunn). But in the outskirt of the region such as in the Slope, Ward, and Stark counties, the model prediction was less precise. For instance, there were five temporary water depots in Slope County (south of the region), but our model did not place any simulated water depots inside this county. Similarly, the model did not simulate any temporary water depots in Ward County (east of the region). However, in Stark County (south of the region), the model overpredicted it with 12 temporary water depots.

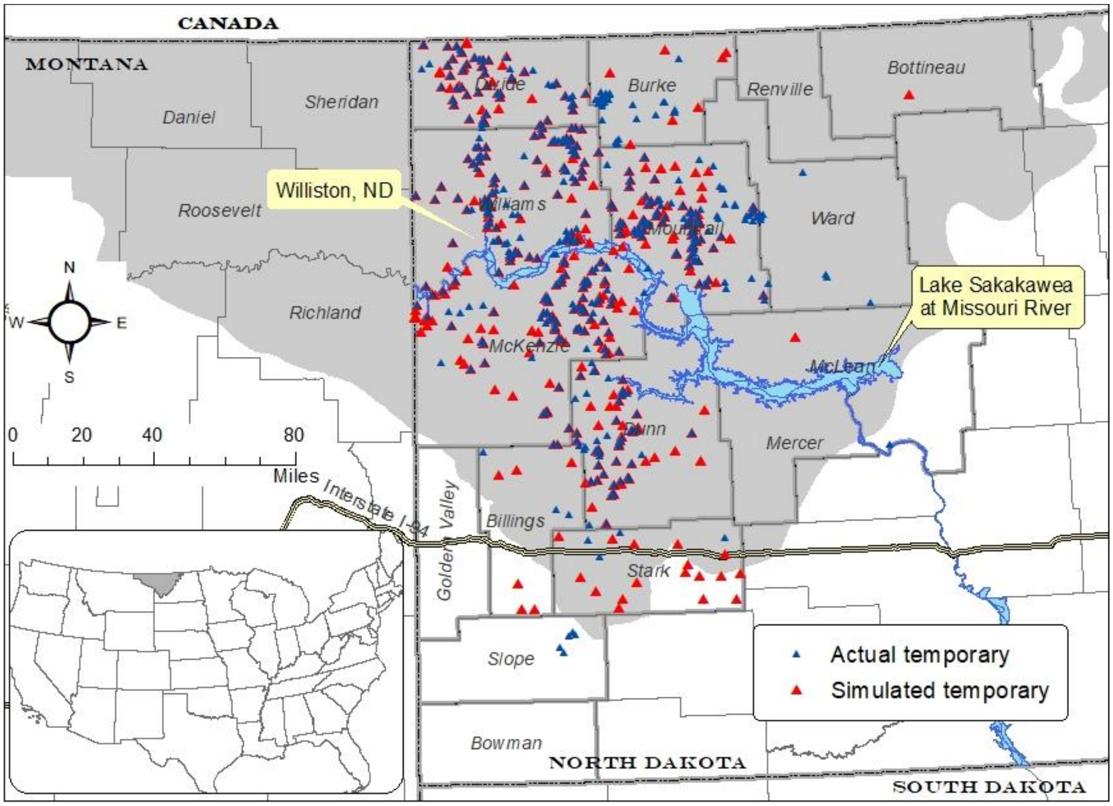

Figure 5.3. Comparison of the actual and model-simulated locations of the *temporary* water depots.

Table 5.4 compares the cells with different numbers of the actual and the model-simulated temporary water depots inside them. It shows that about 34% and 45% of the cells with one or more than one water depot were simulated correctly by the model, respectively, although more than 74% of the cells with no water depot were simulated correctly. Overall, about 59% of the cells were stimulated correctly, with κ=0.320.

Table 5.4. The cells with different numbers of the actual and the model-simulated temporary water depots (κ=0.320).

	Number of the model-simulated water depots			Total
Number of the actual water depots	0	1	>1	
0	449	77	81	607
1	55	82	101	238
>1	60	77	112	249

Figure 5.4 shows the spatial distributions of the actual and the model-simulated locations of the *irrigation transferred* water depots. The figure shows that most of the actual irrigation transferred water depots were located in the north-central area of Williams county where the Little Muddy River and the Yellowstone Buried Channel aquifer are (Lin et al., 2018). But the model-simulated water depots were spread across the Williams, Mountrail, and McKenzie three counties.

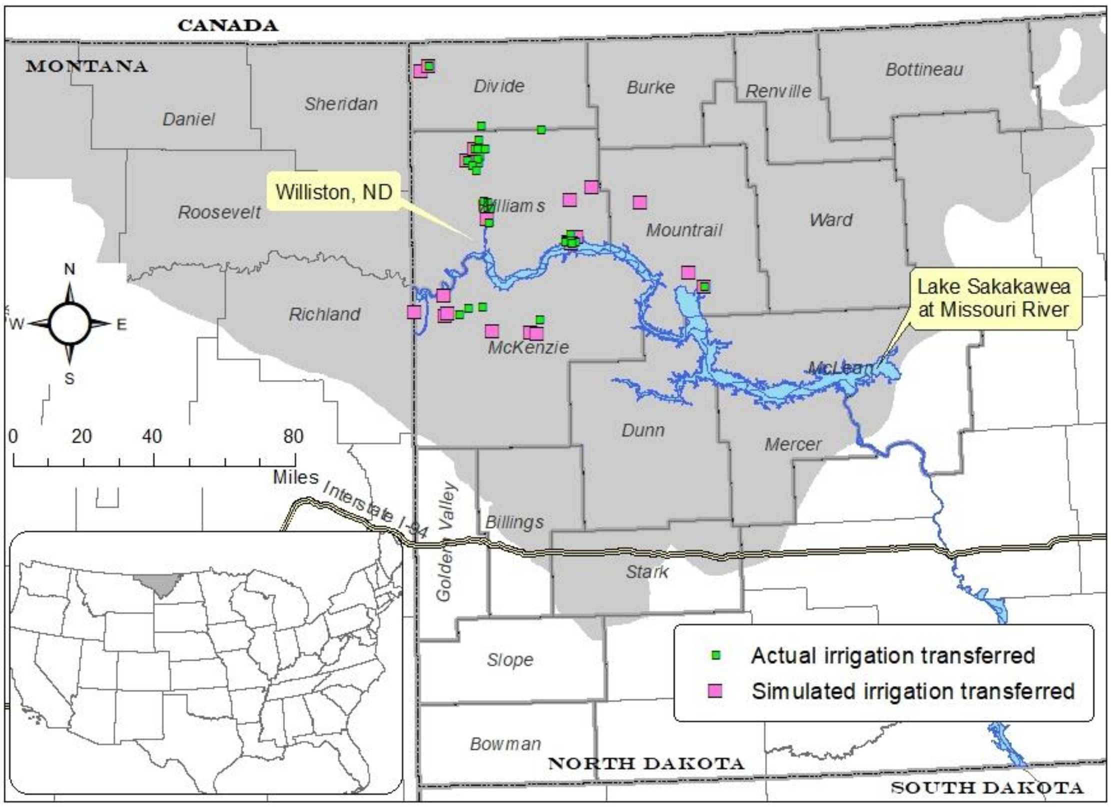

Figure 5.4. Comparison of the actual and model-simulated locations of the *irrigation transferred* water depots.

Table 5.5 compares the cells with different numbers of the actual and the model-simulated irrigation transferred water depots inside them. It shows that only 25-35% of the cells with one or more water depots were correctly simulated by the model, although about 96% of the cells with no water depot were simulated correctly. Overall, about 90% of the cells were stimulated correctly, and the value of κ for the irrigation transferred water depots was 0.390.

Table 5.5. The cells with different numbers of the actual and model-simulated *irrigation transferred* water depots (κ=0.390).

Number of the actual water depots	Number of the model-simulated water depots			Total
	0	1	>1	
0	954	21	22	997
1	20	14	9	43
>1	22	17	15	54

Figure 5.5 shows the spatial distributions of the actual and model-simulated locations of municipal/co-op water depots. The figure shows that most of the simulated and the actual water depot locations coincided. This is because the model used the existing municipal permits and their locations to determine the municipal water depots. Also, for the co-op water depots, the permit-application sub-model used the original 8 co-op water depot locations as the locations for the simulated co-op water depots generated in the year 2011. The locations of the co-op water depots were not simulated because of the difficulty in predicting the pipeline construction plan of the Western Area Water Supply project (WAWS).

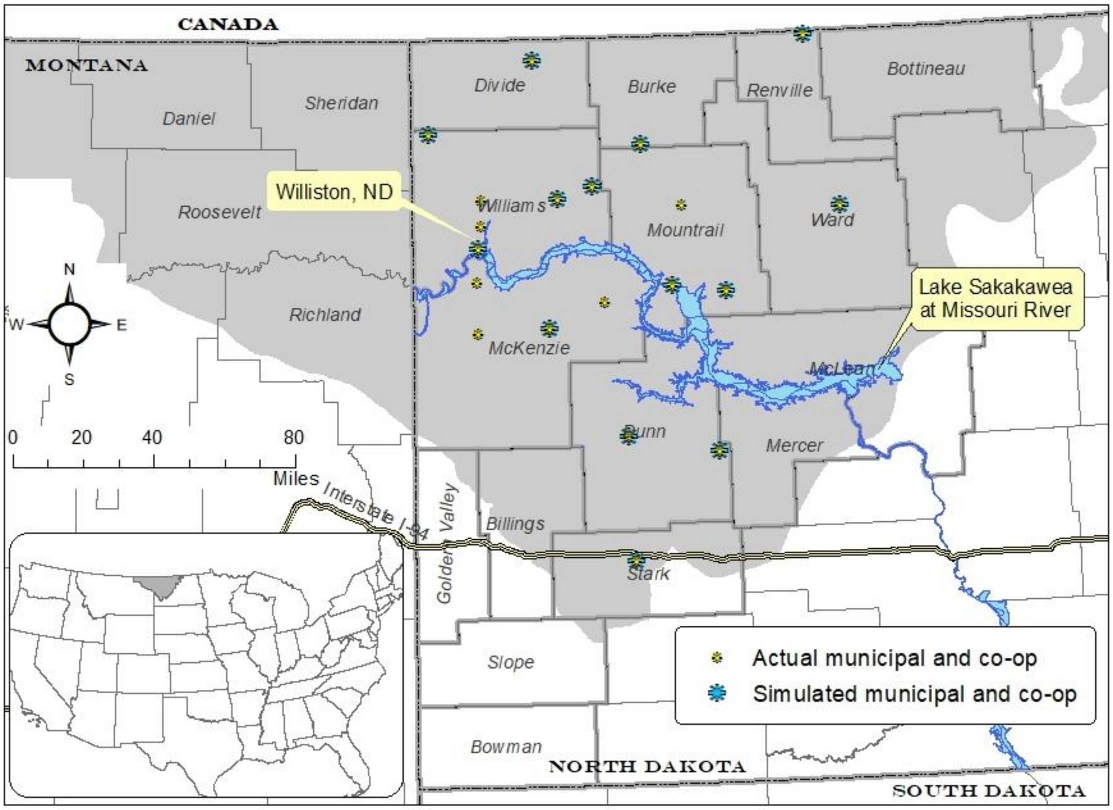

Figure 5.5. Comparison of the actual and the model-simulated locations of the *municipal/co-op* water depots.

Table 5.6 compares the cells with different numbers of the actual and the model-simulated municipal/co-op water depots inside them. Apparently, most of the cells were correctly simulated because of the reason stated above. The κ value for the municipal/co-op water depot spatial distribution was 0.831.

Table 5.6. The cells with different numbers of the actual and the model-simulated municipal/co-op water depots (κ=0.831).

Number of the actual water depots	Number of the model-simulated water depots			Total
	0	1	>1	
0	1072	0	0	1072
1	6	14	0	20
>1	0	0	1	1

5.1.2. Comparison of Water Depot Numbers

Figure 5.6 compares the actual and model-simulated numbers of different types of water depots from 2008 to 2014 (see also Table 5.7). It shows that the model did well in simulating the numbers of permanent and temporary water depots with R^2 equal to 0.926 and 0.998, respectively (Fig. 5.6a, b). The model did a fair job in simulating the number of irrigation transferred water depots (R^2 = 0.880), overpredicting the numbers before 2013 but underpredicting the number in 2014 (Fig. 5.6c). For the municipal/co-op water depots, the model underpredicted the numbers for the entire simulation years with R^2 = 0.672 (Fig. 5.6d). Overall, the model did very well in simulating the total numbers of all water depots with R^2 = 0.997 (Fig. 5.6e).

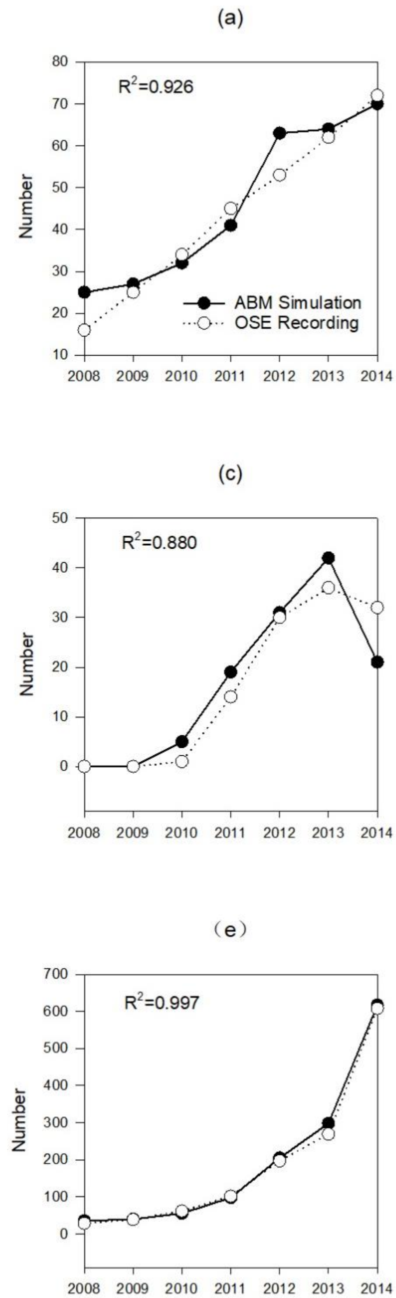

Figure 5.6. Graphical comparisons of the actual and model-simulated numbers of (a) permanent, (b) temporary, (c) irrigation transferred, (d) municipal/co-op, and (e) all types of water depots.

Table 5.7. Comparison of the actual and model-simulated numbers of different types of water depots from 2008 to 2014.

Year	Permanent		Temporary		Irrigation transferred		Municipal /co-op		Total	
	Sim	Act	Sim	Act	Sim	Act	Sim	Act	Sim	Act
2008	25	16	1	2	0	0	10	11	36	29
2009	27	25	3	1	0	0	10	13	40	39
2010	32	34	7	10	5	1	12	17	56	62
2011	41	45	21	23	19	14	17	20	98	102
2012	63	53	92	94	31	30	19	20	205	197
2013	64	62	178	152	42	36	14	19	298	269
2014	70	72	512	483	21	32	14	21	617	608

Note: Act – Actual, Sim – Model-simulated.

Figure 5.7 compares the numbers of the model-simulated and the actual water depots in the four core counties separately and in the other 12 counties in western North Dakota. It appears that the model was able to simulate the actual number of water depots at the county level reasonably well with R^2 values ranging from 0.916 to 0.997.

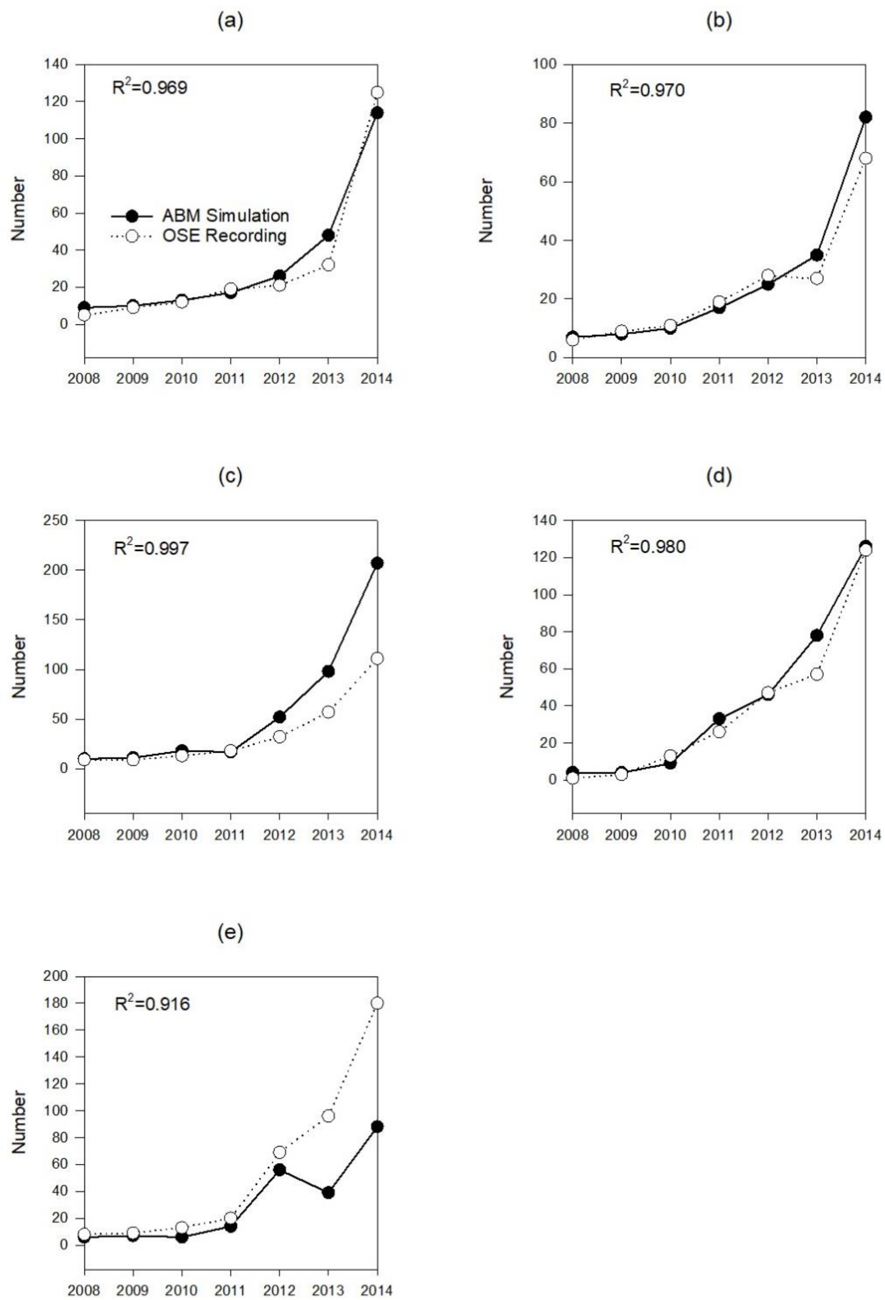

Figure 5.7. Graphical comparisons of the actual and model-simulated numbers of (a)Williams, (b) Mountrail, (c) McKenzie, (d) Dunn, and (e) other counties in western North Dakota.

5.1.3. Water Use Comparison

Figure 5.8 compares the recorded and the model-simulated water uses from different types of water depots during 2008-1014. In general, the model did well in simulating the total water use from the four different types of water depots. A close inspection shows that the model slightly underpredicted the water use from the permanent and the municipal/co-cop water depots while overpredicted the water uses from the temporary and the irrigation transferred water depots.

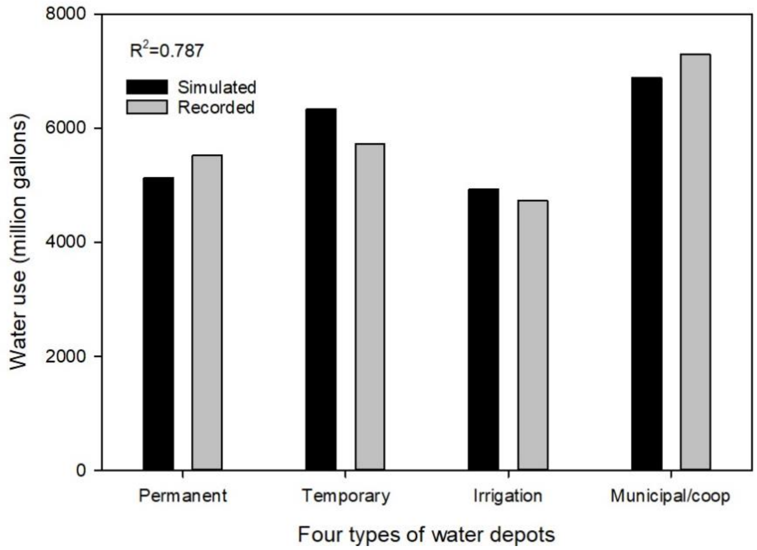

Figure 5.8. Graphical comparison of the recorded and model-simulated water uses (2008-2014) from four different types of water depots.

Figure 5.9 compares the recorded and the model-simulated annual water uses (2008-2014) from surface and groundwater sources. Overall, the model did well in simulating water depot water uses from different water sources. A closer inspection shows that the model overpredicted the water uses from surface water sources in 2008-2010, 2012, and 2013, while underpredicting the water uses in 2011 and 2014. Not surprisingly, the trend reversed for groundwater sources.

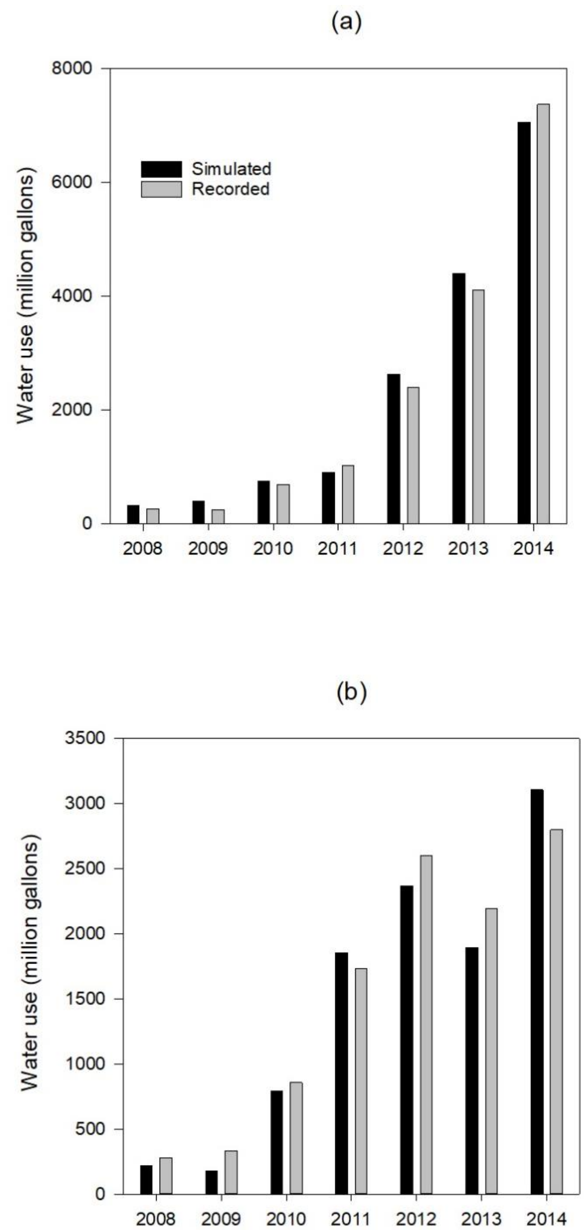

Figure 5.9. Graphical comparisons of the recorded and model-simulated water uses of (a) surface water source and (b) groundwater source.

Figure 5.10 compares the water use of the actual water depots and the model-simulated water depots in the four core counties separately and in other 12 western North Dakota counties. It appears that the model slightly overpredicted the water use in all four core counties but underpredicted the water use in the rest 12 counties.

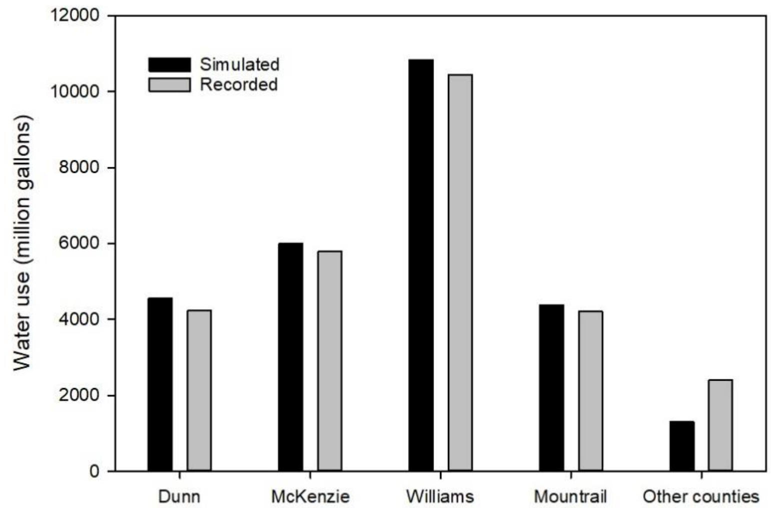

Figure 5.10. Graphical comparisons of water use from the actual and the model-simulated water depots in the four core counties and the other counties in western North Dakota.

5.2. Sensitivity Analysis

5.2.1. Water Depot Location Sensitivity

Figures 5.11-13 show the sensitivity of the model parameters in the permit application, the regulation, and the competition sub-models in terms of Cohen's Kappa coefficient used to measure the agreement between the actual and the model-simulated locations of all types of water depots. We use the sensitivity index (SI) to calculate Cohen's Kappa coefficient difference when varying one input parameter from its minimum value to its maximum value. The sensitivity index is calculated using the formula:

$$\mathrm{SI}(\%) = \frac{D_{max} - D_{min}}{D_{max}} \times 100 \tag{5.2}$$

Where, D_{max} and D_{min} represent the minimum and maximum output values (e.g., Cohen's Kappa coefficient), resulting from varying the parameter over its entire range.

According to the SI, almost all the parameters in the permit application and the regulation sub-models are sensitive (Fig. 5.11-5.12) in terms of simulating the spatial locations of water depots, while none of the parameters in the competition sub-models (Fig. 5.13) are sensitive because the competition sub-model simulates water uses (not the locations) of water depots.

Figure 5.11 also shows that the generation over which genetic programs evolve (G) is the most sensitive parameter in the evolutionary programming and genetic algorithms (SI = 76.2%, Fig. 5.11b), whereas the maximum depth when genetic programs cross (D_{mc}) is the least sensitive parameter (SI = 0.8%, Fig. 5.11d). Figure 5.12 shows that among the four parameters in the regulation sub-model, which govern the difficulty levels of obtaining water permits from different water sources, the difficulty level of obtaining water permits from the Lake Sakakawea and Missouri River (D_l) is the most sensitive parameter in terms of simulating spatial locations of water depots (SI = 43.4%, Fig. 5.12a), while the difficulty level of obtaining water permits from the other surface water sources (D_{osw}) is the least sensitive one (SI = 15.6%, Fig. 5.12b). According to SI, the streamflow threshold under which new water permits withdrawing water from other surface waters will not be approved (S_t) is more sensitive (SI = 37.4%, Fig. 5.12e) than the water level threshold under which new water permits withdrawing water from other groundwaters will not be approved (G_t) (SI = 28.9%, Fig. 5.12f).

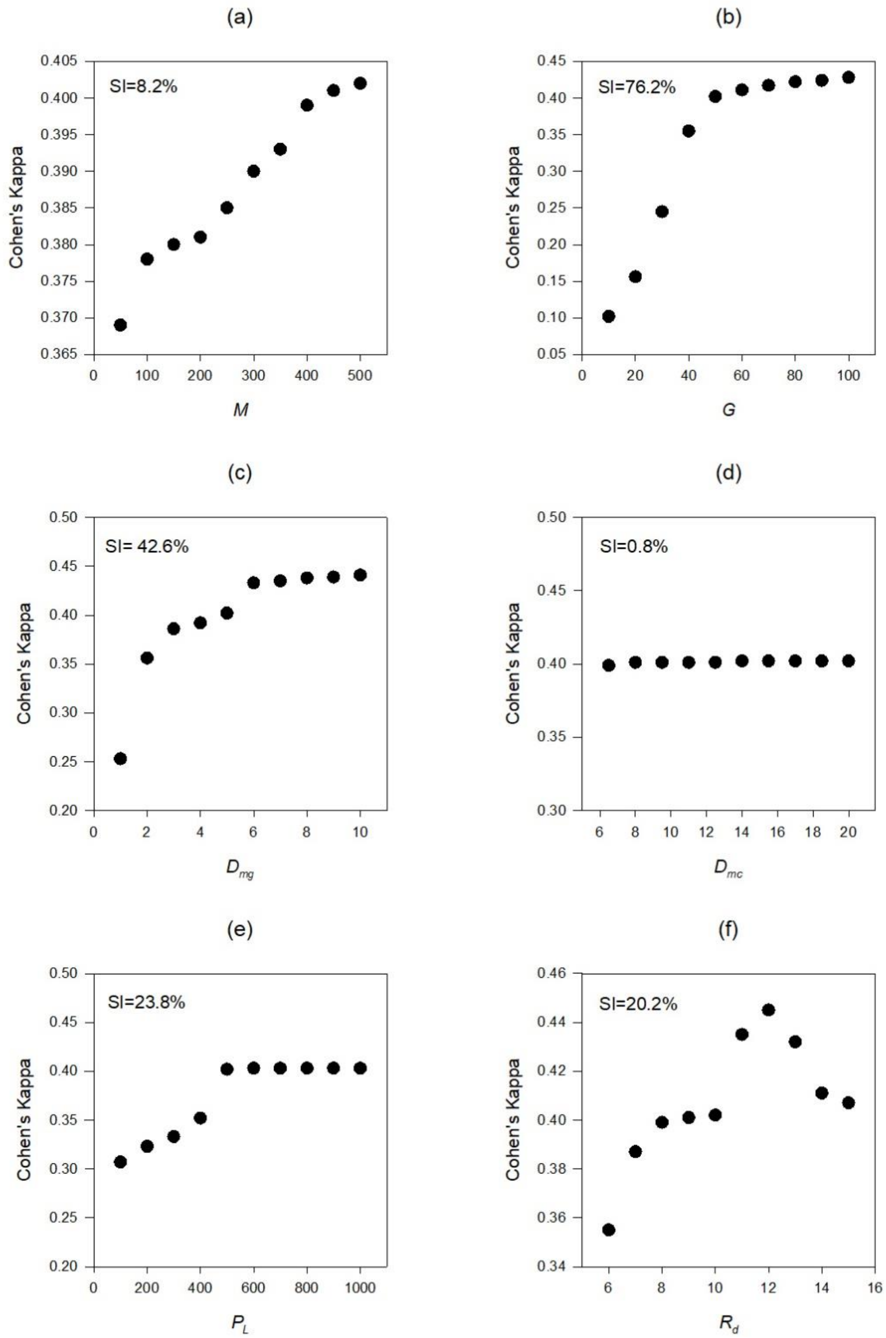

Figure 5.11. The sensitivity of parameters in the permit application sub-model in terms of Cohen's Kappa coefficient.

Note: (a) population size (M), (b) generation over which genetic programs evolve (G), (c) maximum depth of genetic programs when generated (D_{mg}), (d) maximum depth when genetic programs cross (D_{mc}), (e) maximum genetic program length (P_l), and (f) maximum distance for suitability estimation (R_d).

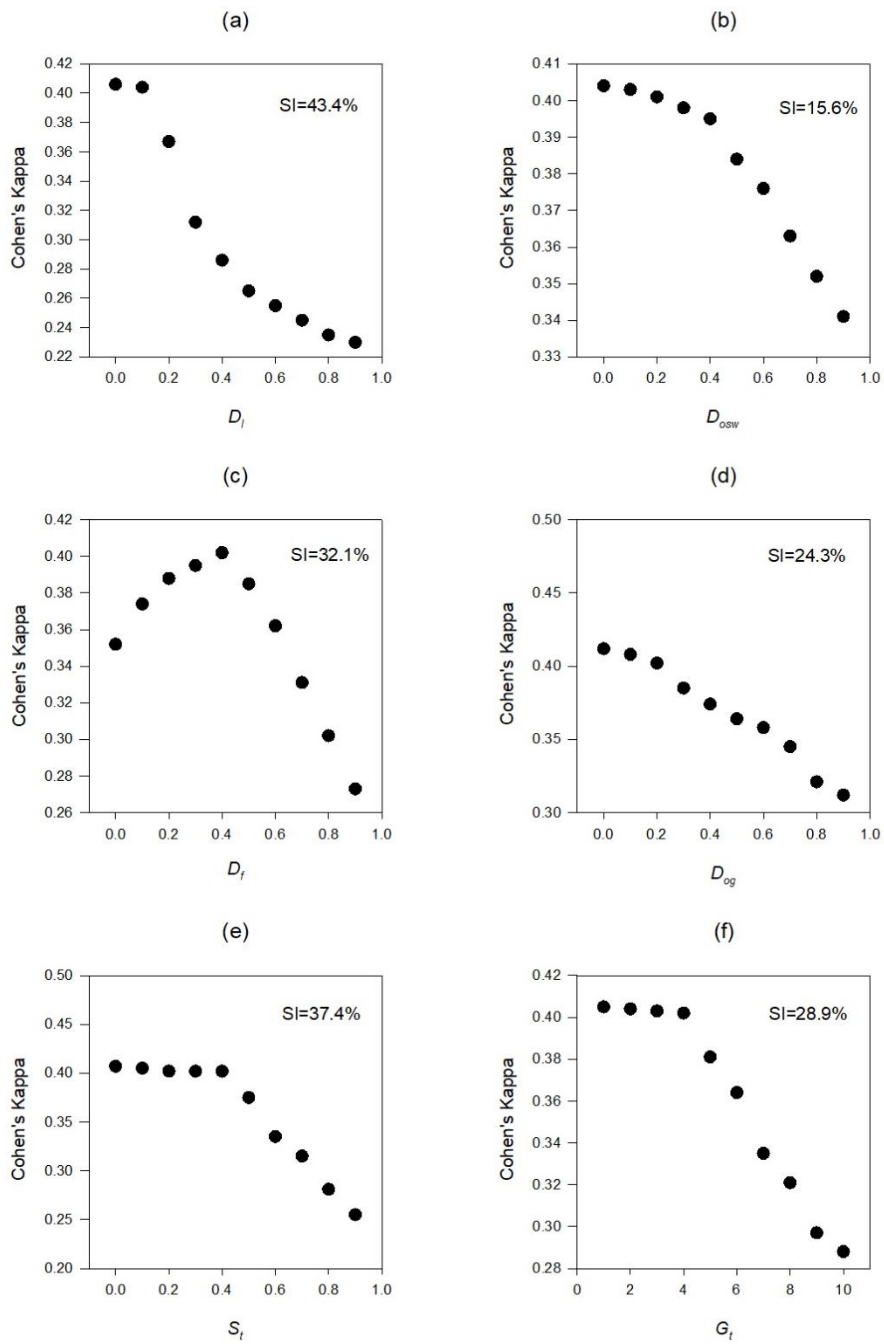

Figure 5.12. The sensitivity of parameters in the regulation sub-model in terms of Cohen's Kappa coefficient.

Note: (a) the difficulty level of obtaining water permits from the Lake Sakakawea and Missouri River (Dl), (b) the difficulty level of obtaining water permits from other surface water sources (Dosw), (c) the difficulty level of obtaining water permits from the Fox Hills-Hell Creek aquifer (Df), (d) the difficulty level of obtaining water permits from other groundwater sources (Dog), (e) streamflow threshold under which new water permits withdrawing water from other surface waters will not be approved (St), and (f) water level threshold under which new water permits withdrawing water from other groundwaters will not be approved (Gt).

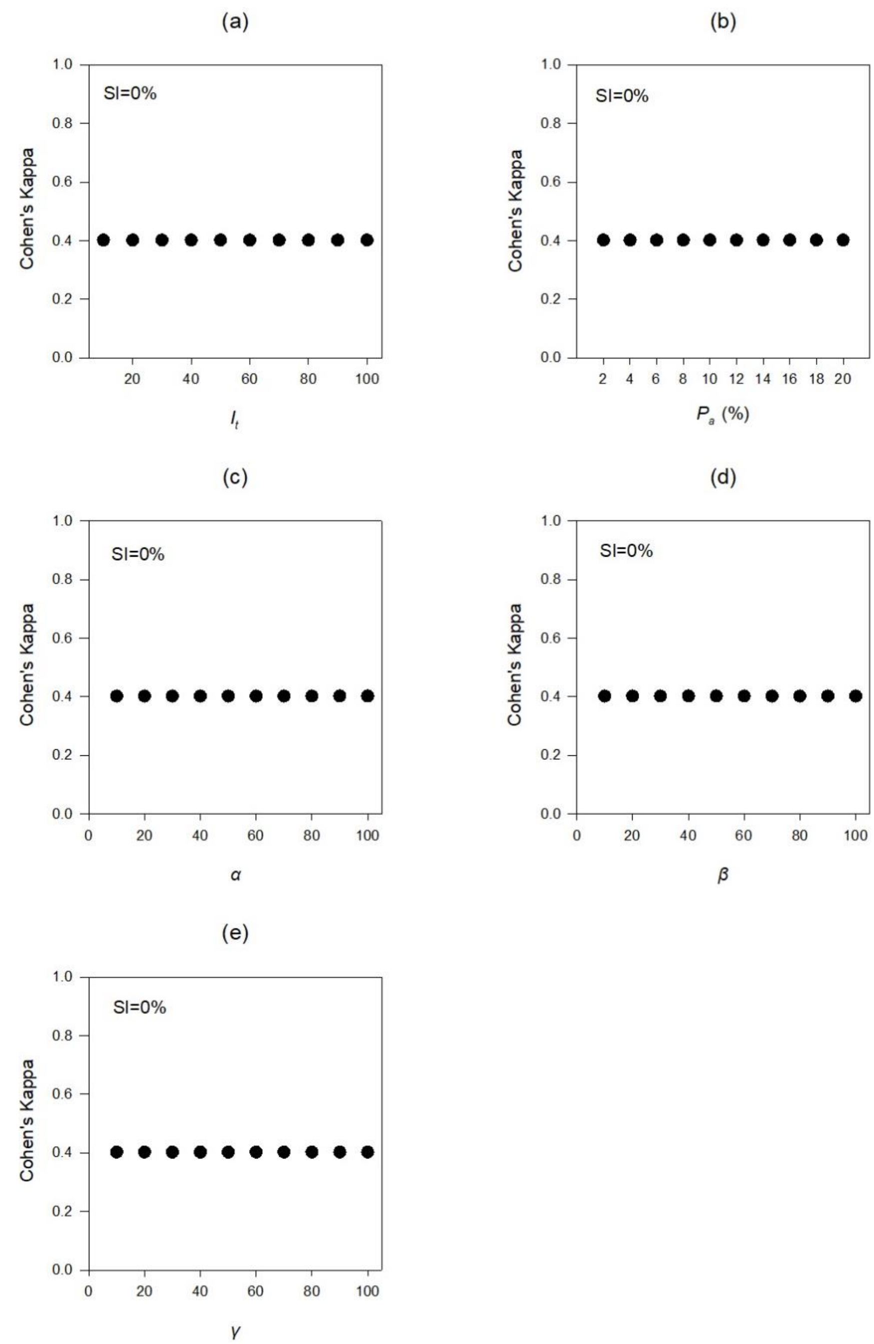

Figure 5.13. The sensitivity of parameters in the competition sub-model in terms of Cohen's Kappa coefficient.
Note: (a) competition intensity threshold (I_t), (b) permits abeyance ratio (P_a), (c) weight for water quality (α), (d) weight for water price (β), and (e) weight for road distance (γ).

5.2.2. Water Use Sensitivity

Figures 5.14-16 show the sensitivity of the model parameters in the permit application, the regulation, and the competition sub-models in terms of coefficient of determination (R^2) used to measure the agreement between the recorded and the model-simulated water uses from the four different types of water depots (referring to Fig. 5.8). According to the SI, almost all the parameters in the three sub-models are sensitive in terms of simulating the water depot water uses even though the permit application and the regulation sub-models mainly simulate the locations and approved water permits (not the actual water uses) of water depots. This is because water depot locations affect the actual water uses.

Figure 5.14 also shows that the maximum distance for suitability estimation (R_d) is the most sensitive parameter in the evolutionary programming and genetic algorithms (SI = 30.4%, Fig. 5.14f), whereas the maximum depth when genetic programs cross (D_{mc}) (SI = 0.4%, Fig. 5.14d) and the maximum genetic program length (P_l) (SI = 0.1%, Fig. 5.14e) are not sensitive. Figure 5.15 shows that among the four parameters in the regulation sub-model, which govern the difficulty levels of obtaining water permits from different water sources, the difficulty level of obtaining water permits from the Lake Sakakawea and Missouri River (D_l) is the most sensitive parameter in terms of simulating the water depot water uses (SI = 24.8%, Fig. 5.15a), and the difficulty level of obtaining water permits from the Fox Hills-Hell Creek aquifer (D_f) is the least sensitive one (SI = 0.4%, Fig. 5.15c). According to SI, the streamflow threshold under which new water permits withdrawing water from other surface waters will not be approved (S_t) is as sensitive (SI = 17.8%, Fig. 5.15e) as the water level threshold under which new water permits withdrawing water from other groundwaters will not be approved (G_t) (SI = 17.7%, Fig. 5.15f). Figure 5.16 shows that the competition intensity threshold (I_t) is the most sensitive parameter in terms of simulating actual water uses (SI = 36.1%, Fig. 5.16a), whereas the permits abeyance ratio (P_a) is the least sensitive parameter (SI = 1.0%, Fig. 5.16b).

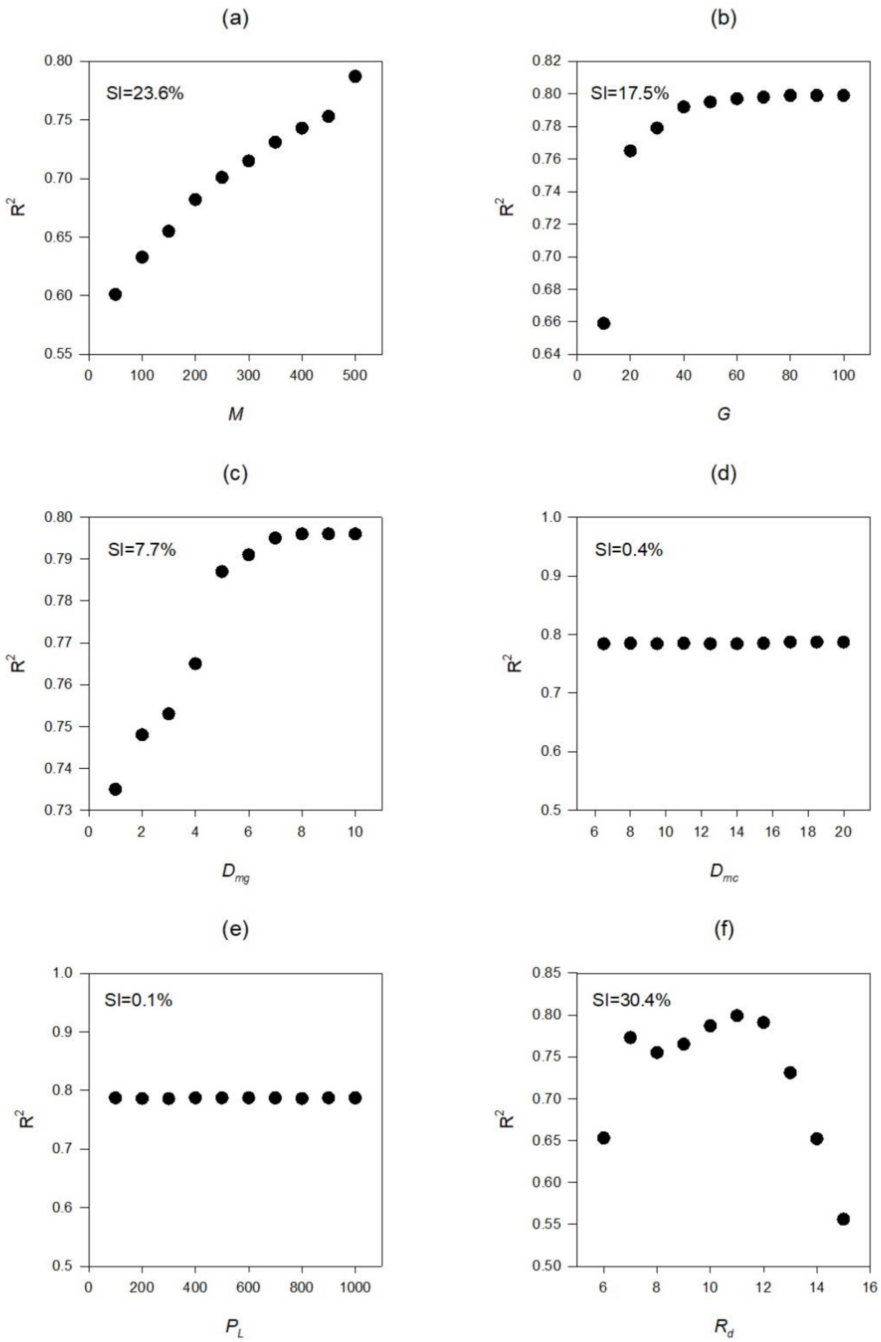

Figure 5.14. The sensitivity of parameters in permit application sub-model in terms of R^2 of water use of different types of water depots.
Note: (a) population size (M), (b) generation over which genetic programs evolve (G), (c) maximum depth of genetic programs when generated (D_{mg}), (d) maximum depth when genetic programs cross (D_{mc}), (e) maximum genetic program length (P_l), and (f) maximum distance for suitability estimation (R_d).

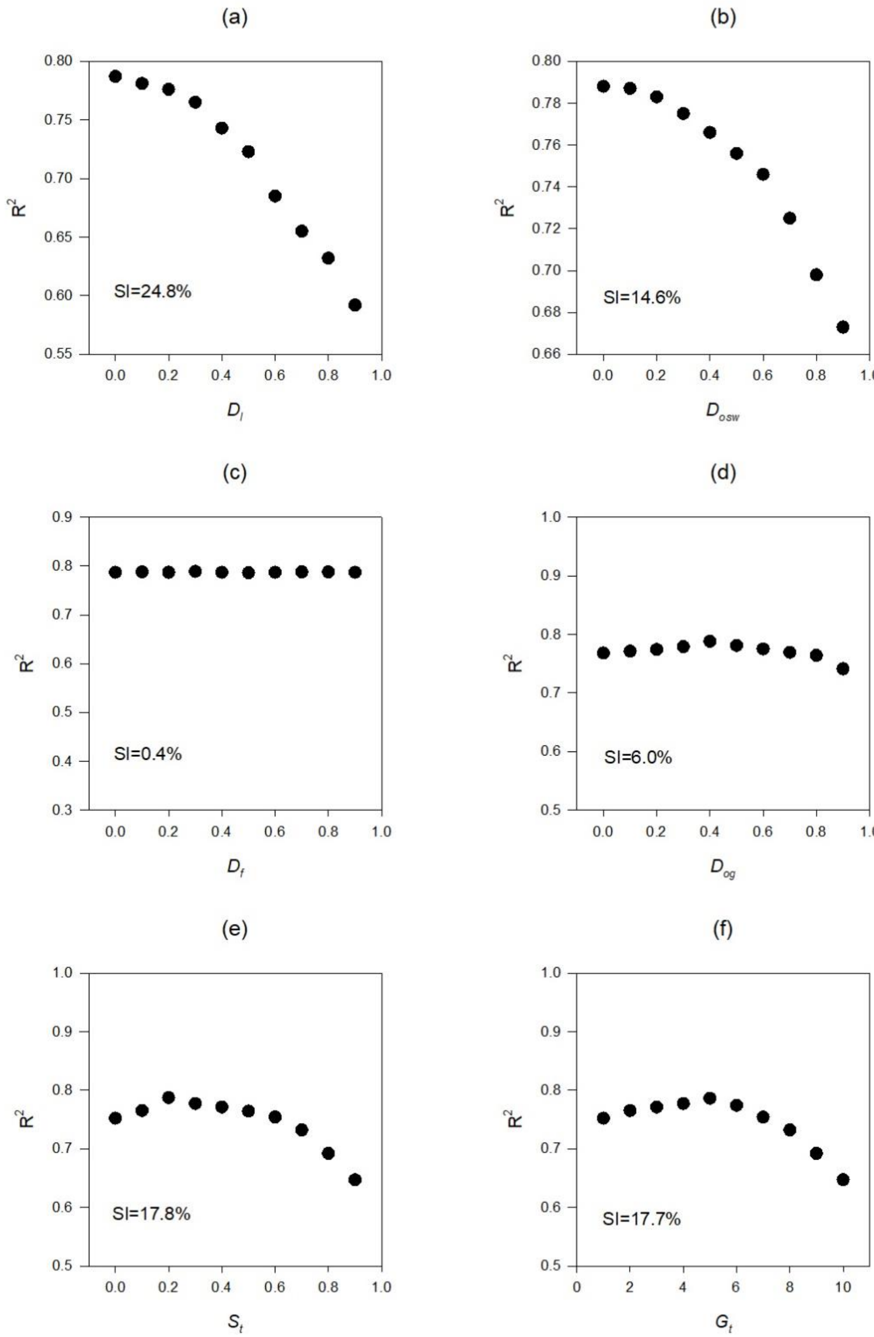

Figure 5.15. The sensitivity of parameters in regulation sub-model in terms of R^2 of water use of different types of water depots.
Note: (a) the difficulty level of obtaining water permits from the Lake Sakakawea and Missouri River (D_l), (b) the difficulty level of obtaining water permits from other surface water sources (D_{osw}), (c) the difficulty level of obtaining water permits from the Fox Hills-Hell Creek aquifer (D_f), (d) the difficulty level of obtaining water permits from other groundwater sources (D_{og}), (e) streamflow threshold under which new water permits withdrawing water from other surface waters will not be approved (S_t), and (f) water level threshold under which new water permits withdrawing water from other groundwaters will not be approved (G_t).

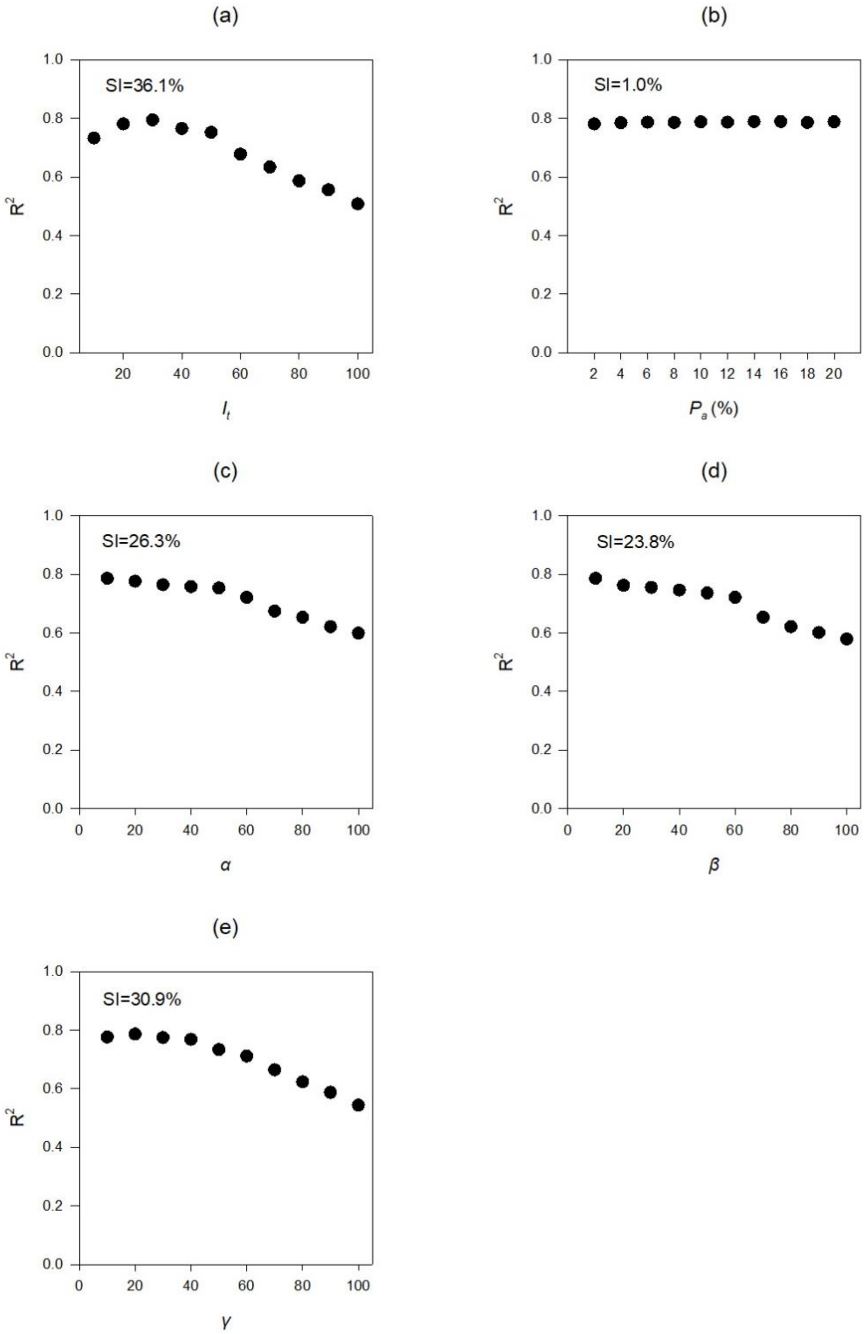

Figure 5.16. The sensitivity of parameters in the competition sub-model in terms of R^2 of water use of different types of water depots.
Note: (a) competition intensity threshold (I_t), (b) permits abeyance ratio (P_a), (c) weight for water quality (α), (d) weight for water price (β), and (e) weight for road distance (γ).

6. COUPLING AGENT-BASED WITH HYDROLOGICAL MODELS FOR WATER RESOURCES MANAGEMENT

In this chapter, the calibrated ABM was first coupled with the Soil and Water Assessment Tool (SWAT) model and the MODFLOW groundwater model to understand and estimate the potential impacts of the HF water use on surface water streamflow and groundwater levels in the Bakken region of western North Dakota under different scenarios, such as increasing HF water demands and population, decreasing precipitation, as well as changing regulatory policies.

6.1. SWAT Model Development and Calibration

We selected the Little Muddy River watershed (see Fig 6.1) as our study -area of interest. The study area includes the northern surface drainage of the Little Muddy River in Western North Dakota. The area is inside two counties, Divide and Williams, and the watershed under the study drain approximately an area of 2415 km^2. The Little Muddy river is a tributary of the Missouri River, approximately 45 miles long in northwestern North Dakota. It rises in the prairie country of northern Williams County and flows west, then south, joining the Missouri River near Williston.

Since 2012, the Little Muddy River has been tapped to support hydraulic fracturing in western North Dakota. From 2012 to 2015, there were 22 temporary and one conditional industrial water permit issued on the Little Muddy River. There were also 13 water depots built along the river, among which eight were within our study area.

According to the water-use dataset obtained from NDSWC, the Missouri River and Lake Sakakawea were the most frequently used surface water sources for HF in the region. However, they are not likely to be affected by the HF water uses compared to other surface water sources because of their massive streamflows and water volume. The Little Muddy River was the second most frequently used surface water source only behind the Missouri River and Lake Sakakawea. From 2012 to 2015, 23 industrial water permits were issued on the Little Muddy River, and accumulated industrial water uses were 1639 acre-feet. Both the number of permits and total HF water uses of the Little Muddy River were ranked second only behind the Missouri River and Lake Sakakawea. Although the average annual 7-day low flows of the Little Muddy River increased about 88 percent during 2008 -2014, this increase was the least compared to other surface water sources in the region due to HF water use (Lin et al., 2017). It appeared that the Little Muddy River had been affected by the HF water use, therefore it was selected to study the impact of unconventional oil development on surface water sources in western North Dakota.

To develop the SWAT model for the Little Muddy River watershed, A 10-m DEM (https://earthexplorer.usgs.gov/) was used to delineate the watershed into 21 subbasins shown in Figure 6.1. The United States Geological Survey (USGS) National Land Cover Database (NLCD) and STASTSGO databases were used to classify land cover and soil types, respectively. Based on the DEM data, the watershed was classified into three slope groups: 0-5%, 5%-10%, and greater than 10%. These land use, soil type, and slope classes with an area larger than 10% respectively are taken into consideration and then combined into 154 Hydrologic Response Units (HRUs) and each HRU has specific land use, soil type, and slope class. Daily precipitation, daily maximum and minimum temperature, solar radiation, relative humidity, and wind speed data are obtained from Climate Forecast System Reanalysis (CFSR) (https://globalweather.tamu.edu/) and the climate data from six stations (p479-1031, p479-1034, p479-1038, p482-1031, p482-1034, p482-1038) were used in this study shown in Figure 6.1. For each HRU, the water balance, potential evapotranspiration, and surface runoff were calculated by the variable storage coefficient method (Williams 1969), Hargreaves method (Hargreaves et al. 1985), and the Soil

Conservation Service (SCS) Curve Number method (USDA, 1972), respectively. In the simulation process, the SWAT model prints all daily, monthly, and yearly results of hydrologic components into output files for each HRU and each subbasin.

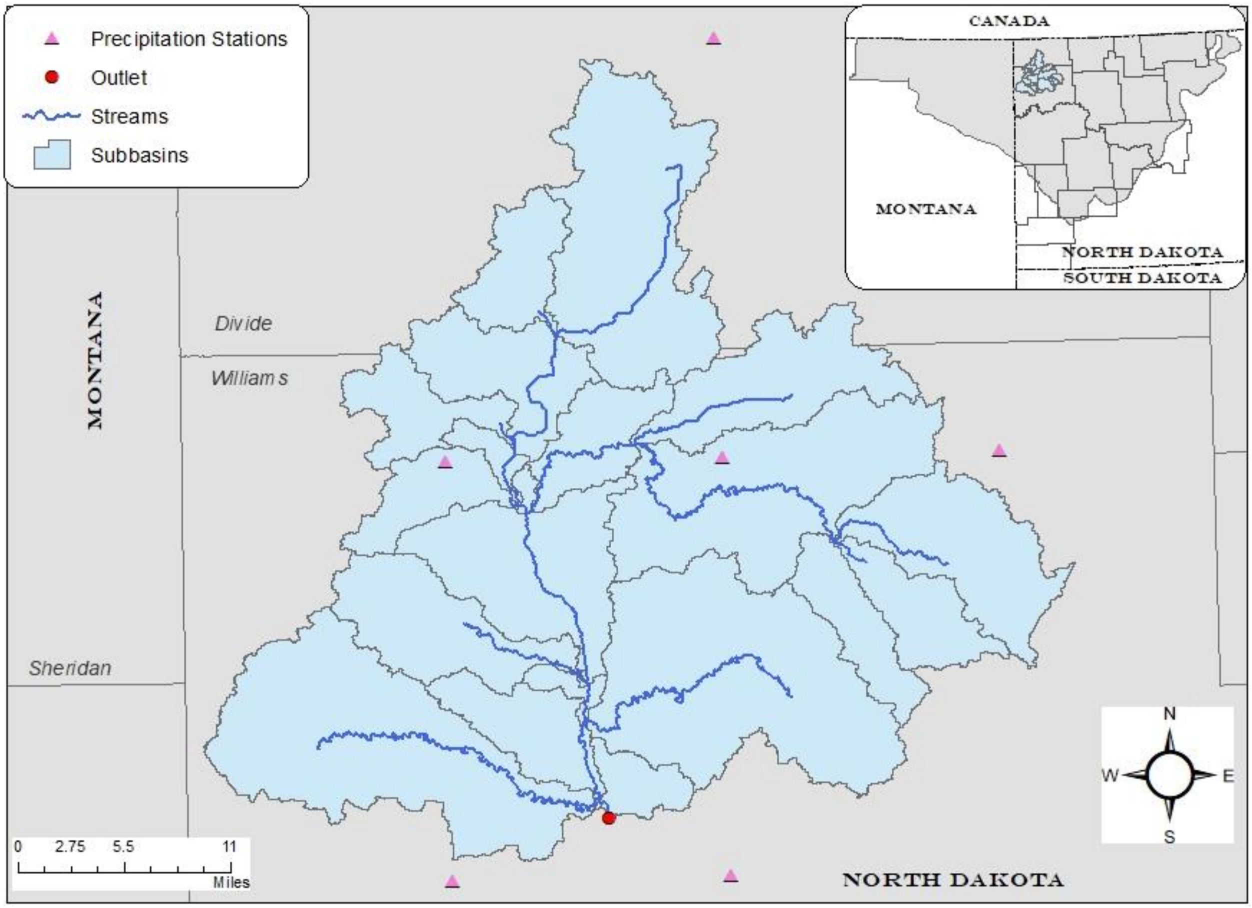

Figure 6.1. The delineation of the Little Muddy River watershed.

The simulation period of the SWAT model was selected from January 1st, 2004 to December 31st, 2014. Furthermore, the simulation period was separated into two segments for calibration from January 1st, 2004 to December 31st, 2011, and validation from January 1st, 2012 to December 31st, 2014, respectively. The daily streamflows measured at one USGS stream gage station (06331000), which is designated as the outlet of the watershed (Figure 6.1), were downloaded from the USGS National Water Information System (http://waterdata.usgs.gov/nwis) to be compared with the model-simulated streamflows during the calibration and validation processes. In the model validation periods, six-point sources were added to represent the water depots that withdrew water from the little Muddy River from the year 2012 to 2014 since industrial water permits were issued on the Little Muddy River beginning in the year 2012.

The SUFI2 (Sequential Uncertainty Fitting Procedure 2) algorithm included in the SWAT-Cup 2012 (Abbaspour, 2013) was used to calibrate the SWAT model. Three iterations were processed to make the simulated streamflows fit the observed daily stream discharge, and each iteration has 1000 model runs. After one iteration of SUFI2, some insensitive parameters were removed, and the confidence intervals obtained in this iteration were used to set the new ranges of parameter values for the remaining parameters in the next iteration of SUFI2. After the model being calibrated against the observed streamflows, the parameter values obtained in the last iteration were applied for model validation. The adjusted model parameters using SUFI2 are listed in Table 6.1.

Table 6.1. SWAT model parameters calibration.

	Parameter	File	Definition	Method	Calibrated value		
					Fitted value	Min value	Max value
1	CN2	.mgt	SCS runoff curve number	Relative	0.01	-0.03	0.09
2	ALPHA_BF	.gw	Baseflow recession constant (1/day)	Relative	-0.02	-0.06	0.10
3	GW_DELAY	.gw	Groundwater delay (day)	Replace	544.25	441.69	833.46
4	GWQMN	.gw	Threshold depth of shallow aquifer for return flow to occur (mm H2O)	Replace	1279.1	718.1	1287.9
5	ALPHA_BNK	.rte	Baseflow alpha factor for bank storage	Replace	0.31	0.20	0.53
6	CH_K1	. sub	Effective hydraulic conductivity in tributary channel alluvium (mm/h)	Replace	2.64	-71.07	93.28
7	CH_K2	.rte	Effective hydraulic conductivity in main channel alluvium (mm/h)	Replace	1.32	-5.76	10.45
8	EPCO	.hru	Plant uptake compensation factor	Replace	0.36	-0.11	0.39
9	ESCO	.hru	Soil evaporation compensation factor	Replace	0.47	0.07	0.95
10	GW_REVAP	.gw	Groundwater revap coefficient	Replace	0.28	0.19	0.35
11	RCHRG_DP	.gw	Deep aquifer percolation fraction	Replace	0.07	0.01	0.10
12	SOL_AWC(all)	.sol	Available water capacity of all layers (mm H2O/mm Soil)	Relative	0.14	0.01	0.21
13	SOL_K	.sol	Saturated hy draulic conductivity	Relative	-0.45	-0.44	0.45
14	SOL_BD	.sol	Moist bulk density	Relative	0.40	0.14	0.45
15	SURLAG	.bsn	Surface runoff lag time	Replace	7.21	4.20	15.47
16	SFTMP	.bsn	Snowfall temperature (C)	Replace	0.13	-0.44	1.49
17	SMTMP	.bsn	Snowmelt temperature (C)	Replace	2.52	0.15	4.41
18	TIMP	.bsn	Snow pack temperature lag factor	Replace	0.14	-0.02	0.46

The Nash-Sutcliffe efficiency (NSE) coefficient and the percent of bias (PBias) were used to quantify the goodness of fit for model calibration and validation. NSE ranges from $-\infty$ to 1, and if its value is closer to 1, the model has a better fit and the simulation is closer to the observed values. The percent of bias estimates the average tendency of an under-or over-prediction by a model. Negative or positive values of PBias indicate under-prediction or over-prediction by a model, respectively.

The values of NSE and PBias for model calibration were 0.77 and 7.8%, respectively. This means the SWAT model can simulate the streamflows in the Little Muddy River fairly well, but the average streamflow is overestimated slightly overall.

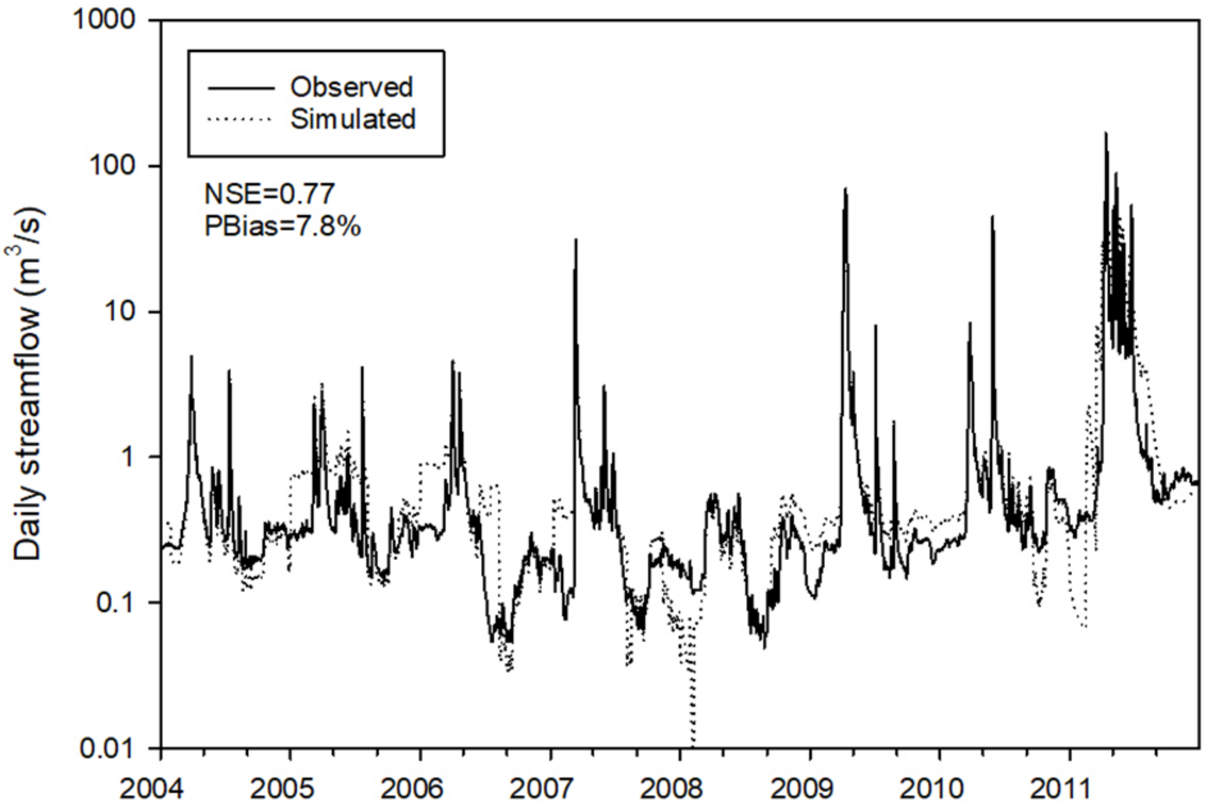

Figure 6.2. Graphical comparisons of the model simulated (dashed lines) and the observed (solid lines) daily streamflows at the little Muddy River gage station for model calibration (2004-2011). Note: NSE – Nash Sutcliffe Efficiency; PBias – percent of bias.

The result of model validation is shown in figure 6.3. The NSE and percent of bias for model validation are 0.74 and 12.7%, respectively. There are several more peaks in simulated streamflow in figure 6.3. The validation results also show that the SWAT model can simulate the streamflows in the Little Muddy River fairly well.

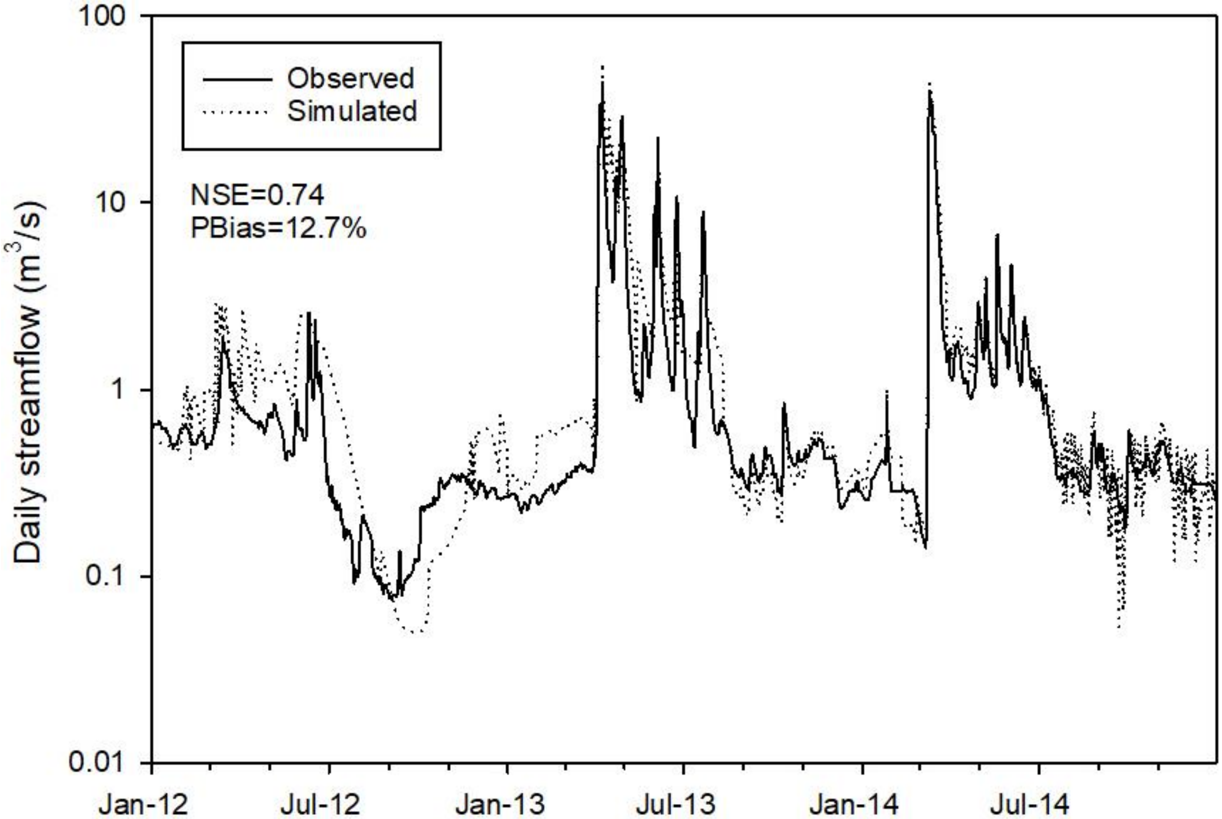

Figure 6.3. Graphical comparisons of the model simulated (dashed lines) and the observed (solid lines) daily streamflows at the little Muddy River gage station for model validation (2012-2014). Note: NSE – Nash Sutcliffe Efficiency; PBias – percent of bias.

6.2. Scenario Analysis for Streamflow Impact

6.2.1. Scenario Definition

After the SWAT model of the Little Muddy River watershed was calibrated, it was then coupled with the ABM to evaluate the impact of the Bakken oil shale development on the Little Muddy River under different future scenarios. The two models were loosely coupled. The HF water demands under different scenarios were first simulated using the ABM. Then, the HF water demands to be satisfied by the water depots withdrawing water from the Little Muddy River were simulated as negative point sources to the SWAT model for the Little Muddy River watershed. Thus, the potential impact of the HF water uses on regional surface water resources was reflected in the changes in the simulated streamflows of the Little Muddy River.

Table 6.2 lists thirteen scenarios besides the baseline scenario (i.e., Scenario 0), under which both models were calibrated. Scenarios I's are designed to evaluate the impact of the HF water demand increase. Scenarios II's are designed to evaluate the impact of regional population growth. Scenarios III's are designed to evaluate the impact of precipitation changes. It should be noted that the baseline scenario of precipitation was 22.2% higher than the regional 30-year (1980-2010) normal (Lin et al., 2018). Therefore, we should consider Scenario III-1 as 10% wetter-than-normal years, Scenario III-2 as normal precipitation years, and Scenario III-3 as approximately 20% drier-than-normal years. Scenarios IV's are designed to evaluate the impact of three different water management policies. Scenario V is a composite scenario under which there is no HF water demand while the precipitation decreases 20% to the 30-year normal level.

Table 6.2. Definitions of coupled ABM and SWAT model scenarios.

Scenario ID	Definition	Changes made to the coupled models
0	Baseline	No changes
1	Scenario I-1	HF water demand increased by 50%
2	Scenario I-2	HF water demand increased by 100%
3	Scenario I-3	HF water demand increased by 200%
4	Scenario II-1	The regional population increased by 5%
5	Scenario II-2	The regional population increased by 10%
6	Scenario II-3	The regional population increased by 20%
7	Scenario III-1	Precipitation decreased by 10%
8	Scenario III-2	Precipitation decreased by 20%
9	Scenario III-3	Precipitation decreased by 40%
10	Scenario IV-1	North Dakota legislature did not authorize the Western Area Water Supply (WAWS) project (Co-op agents are eliminated)
11	Scenario IV-2	Office of the State Engineer did not adopt the "In-Lieu-Of Irrigation" program (Irrigation transferred agents are eliminated)
12	Scenario IV-3	U. S. Army Corps of Engineers did not relax its restriction on surplus water from the Lake Sakakawea (Agents drawing water from the Missouri River and Lake Sakakawea are eliminated)
13	Scenario V	No HF water demand and precipitation decreased by 20%

6.2.2. Scenario Analysis Results

Table 6.3 lists the average annual seven-day low flows and the annual average flows of the thirteen scenarios. While the *average annual seven-day low flows* decrease from 18% to 88% in all scenarios, the *annual average flows* do not change much (from -0.02% to -4.2%) except under Scenario III's and Scenario V when precipitation decreases by 10-40% of the baseline scenario. As mentioned earlier, the baseline scenario of precipitation was 22.2% higher than the regional 30-year (1980-2010) normal. Therefore, Scenario III-2 and Scenario V are considered normal precipitation years. It is interesting to note that the average annual seven-day flow of the Little Muddy River decreased by 87% under Scenario III-2. When comparing the average annual seven-day low flows recorded at 12 USGS streamgages in 9 small-to-medium streams (including the Little Muddy River) in western North Dakota. At all 12 USGS stations, the average seven-day annual low flows during 2008-2014 were all greater than those during 2000-2007 mainly due to the fact that the region had experienced wetter than normal weather during 2008-2014 (Lin et al., 2018). Specifically, the average annual seven-day low flow in the Little Muddy River (USGS streamgage #06331000) increased 88 % (Table S13 in Lin et al., 2018). In other words, the increase of the average annual seven-day flow in the Little Muddy River during 2008-2014 would be equalized if the region had received a normal amount of precipitation according to our simulation.

To assess the impact of HF water demand on the Little Muddy River streamflow under a normal precipitation scenario, we may compare the simulation results under Scenario III-2 and Scenario V. The impact on the annual average flow was minimal. Table 6.3 shows that the annual average flow under Scenario V (without HF water demand) is only 0.3 percentage points higher than that under Scenario III-2 (with the current level of HF water demand). However, the impact on the average annual seven-day low flow was a different story. The average annual seven-day low flow when there was no HF water demand (Scenario III-2) was 14 percentage points higher than that when the HF water demand is at the current level.

Table 6.3 also indicates that precipitation and policy changes (Scenarios III's and IV's) are generally the more influential factors than the HF water demand and the regional population increase (Scenarios I's and II's) in reducing the streamflows in the Little Muddy River.

Table 6.3. The average annual seven-day low flows of different scenarios (defined in Table 6.2).

Scenarios	Average annual seven-day low flows (ft^3/s)	Annual average flows (ft^3/s)
Baseline	2.38	62.76
Scenario I-1	1.95 (-18%)	62.75 (-0.02%)
Scenario I-2	1.61 (-32%)	62.74 (-0.03%)
Scenario I-3	1.37 (-42%)	62.67 (-0.14%)
Scenario II-1	1.79 (-25%)	62.74 (-0.03%)
Scenario II-2	1.31 (-45%)	62.63 (-0.21%)
Scenario II-3	0.99 (-58%)	62.45 (-1.0%)
Scenario III-1	0.73 (-69%)	45.23 (-27.9%)
Scenario III-2	0.31 (-87%)	24.19 (-61.5%)
Scenario III-3	0.27 (-88%)	11.77 (-81.3%)
Scenario IV-1	0.61 (-74%)	62.08 (-1.1%)
Scenario IV-2	0.68 (-71%)	62.06 (-1.1%)
Scenario IV-3	0.29 (-88%)	60.14 (-4.2%)
Scenario V	0.64 (-73%)	24.37 (-61.2%)

Notes: Scenario I's: hydraulic fracturing water demand increases 50-200%; Scenarios II's: population increases 5-20%; Scenarios III's: precipitation decreases by 10-40%; Scenarios IV's: various changes of water management policies; and Scenario V: precipitation decreases 20% with no hydraulic fracturing water demand (a composite scenario).

Figures 6.4-6.8 compare the daily streamflow time series (2012-2014) in the Little Muddy River under different scenarios with that under the baseline scenario.

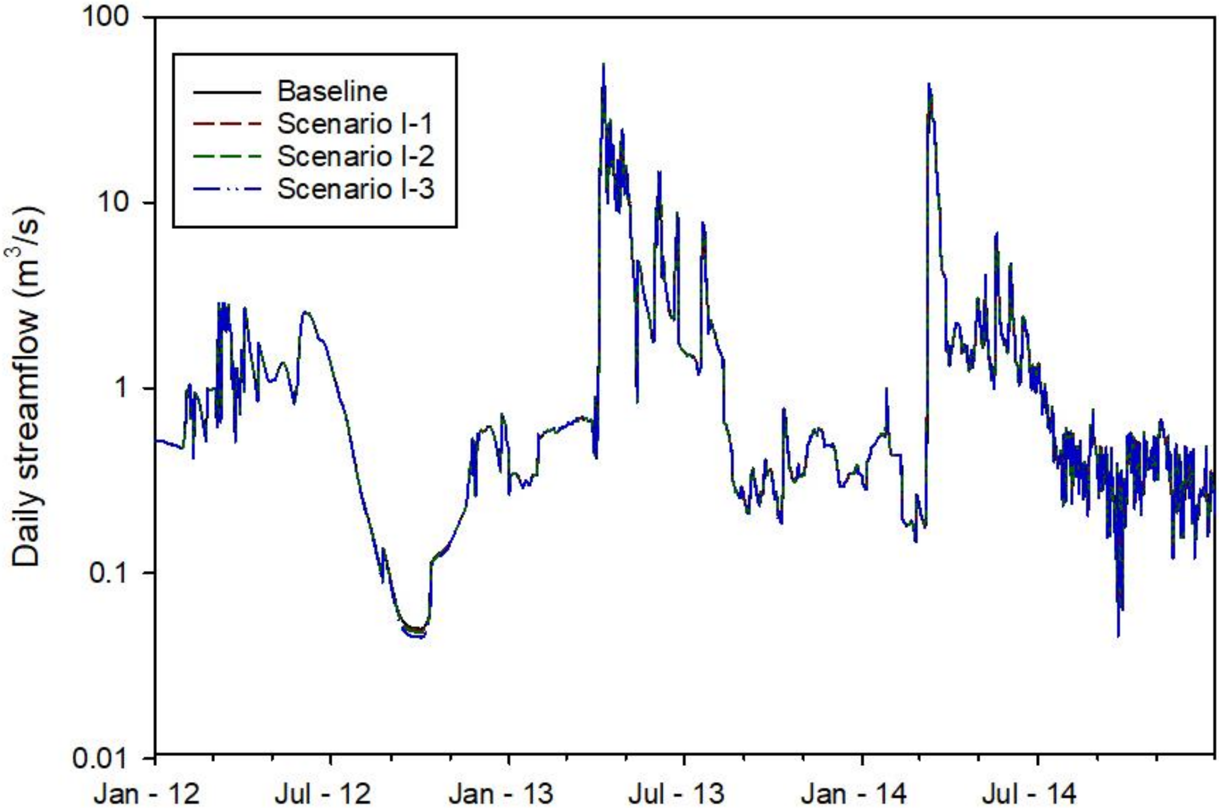

Figure 6.4. Graphical comparisons of the daily streamflows of the baseline and the hydraulic fracturing (HF) water demand scenarios (Scenario I's) at the little Muddy River gage station. Notes: Scenario I-1: HF water demand increased by 50 percent, Scenario I-2, HF water demand increased by 100 percent, Scenario I-3, HF water demand increased by 200 percent.

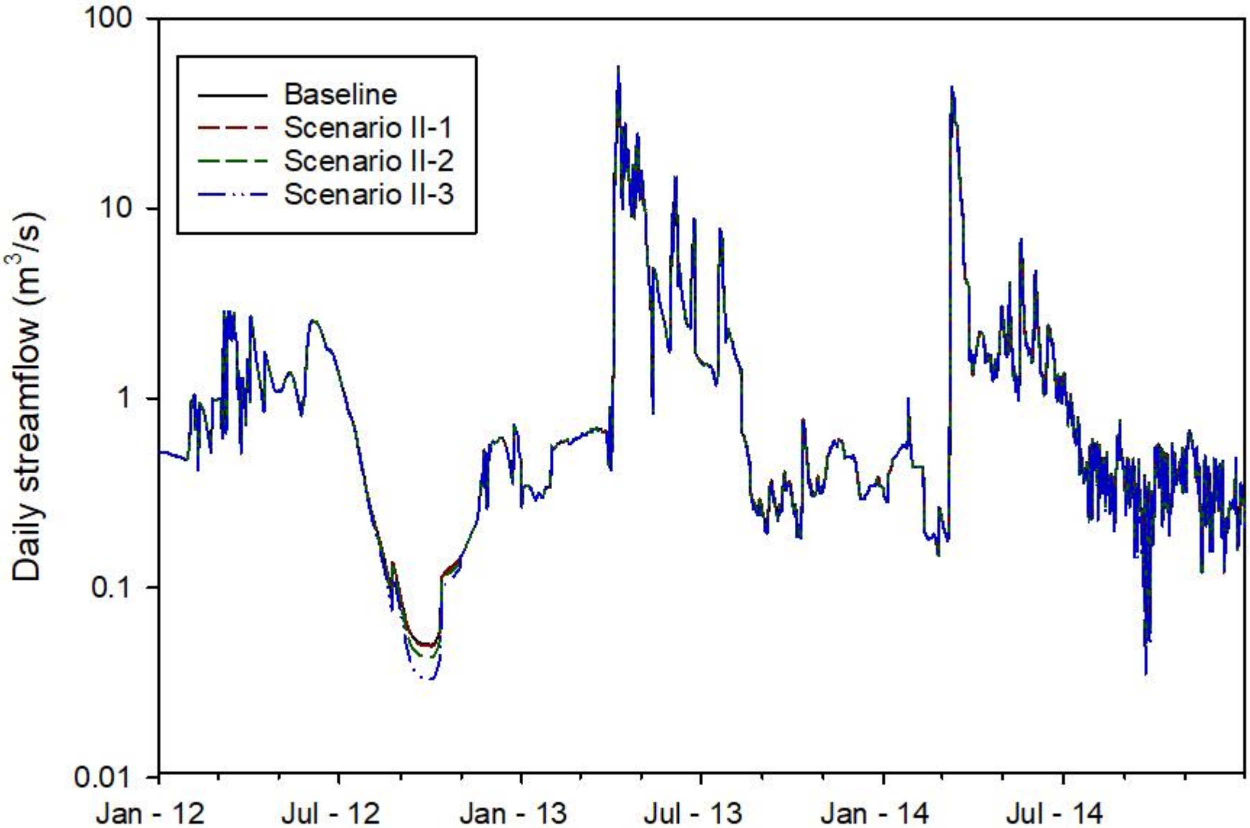

Figure 6.5. Graphical comparisons of the daily streamflows of the baseline and the regional population scenarios (Scenario II's) at the little Muddy River gage station.
Notes: Scenario II-1: the regional population increased by 5 percent, Scenario II-2, the regional population increased by 10 percent, Scenario II-3, the regional population increased by 20 percent.

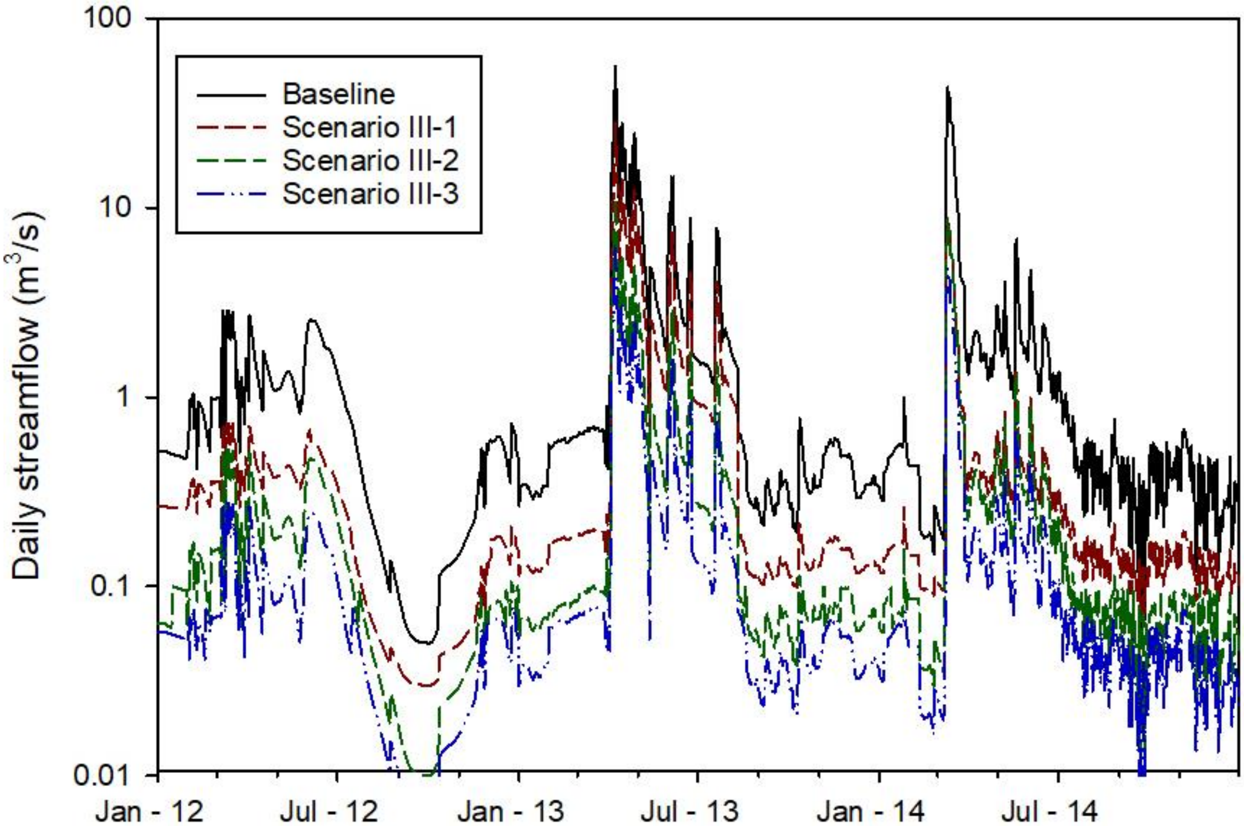

Figure 6.6. Graphical comparisons of the daily streamflows of the baseline and the precipitation scenarios (Scenario III's) at the little Muddy River gage station.
Notes: Scenario III-1: the precipitation decreased by 10 percent, Scenario III-2, the precipitation decreased by 20 percent, Scenario III-3, the precipitation decreased by 40 percent.

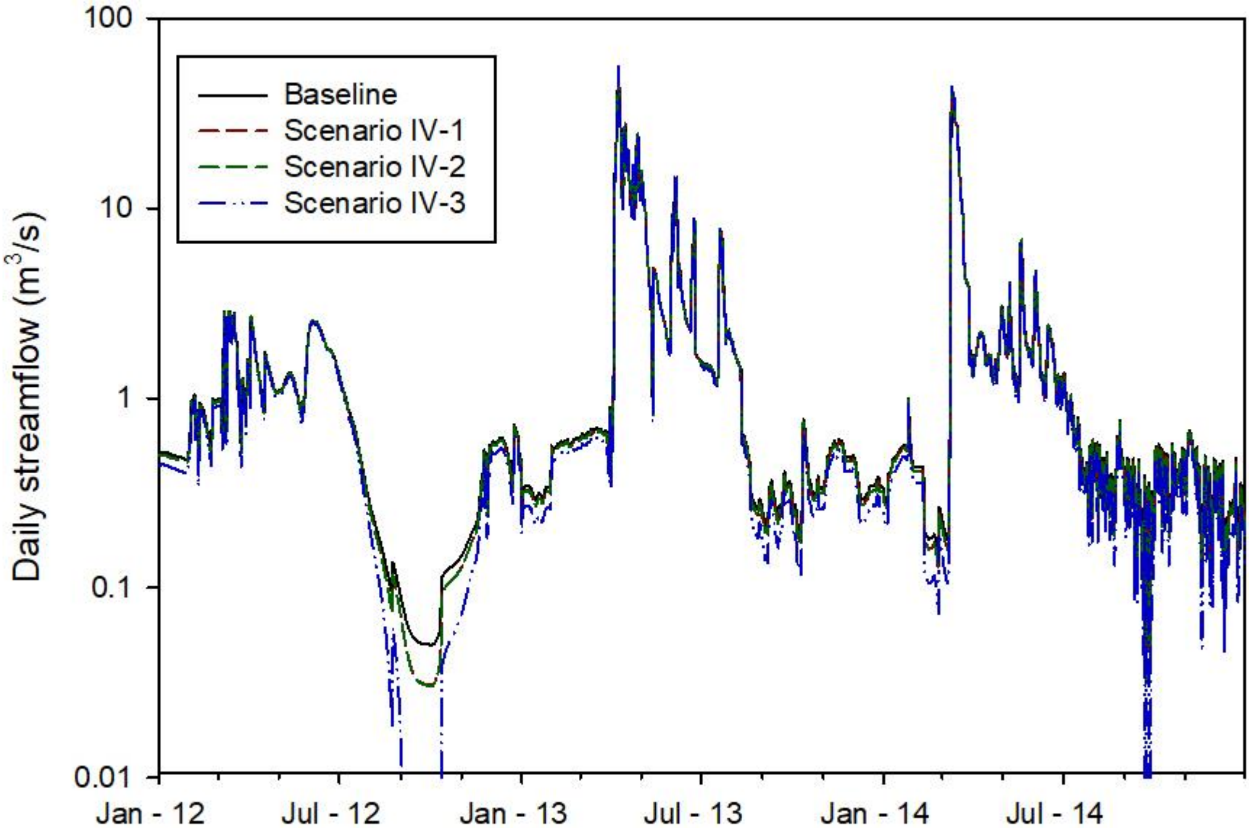

Figure 6.7. Graphical comparisons of the daily streamflows of the baseline and the water management policy scenarios (Scenario IV's) at the little Muddy River gage station.
Notes: Scenario IV-1: North Dakota legislature did not authorize the Western Area Water Supply (WAWS) project, Scenario IV-2, Office of the State Engineer did not adopt the "In-Lieu-Of Irrigation" program, Scenario IV-3, U. S. Army Corps of Engineers did not relax its restriction on surplus water from the Lake Sakakawea.

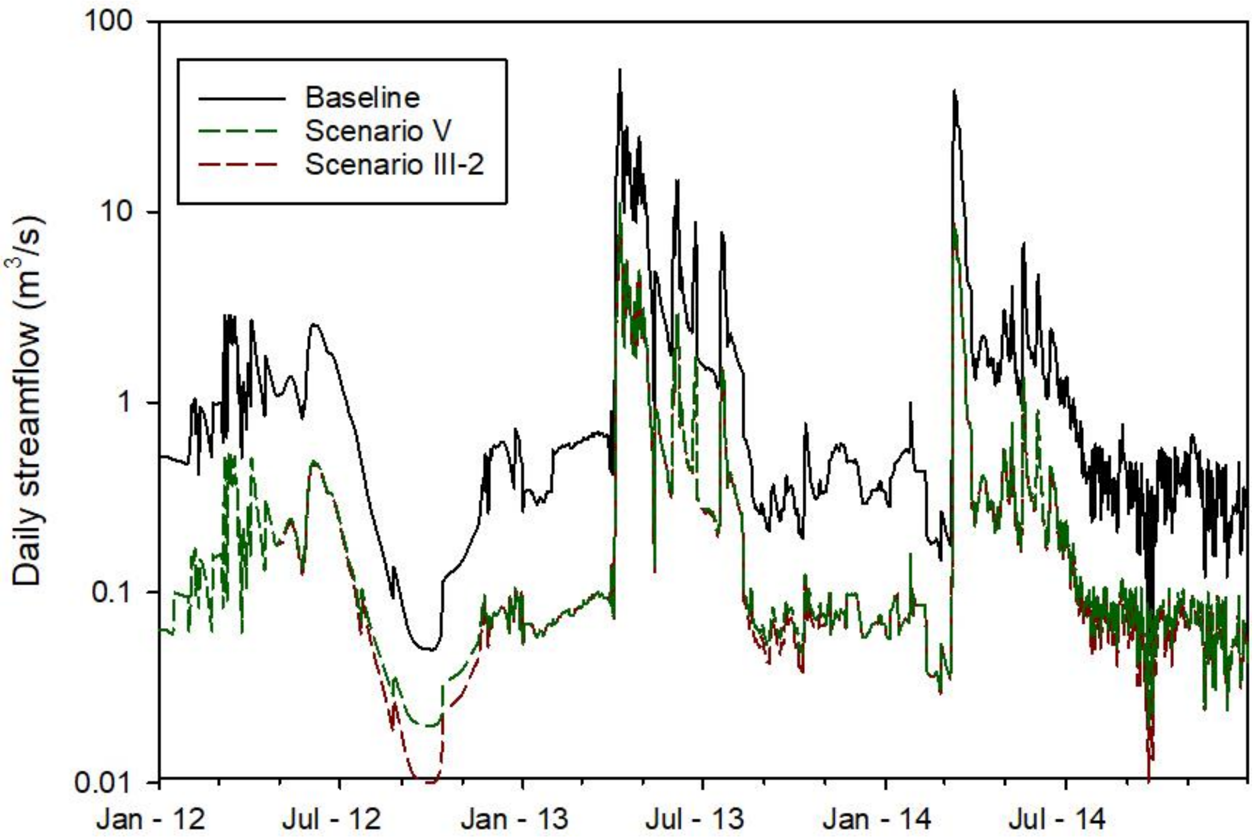

Figure 6.8. Graphical comparisons of the daily streamflows of the baseline, a composite scenario (Scenario V), and the precipitation scenario (Scenario III-2) at the little Muddy River gage station.
Notes: Scenario V, no hydraulic fracturing water demand the precipitation decreased by 20 percent, Scenario III-2, the precipitation decreased by 20 percent.

6.2.3. Scenario Analysis Conclusions

In order to understand and estimate the potential impact of the HF water use on surface water streamflows in the Bakken region of western North Dakota, a SWAT model was developed for the Little Muddy River basin and coupled with the agent-based model to simulate the streamflow changes under different scenarios. The SWAT model was calibrated from January 1st, 2004 to December 31st, 2011 when there is no HF water use. Then the model was validated from January 1st, 2012 to December 31st, 2014 with HF water use in the river. The calibration and validation results show that the SWAT model can simulate the streamflows in the Little Muddy River fairly well, regardless the HF water use was applied or not. After the calibration and validation, the SWAT model was coupled with the agent-based model to simulate the streamflow of the Little Muddy River under thirteen scenarios, including HF water demand increase, precipitation decrease, population increase, and policy changes scenarios. Comparing these thirteen scenarios with the baseline scenario, the average annual seven-day low flows decrease from 18% to 88%, while the annual average flows do not change much (from -0.02% to -4.2%) except under Scenario III's and Scenario V when precipitation decreases by 10-40% of the baseline scenario. When the precipitation decreases to the 30-year normal precipitation level, the HF water demand has a more significant impact on the average annual seven-day low flows (14% decrease) compared with the annual average flows (0.3% decrease). The scenario analysis results also indicate that precipitation and policy changes are generally the more influential factors than the HF water demand and the regional population increases in reducing the streamflows in the Little Muddy River. Our research helps to understand the impact of the increasing hydraulic fracturing water use on regional surface water sources under different conditions. This coupled SWAT and agent-based models can be used to help policy and decision-makers devise appropriate policy tools to manage regional water resources for long-term and sustainable use in the future.

6.3. Coupling Agent-based Model and Groundwater Model

The Fox Hills - Hell Creek (FH-HC) aquifer is the only groundwater source capable of producing large amounts of fresh water in the region. Historically it has provided water for many municipal, domestic, livestock, and industrial users in local areas. Many farms and ranches in rural North Dakota and Montana are dependent on flowing wells completed in the FH-HC aquifer. From 2007 to 2014, only five industrial water permits in the FH-HC aquifer used water for hydraulic fracturing, and the accumulated HF water uses were merely 962 acre-feet. The HF water use from the FH-HC aquifer is limited mainly because of the strict policy on issuing industrial water permits on the aquifer. But, as the only reliable groundwater source in the region, FH-HC can become a major water supply when fierce water competition arises.

As mentioned in Chapter 3, North Dakota State Water Commission hydrologists have developed and calibrated the MODFLOW-2005 groundwater model for the FH-HC aquifer (Fisher, 2013). This FH-HC groundwater model covers an area of approximately 35,000 square miles shown in figure 6.9 (reproduced from figure 3.8), and the area is divided into 345 rows by 303 columns, oriented north-south, with 73,241 cells of 3,650ft by 3,650ft. The grid origin is located in the north-western corner of the modeled area at easting 849,530.25ft and northing 1,247,491.55ft. Vertically, the aquifer is represented as one confined layer. The model was discretized into a steady-state stress period followed by transient yearly stress periods. The yearly transient stress periods were further divided into 15-time steps. The steady-state stress period, representing conditions in 1942, was to allow the simulated water levels to come into equilibrium with the boundary conditions. Hydrologic stresses and groundwater flow rates are assumed to have been constant or steady-state before 1942. The calibrated transient model runs from January 1, 1943, through December 31, 2009 (Fisher, 2013).

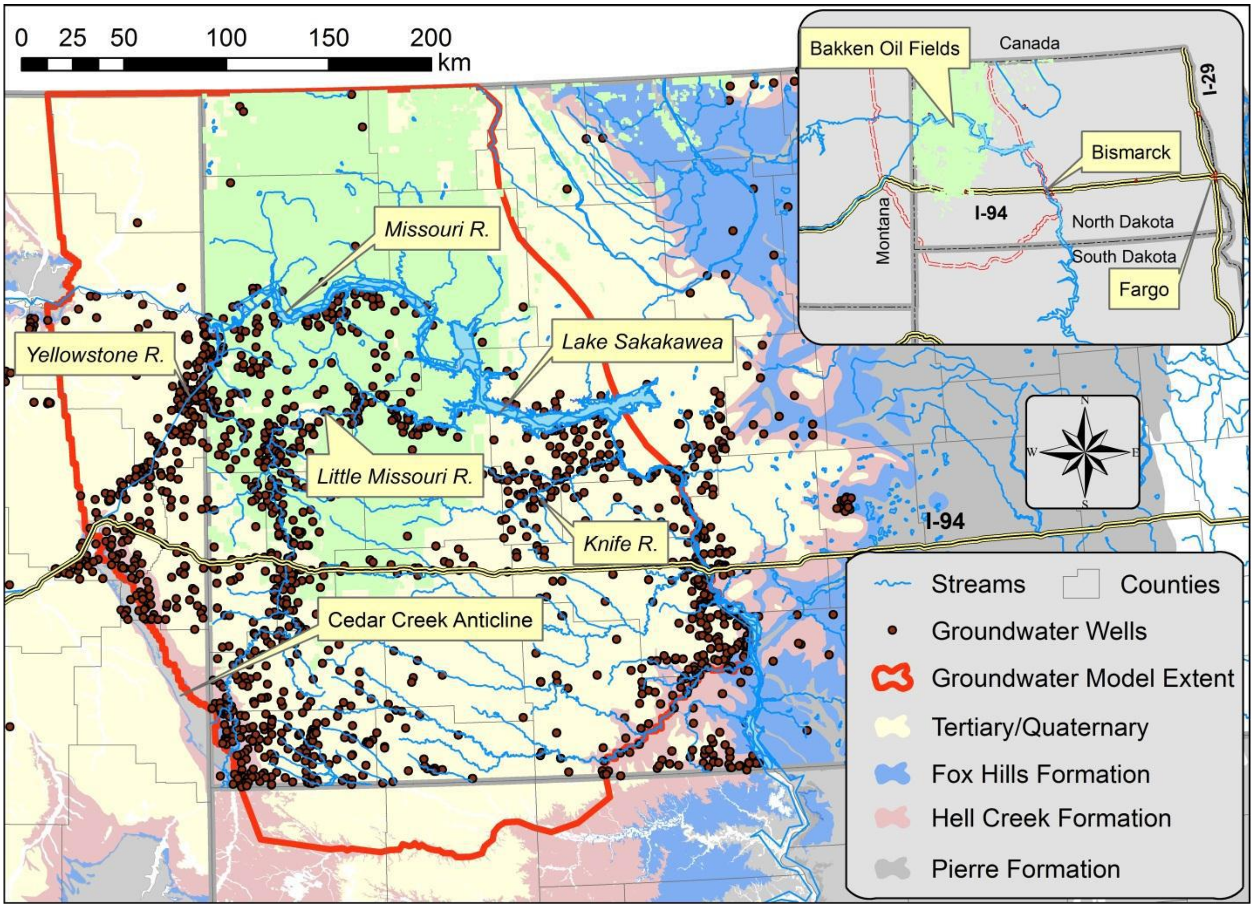

Figure 6.9. The Fox-Hills-Hell Creek aquifer in western North Dakota.
Note: Reproduced from figure 3.8.

This developed FH-HC groundwater model was loosely coupled with our calibrated agent-based model. The HF water demands under different scenarios were first simulated using the ABM. Then, the HF water demands to be satisfied by the water depots withdrawing water from the FH-HC aquifer were simulated as pumping wells to the FH-HC groundwater model. Thus, the potential impact of the HF water uses on regional groundwater resources was reflected in the changes in the simulated groundwater levels of the FH-HC aquifer.

6.4. Scenario Analysis for Groundwater Impact

6.4.1. Scenario Definition

Table 6.4 lists the fourteen scenarios including the baseline scenario (i.e., Scenario 0), under which both models were previously calibrated. Scenarios I's are designed to evaluate the impact of the HF water demand increase. Scenarios II's are designed to evaluate the impact of regional population growth. Scenarios III's are designed to evaluate the impact of precipitation changes. It should be noted that the baseline scenario of precipitation was 22.2% higher than the regional 30-year (1980-2010) normal (Lin et al., 2018). Therefore, we should consider Scenario III-1 as 10% wetter-than-normal years, Scenario III-2 as normal precipitation years, and Scenario III-3 as approximately 20% drier-than-normal years. Scenarios IV's are designed to evaluate the impact of four different water management policies.

Table 6.4. Definitions of the scenarios for running the coupled ABM and FH-HC groundwater model.

Scenario ID	Definition	Changes made to the coupled models
0	Baseline	No changes
1	Scenario I-1	HF water demand increased by 50%
2	Scenario I-2	HF water demand increased by 100%
3	Scenario I-3	HF water demand increased by 200%
4	Scenario II-1	The regional population increased by 5%
5	Scenario II-2	The regional population increased by 10%
6	Scenario II-3	The regional population increased by 20%
7	Scenario III-1	Precipitation decreased by 10%
8	Scenario III-2	Precipitation decreased by 20%
9	Scenario III-3	Precipitation decreased by 40%
10	Scenario IV-1	North Dakota legislature did not authorize the Western Area Water Supply (WAWS) project (Co-op agents are eliminated)
11	Scenario IV-2	Office of the State Engineer did not adopt the "In-Lieu-Of Irrigation" program (Irrigation transferred agents are eliminated)
12	Scenario IV-3	U. S. Army Corps of Engineers did not relax its restriction on surplus water from the Lake Sakakawea (Agents drawing water from the Missouri River and Lake Sakakawea are eliminated)
13	Scenario IV-4	Office of the State Engineer would remove its industrial water use restriction on the Fox Hill-Hell Creek aquifer

6.4.2. Scenario Analysis Results

Table 6.5 lists the minimum, maximum, and average water-level drawdowns in the Fox Hill-Hell Creek aquifer from 2007 to 2014 under the fourteen scenarios. It is not surprising that the hydraulic fracturing water demand scenarios (Scenario I's) and the population increase scenarios (Scenario II's) did not cause any changes in the groundwater drawdown because the industrial water use restriction policy on the aquifer would still be in place. It was probably due to the same reason that the groundwater level did not change much either under Scenarios III-1 and III-2 (i.e., precipitation decreasing by 10-20%) and under Scenario IV-1 (i.e., no authorization of the WAWS project) and Scenario IV-2 (i.e., no "In Lieu Of Irrigation" program).

Table 6.5. The water-level drawdowns in the Fox Hill-Hell Creek aquifer during 2007-2014 under different scenarios (defined in Table 6.4).

Scenarios	Number of grid cells	Minimum water-level drawdown (m)	Average water-level drawdown (m)	Maximum water-level drawdown (m)
Baseline	73241	0.1	2.32	3.61
Scenario I-1	73241	0.1	2.32 (0%)	3.61 (0%)
Scenario I-2	73241	0.1	2.32 (0%)	3.72 (3%)
Scenario I-3	73241	0.1	2.33 (0%)	3.72 (3%)
Scenario II-1	73241	0.1	2.32 (0%)	3.61 (0%)
Scenario II-2	73241	0.1	2.32 (0%)	3.61 (0%)
Scenario II-3	73241	0.1	2.32 (0%)	3.61 (0%)
Scenario III-1	73241	0.1	2.32 (0%)	3.72 (3%)
Scenario III-2	73241	0.1	2.40 (4%)	3.81 (5%)
Scenario III-3	73241	0.1	2.61 (13%)	4.19 (16%)
Scenario IV-1	73241	0.1	2.32 (0%)	3.68 (2%)
Scenario IV-2	73241	0.1	2.33 (0%)	3.78 (5%)
Scenario IV-3	73241	0.1	2.62 (13%)	4.30 (18%)
Scenario IV-4	73241	0.8	3.83 (65%)	6.55 (81%)

Notes: (1) Scenario I's: hydraulic fracturing water demand increases 50-200%; Scenarios II's: population increases 5-20%; Scenarios III's: precipitation decreases by 10-40%; and Scenarios IV's: various water management policy changes. (2) The percentages in the parentheses in the last two columns are the relative changes of water-level drawn compared to the baseline scenario.

Although the industrial water-use restriction policy did not change under Scenario III-3 (i.e., precipitation decreasing by 40%) and under Scenario IV-3 (i.e., no relaxation of restrictions on surplus water from Lake Sakakawea), the average water-level drawdown decreased by 13% under these two scenarios. This was because the number of agents increased (See Figure 6.10 and Table 6.6), and also the amount of water use from these agents increased by ~3 times.

However, the largest decrease (65%) of the average groundwater level in the Fox Hill-Hell Creek aquifer occurred under Scenario IV-4 when the industrial water-use restriction policy on the aquifer was removed by the ND Office of Engineer. The number of agents withdrawing water from this aquifer was increased from 5 to 27, and the amount of water use was increased from 962 acre-feet to 14,358 acre-feet between 2007 and 2014 (Table 6.6).

Figures 6.10 compare the simulated water-level changes in the Fox Hill-Hell Creek aquifer from 2007 to 2014 under the baseline scenario and the other three different scenarios under which the simulated impacts are significant. It appears that the largest water-level drawdown occurred in the western and southeastern regions, the outskirts of the core four-county area.

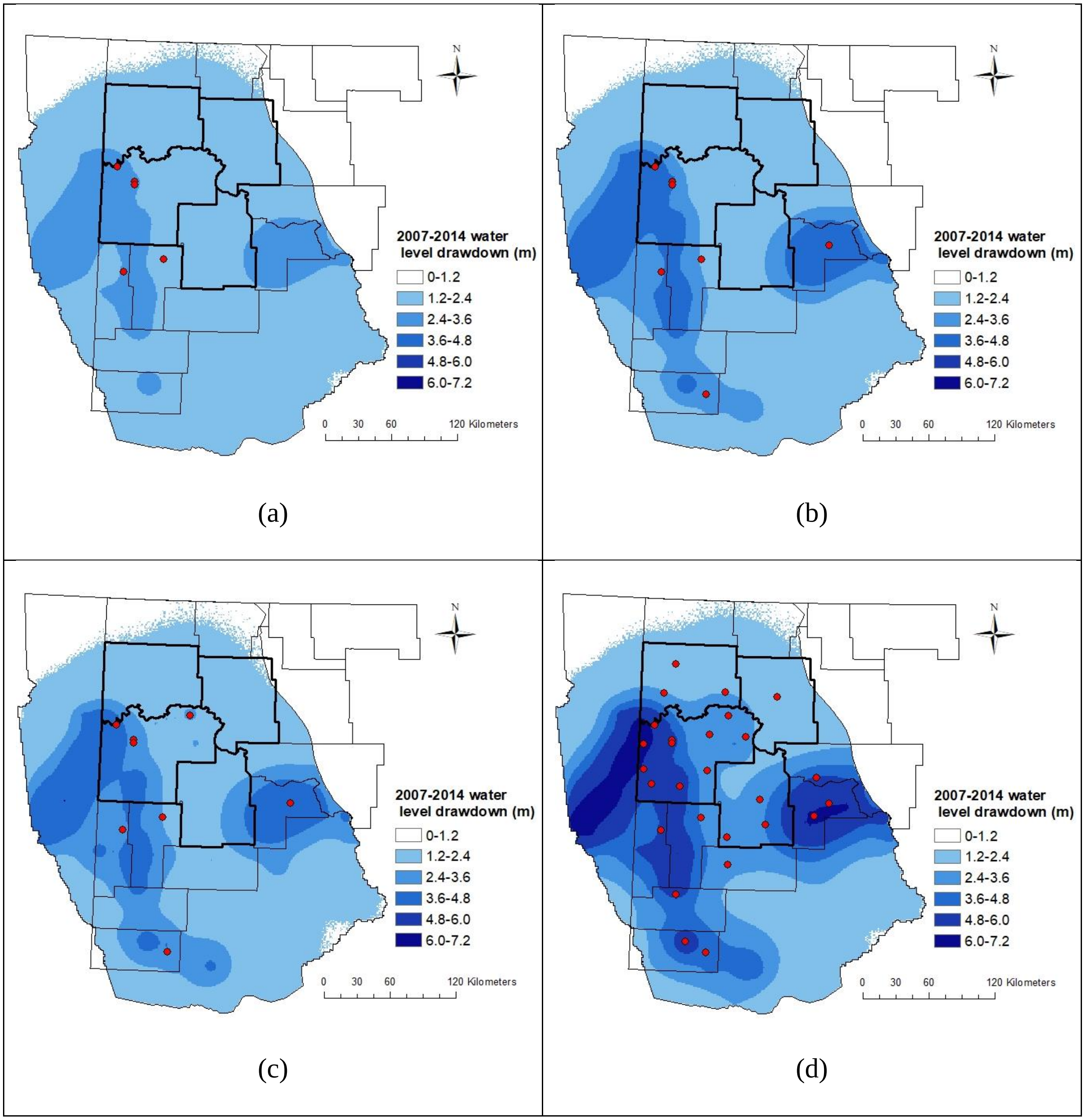

Figure 6.10. Spatial distribution of the water-level drawdown in the Fox Hill-Hell Creek aquifer during 2007-2014 under (a) Baseline Scenario, (b) Scenario III-3, (c) Scenario IV-3, and (d) Scenario IV-4.

Note: The red points are simulated water depots withdrawing water from the Fox Hill-Hell Creek aquifer.

Table 6.6. The number of agents and their water uses from the Fox Hill-Hell Creek aquifer during 2007-2014 under four scenarios.

Scenarios	Number of agents	Water uses (acre-feet)
Baseline	5	962
Scenario III-3	7	2,785
Scenario IV-3	8	2,964
Scenario IV-4	27	14,358

6.4.3. Scenario Analysis Conclusions

In order to understand and estimate the potential impact of the HF water use on groundwater level in the Bakken region of western North Dakota, a developed MODFLOW groundwater model was loosely coupled with the agent-based model to simulate the groundwater level changes under different scenarios. The coupled models were designed to simulate the groundwater level changes of the Fox Hill-Hell Creek aquifer under fourteen scenarios, including HF water demand increase, precipitation decrease, population increase, and policy change scenarios. Comparing these fourteen scenarios with the baseline scenario, the hydraulic fracturing water demand scenarios (Scenario I's), the population increase scenarios (Scenario II's), the precipitation scenarios (Scenarios III-1 and III-2), and two policy change scenarios (Scenario IV-1and Scenario IV-2) did not cause any changes in the groundwater drawdown because of the industrial water use restriction policy on the aquifer. However, when the industrial water-use restriction policy on the aquifer was removed by the ND Office of Engineer (i.e., Scenario IV-4), the largest decrease (65%) of the average groundwater level in the Fox Hill-Hell Creek aquifer occurred. The number of agents withdrawing water from this aquifer was increased from 5 to 27, and the amount of water use was increased from 962 acre-feet to 14,358 acre-feet between 2007 and 2014. These coupled groundwater and agent-based models can be used to help policy and decision-makers devise appropriate policy tools to manage regional water resources for long-term and sustainable use in the future.

7. CONCLUSIONS

An agent-based model is a useful tool to simulate the dynamic of water systems, and to predict the outcomes of policymaking in water resources planning and management. However, bounded rationality is not commonly used in the ABM development for water resources management. We explored different agent behavior theories and developd an agent-based model by combining three different agent behavior methodologies to fulfill the bounded rationality. In this agent-based model, institution theory is used to model the regulation policies from the North Dakota State Water Commission, while evolutionary programming allows water-depot agents to select appropriate strategies when applying for potential water use permits. Cognitive maps endow agents' ability and willingness to compete for more water sales. The decision-making process is constructed and parameterized with both quantitative and qualitative information, i.e., empirical water use data and knowledge gained from surveys with stakeholders. By linking institution theory, evolutionary programming, and cognitive maps, our approach addresses the high complexity of the decision-making process involved in modeling the dynamics of the coupled human-natural systems. When this agent-based model was calibrated against the real HF water use data in the Bakken area, the model did reasonably well in simulating the number and spatial locations of water depots, and depot water use.

Then we developed a SWAT model for the Little Muddy River. The SWAT model was also calibrated, and the calibration results show that it can simulate the streamflows in the Little Muddy River fairly well. The agent-based model was coupled with this SWAT model to simulate the streamflow of the Little Muddy River under thirteen scenarios, including HF water demand increase, precipitation decrease, population increase, and policy change scenarios. The scenario analysis results indicate that precipitation and policy changes are generally the more influential factors than the HF water demand and the regional population increases in reducing the streamflows in the Little Muddy River. When the precipitation decreases to the 30-year normal precipitation level, the HF water demand has a more significant impact on the average annual seven-day low flows compared with the annual average flows.

The agent-based model was then loosely coupled with a developed MODFLOW groundwater model. The coupled models were designed to simulate the groundwater level changes of the Fox Hill-Hell Creek aquifer under fourteen scenarios. The results show that the hydraulic fracturing water demand scenarios, the population increase scenarios, the precipitation scenarios, and two policy change scenarios did not cause any changes in the groundwater drawdown because of the industrial water use restriction policy on the aquifer. However, when the industrial water-use restriction policy on the aquifer was removed by the ND Office of Engineer, the largest decrease (65%) of the average groundwater level in the Fox Hill-Hell Creek aquifer occurred. The number of agents withdrawing water from this aquifer was increased from 5 to 27, and the amount of water use was increased from 962 acre-feet to 14,358 acre-feet between 2007 and 2014. The largest water-level drawdown occurred in the western and southeastern regions, the outskirts of the core four-county area.

The coupled agent-based, SWAT, and groundwater models intuitively identify the HF water impact on regional water resources. These coupled models are also very useful to help understand the impact of the increasing hydraulic fracturing water use on regional sources under different conditions. In the future, the coupled models can be used to support making scientifically sound policies in water allocation and management.

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APPENDIX A. 2015 WATER DEPOT INTERVIEW QUESTIONNAIRE

Information provided for this survey/interview will be used for research purposes only. Any company-specific information will be masked and will not be identifiable by individuals not on the research team.

Water Depot Interview/Survey

For Researchers' Use Only. Company's Name: ________________________________ Date: ____________________ Person interviewed: _____________________ ______________

Questions about water depot and water:

1. What is the average distance between your water depots to the points of diversion?
2. On average, how many oil companies do you serve? What do you think is the main reason for the oil companies to buy water from your water depots?
3. Do you sell hot or cold water or both? What percentage of the water you sell is hot water?
4. What are the challenges facing your company?

Questions about water pricing:

5. How much does it cost to build a water depot?
6. What constitutes a significant share of the start-up cost?
7. What is the approximate yearly (or monthly) cost of operation?
8. What is the largest share of your operating cost?
9. On average, what was the price per 1000 gallons of water at your water depots in the past 3 months?
10. Would you say the price of water at the Bakken changes frequently? Yes/No
11. What are the main determinants of water price?
12. If you sell both cold and hot water, how much more do you charge for hot water?

APPENDIX B. 2015 OIL COMPANY INTERVIEW QUESTIONNAIRE

Information provided for this survey/interview will be used for research purposes only. Any company-specific information will be masked and will not be identifiable by individuals not on the research team.

Oil Company/OGD Personnel Interview/Survey

For Researchers' Use Only. Company's Name: ______________________________ Date: __________________ Person interviewed: ____________________ Position: _________________________

1. How many years have you been working in the oil industry?
2. Does your company reuse/recycle flowback water and/or produced water for hydraulic fracturing?
3. If yes, what percentage of the total water used for well stimulation is reused/recycled water (including flowback, produced, and wastewater)?
4. What percentage of the oil wells requires refracking? What are the main reasons these wells require refracking?
5. For the wells that require refracking, on average how many refracking jobs do they require?
6. In your opinion, what are the main factors that affect the volume of water used for fracking (e.g., geology, type of HF fluid, pressure, number of stages, lengths of laterals, etc)?
7. How far do oil companies normally transport water from water depots to well fracking sites?

APPENDIX C. 2016 PERMANENT AND TEMPORARY WATER DEPOT INTERVIEW QUESTIONNAIRE

Information provided for this survey/interview will be used for research purposes only. Any company-specific information will be masked and will not be identifiable by individuals not on the research team.

Interview/Survey

For Researchers' Use Only.
Company's Name: _____________________________ Date: __________________
Person interviewed: ___________________ _____________

Questions for conditional and temporary permit holders (private depots)

13. What types of permits do you have?
14. If you have both conditional and temporary water permits, why do you have both, or why do you think others would have both types of permits?
15. What information do you consider before applying for a water permit? (e.g. Water Demand, Water Sources, Road Condition) Which factors are most important?
16. Do you build your water depot after talking with oil companies or potential water consumers, or do you build with an expectation of being able to sell water?
17. How do you decide if you want to apply for a conditional or temporary water permit?
18. How do you estimate the water demand nearby? Where do you get the water demand information?
19. How do you decide which water sources you want to use?
20. How do you determine the length of time you plan on using the water requested when applying for a water permit?
21. How do you decide the depot location and point of diversion location? (What are the acceptable distance between the depot and the existing road?)
22. How do you estimate the amount of water to apply for?
23. How do you estimate the water withdrawal rate?
24. How many points of diversion do you have? Why do you have different POD for the same water sources?
25. How much time do you spend planning before actually applying for a water permit?
26. Is water price an important factor in the competition for water sales with other water depots?
27. What would you estimate the capital cost to build your water depot to be? (construction, pipeline cost, pump)
28. What is the approximate operating cost for your water depot? (electricity and labor)

APPENDIX D. 2016 IRRIGATION TRANSFERRED WATER DEPOT INTERVIEW QUESTIONNAIRE

Information provided for this survey/interview will be used for research purposes only. Any company-specific information will be masked and will not be identifiable by individuals not on the research team.

Interview/Survey

For Researchers' Use Only. Company's Name: ______________________________ Date: __________________ Person interviewed: ____________________ _____________

Questions for farmers with water depots (private depots):

1. What types of permits do you have?
2. What information do you consider before applying to transfer your water permit for selling water?
3. If you consider precipitation, and what kind of forecast precipitation information will you use?
4. How do you make a decision based on forecast precipitation data?
5. Do you apply for a change in the use of water permits after talking with oil companies or potential water consumers, or do you apply with an expectation of being able to sell water?
6. How do you estimate the water demand nearby? Where do you get the water demand information?
7. How do you decide the water amount for transferring? Is water demand or surplus water a larger factor?

APPENDIX E. 2016 OIL OPERATOR INTERVIEW QUESTIONNAIRE

Information provided for this survey/interview will be used for research purposes only. Any company-specific information will be masked and will not be identifiable by individuals not on the research team.

Interview/Survey

For Researchers' Use Only. Company's Name: ______________________________ Date: ___________________ Person interviewed: ____________________ ______________

Questions for oil operators:

1. Do you know where you will obtain water for fracking before deciding on an oil well location?
2. Do you communicate with water depot owners before making decisions on where you will obtain water and regarding the amount of water you are planning to use for fracking purposes?
3. What is the main factor when deciding where to build a new oil well? (e.g., Geology, Available water sources, Available oil sources)
4. How much money do you budget for water use for each oil rig or well including transportation and other fees associated with making the water ready to use for fracking? (As a percentage, base amount, …)

APPENDIX F. 2016 NDSWC AND MUNICIPAL CO-OP WATER DEPOT INTERVIEW QUESTIONNAIRE

Information provided for this survey/interview will be used for research purposes only. Any company-specific information will be masked and will not be identifiable by individuals not on the research team.

Interview/Survey

For Researchers' Use Only. Company's Name: ______________________________ Date: ___________________ Person interviewed: ____________________ ______________

Questions for NDSWC and coops:

1. Do you have any contact information for Coops or city depots? (phone number)
2. What information is considered before applying for a water permit to sell water? (extra water, population growth, water demand)
3. Does the NDSWC have a ranking order in determining which water depot (municipal, coop, private) will get a water permit approved if multiple permits are applied for at the same time?
4. How many permits are typically approved and rejected by the NDSWC each year or what is the average approval rate?