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A Multi-Agent System of Water Allocation and Management in the Bakken Region

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Abstract: A water-depot based water allocation system has emerged in western North Dakota to distribute a large quantity of freshwater for shale oil development activities at the Bakken. This novel, multi-agent system of regional water allocation has never been previously examined. An agent-based model was developed for the system optimized at the agent-level using a penalty-based decentralized algorithm. The model was calibrated against annual water use data recorded by a state agency during 2007 to 2014, with R^2 values ranging between 0.432 to 0.998. The benefit functions also compared favorably against the estimated water sales for the water depot industry. The calibrated model was then used to evaluate the impacts of water policies and to devise effective water management strategies in the Bakken region. Our analysis shows that the authorization of the Western Area Water Supply Project, implementation of the "In-Lieu-Of Irrigation" program, and an accelerated issuance of temporary surface water permits were the most important water policies adopted by the state of North Dakota to manage the limited regional water resources during the recent oil boom. The uses of the agent-based model for water allocation and management analysis in the Bakken region will assist and inform other policymakers and water practitioners to develop pertinent water policies and management apparatus to address increased industrial water demands associated with the unconventional oil and gas development in their regions.

Keywords: *agent-based modelling; Bakken shale; CHANS; decentralized optimization; hydraulic fracturing*

1 INTRODUCTION

The Bakken shale formation in western North Dakota is one of the largest unconventional oil fields in the United States. The expansion of the oil industry in North Dakota as a result of the hydraulic fracturing and drilling technologies and favourable oil prices led to tremendous increases in the demand for water among other natural, physical, social and economic resources between 2007 and 2014. A recent USGS study (Haines et al., 2017) estimated that the mean total water required for hydraulic fracturing related activities in the Bakken would exceed 645 Mm^3. Trying to understand the complexities of the energy-water nexus with the rapid changes in western North Dakota proves to be difficult as the recent oil boom has become a "policy conundrum" facing North Dakota and the country as a whole (Craig, 2013).

A water-depot based water allocation system has emerged in the Bakken region of western North Dakota to distribute a large quantity of freshwater for shale oil development activities throughout the Bakken (Figure 1). This novel, multi-agent system of competing water depots has, to our knowledge, never been examined. A clear understanding of the system and its unique role of interfacing water management policies and physical water resources will help shed light on the dynamics of the coupled human and natural systems (CHANS) of the Bakken region where water regulation and distribution systems (which constitute the human components) and surface-water and groundwater systems (which are the natural components) interact. In this study, we will develop an agent-based model for the water-depot based water allocation system, which may be used by policy and decision makers to evaluate and devise water management policies and strategies to manage the regional water resources for sustainable use.

2 STUDY AREA AND DATA SOURCES

2.1 The Bakken Region

The term "Bakken" in this study refers to the oil shale plays in western North Dakota comprised of the Late Devonian-Mississippi Bakken Formation and the underlying Devonian Three Forks Formation (46.5ºN-49.0ºN, 99.5ºW-107.2ºW). The extent of the Bakken Formation is shown in Figure 1 and the underlying Three Forks Formation (not shown in the map) extends further south into South Dakota. Oil production in the Bakken is primarily concentrated in a 35,000 km^2 area (Scanlon et al., 2016) with more than 85% of the horizontal wells drilled in a core area of four North Dakota counties (i.e., Dunn, McKenzie, Mountrail, and Williams Counties, shown in the hatched area in Figure 1).

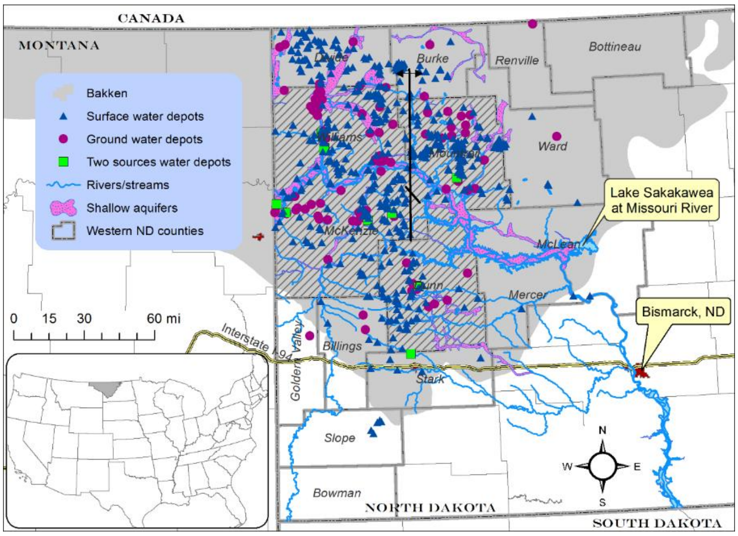


Figure 1. Water depots and water resources in the Bakken region of western North Dakota.

Since the water-permit application process takes months or years to complete, almost all oil companies obtain water for hydraulic fracturing related activities by trucking it from water depots to their oil wells in the Bakken Shale. Water depots are individual or institution owned businesses that have already acquired permanent and/or temporary water permits from the North Dakota Office of the State Engineer to withdraw freshwater from North Dakota streams/lakes and aquifers and sell it to oil companies for hydraulic fracturing and other related activities. From 2007 to 2014, the number of water depots increased from 18 to 608.

For modelling purposes, we categorized these water depots into four types as summarized in Table 1. *Permanent* water depots are owned by individuals who successfully obtained conditional or perfected water permits to sell water to the oil industry. Once a permit application is approved or partially approved by the Office of the State Engineer, it becomes a conditional permit, which may be perfected or cancelled after three years contingent upon whether the water has been put into beneficial use. Once a permit is perfected, a water right is also established. It should be noted that a perfected permit could also be cancelled if the water source is deemed insufficient or for other reasons. *Temporary* water depots are those owned by individuals who obtained temporary water permits to sell water to the oil industry. The sources of water for temporary water permits are primarily surface water, including the Missouri River and Lake Sakakawea (Lin et al., 2017). *Irrigation transferred* water depots are owned by the farmers who obtained permanent water permits for irrigation. Under the "In-Lieu-Of Irrigation" program, they may be approved by the Office of the State Engineer to transfer part of their irrigation water permits for industrial water use. *Cooperative-owned* water depots are the water depots that sell water from the newly constructed Western Area Water Supply Project or excess municipal water from several local towns to increase the city's revenue.

Table 1 also summarizes the water depots in terms of water sources where the water is drawn. A few water depots draw water from more than one type of water source and they are considered as different water-depot types. That is why the total numbers of water depots in some years (2012-2014) are not the same in Columns 6 and 11. The locations of these water depots are shown in Figure 1, along with the oil-production counties and major regional water resources in western North Dakota.

Table 1. Number of water depots in the Bakken region of western North Dakota.

Year	In terms of water depot types					In terms of water sources				
	Permanent	Temporary	Irrigation transferred	Cooperative owned	Total	LSMR	OSW	FHHC	OGW	Total
2007	16	0	0	2	18	1	1	5	11	18
2008	21	2	0	4	27	2	1	5	19	27
2009	25	1	0	6	32	2	1	5	24	32
2010	34	10	1	10	55	5	2	5	43	55
2011	45	23	14	13	95	8	8	5	74	95
2012	53	94	30	18	195	17	63	5	111	196
2013	62	152	36	18	268	25	111	4	130	270
2014	72	483	32	21	608	28	443	4	136	611

Note: FHHC – Fox Hills and Hell Creek aquifer; OGW – other (mainly shallow glaciofluvial) aquifers; LSMR – Lake Sakakawea and Missouri River; OSW – other surface waters.

2.2 Data Sources

Water depots are required to report the actual water uses to the Office of the State Engineer annually (North Dakota State Water Commission, 2016). Both the water depot shapefile and the permitted water use data were obtained from the Office of the State Engineer, which maintains a database of all reported water withdrawals in North Dakota. The water use database contains annual water uses for all water permits issued by the Office of the State Engineer, water use types, locations of the point of diversion, as well as water sources (i.e., specific river basins for surface water or specific aquifers for groundwater), etc. The water depot shapefile was then merged with the water use data through the unique water permit numbers to estimate annual water volumes sold by all water depots. The recorded water use and permit data during 2007-2014 was used in the development of the agent-based model for the water depot-based water allocation system in the Bakken region of western North Dakota.

3 MODEL DEVELOPMENT

3.1 Agent Definition and Formulation

The water-depot based water allocation system in the Bakken region of western North Dakota can be naturally seen as a multi-agent system with individual water depots treated as agents. We divided these individual water depots into nine groups from which we define nine agents in our model, each representing one group of water depots. Each water depot group is defined as all water depots that have the same type of water permit or ownership and draw water from the same type of water source (see Table 1). As shown in Table 2, each water depot group's name is composed of two parts – the first part describing the group's water permit or ownership type and the second part describing its water source.

We assume that each water-depot agent maximizes its benefit of water use following Equations (1) and (2).

$$\max_{x_{it}} f_i(x_{it}), \tag{1}$$

$$\text{Subject to} \begin{cases} l_i(x_{it}) \leq 0, \\ g_i\left(x_{it} | \{x_{jt}\}_i\right) \leq 0, \end{cases} \tag{2}$$

where x_{it} is the decision variable, i.e., the water use of agent *i* in year *t; f_i* is the benefit function or water sale of agent *i*; $l_i(x_{it})$ is the local constraint for agent *i*, and $g_i\left(x_{it}|\{x_{jt}\}_i\right)$ is the interconnecting constraint for agent *i*, meaning that agent *i* receives the value of $\{x_{jt}\}_i$ from agent *j* and needs to accept that value. The interconnecting constraint allows the decision of agent *i*, x_{it}, to be affected by the decision of its neighboring agent *j*, x_{jt}. In this study, the local constraint (or permit constraint) for an agent is specified as the total water permits issued to that agent (i.e., a group of water depots), while the interconnecting constraint (or source constraint) is specified as the total water permits associated with one particular water source, from which multiple agents may draw water. The benefit function, f_i, usually takes the form of a quadratic concave function as defined by Equation (3) when little information is available (Yang et al., 2009).

$$f_i(x_{it}) = -\, a_i x_{it}{}^2 + b_i n_{it} x_{it} - c_i n_{it}, \tag{3}$$

where x_{it} is the water use of agent *i* in year *t* as defined above; n_{it} is the number of water depots that agent *i* represents in year *t*; a_i, b_i and c_i are constants; b_i and c_i are multiplied by n_{it} to ensure that the water use and water sale (i.e. benefit) for agent *i* in year *t* is equal to zero when the number of water depots represented by agent *i* in year *t* is zero; c_i can be approximately interpreted as the average annual fixed costs associated with the water depots represented by agent *i*. The specific formulations for the nine agents are summarized in Table 2.

Table 2. Definitions and formulations of the nine water-depot agents.

Agent	Water-depot group	Definition	Formulation
1	Permanent – FHHC	Privately owned water depots (WD) with permanent (i.e., conditional or perfected) industrial permits to withdraw water from the Fox Hills and Hell Creek aquifer.	$\max_{x_{1t}} f_1(x_{1t}) = -a_1 x_{1t}{}^2 + b_1 n_{1t} x_{1t} - c_1 n_{1t}$ subject to $\begin{cases} x_{1t} - WP_{1t} \le 0 \\ x_{1t} - FHHC_t \le 0 \end{cases}$
2	Permanent – OGW	Privately owned WDs with permanent industrial permits to withdraw water from shallow glaciofluvial groundwater (GW) aquifers.	$\max_{x_{2t}} f_2(x_{2t}) = -a_2 x_{2t}{}^2 + b_2 n_{2t} x_{2t} - c_2 n_{2t}$ subject to $\begin{cases} x_{2t} - WP_{2t} \le 0 \\ x_{2t} + x_{6t} + x_{7t} - OGW_t \le 0 \end{cases}$
3	Permanent – LSMR	Privately owned WDs with permanent industrial permits to withdraw water from Lake Sakakawea (LS) and/or the Missouri River (MR).	$\max_{x_{3t}} f_3(x_{3t}) = -a_3 x_{3t}{}^2 + b_3 n_{3t} x_{3t} - c_3 n_{3t}$ subject to $\begin{cases} x_{3t} - WP_{3t} \le 0 \\ x_{3t} + x_{5t} + x_{8t} - LSMR_t \le 0 \end{cases}$
4	Permanent – OSW	Privately owned WDs with permanent industrial permits to withdraw water from surface water sources other than LS and/or MR.	$\max_{x_{4t}} f_4(x_{4t}) = -a_4 x_{4t}{}^2 + b_4 n_{4t} x_{4t} - c_4 n_{4t}$ subject to $\begin{cases} x_{4t} - WP_{4t} \le 0 \\ x_{4t} + x_{9t} - OSW_t \le 0 \end{cases}$
5	Cooperative – LSMR	Cooperative-owned WDs with permanent industrial permits to withdraw water from LS and/or MR.	$\max_{x_{5t}} f_5(x_{5t}) = -a_5 x_{5t}{}^2 + b_5 n_{5t} x_{5t} - c_5 n_{5t}$ subject to $\begin{cases} x_{5t} - WP_{5t} \le 0 \\ x_{3t} + x_{5t} + x_{8t} - LSMR_t \le 0 \end{cases}$
6	City – OGW	City-owned WDs with temporary permits to transfer excess municipal permits for industrial water uses that withdraw water from shallow glaciofluvial GW aquifers.	$\max_{x_{6t}} f_6(x_{6t}) = -\, a_6 x_{6t}{}^2 + b_6 n_{6t} x_{6t} - c_6 n_{6t}$ subject to $\begin{cases} x_{6t} - WP_{6t} \le 0 \\ x_{2t} + x_{6t} + x_{7t} - OGW_t \le 0 \end{cases}$
7	Irrigation – OGW	Privately owned WDs with temporary permits to transfer irrigation permits for industrial water uses that withdraw water from shallow glaciofluvial GW aquifers.	$\max_{x_{7t}} f_7(x_{7t}) = -a_7 x_{7t}{}^2 + b_7 n_{7t} x_{7t} - c_7 n_{7t}$ subject to $\begin{cases} x_{7t} - WP_{7t} \le 0 \\ x_{2t} + x_{6t} + x_{7t} - OGW_t \le 0 \end{cases}$
8	Temporary – LSMR	Privately owned WDs with temporary industrial permits to withdraw water from LS and/or MR.	$\max_{x_{8t}} f_8(x_{8t}) = -\, a_8 x_{8t}{}^2 + b_8 n_{8t} x_{8t} - c_8 n_{8t}$ subject to $\begin{cases} x_{8t} - WP_{8t} \le 0 \\ x_{3t} + x_{5t} + x_{8t} - LSMR_t \le 0 \end{cases}$
9	Temporary – OSW	Privately owned WDs with temporary industrial permits to withdraw water from surface water sources other than LS or MR.	$\max_{x_{9t}} f_9(x_{9t}) = -\, a_9 x_{9t}{}^2 + b_9 n_{9t} x_{9t} - c_9 n_{9t}$ subject to $\begin{cases} x_{9t} - WP_{9t} \le 0 \\ x_{4t} + x_{9t} - OSW_t \le 0 \end{cases}$

Notations: x_{it} – water use of agent *i* in year *t*. n_{it} – number of water depots represented by agent *i* in year *t*. $f_i(x) = -a_i x^2 + b_i n_{it} x - c_i n_{it}$ – benefit function of agent *i* by selling *x* amount of water, where a_i, b_i, and c_i are constants. WP_{it} – water permits issued to agent *i* in year *t*. $FHHC_t$ – total water permits issued to all agents in year *t*, which draw water from the Fox Hills and Hell Creek (FHHC) aquifer. $LSMR_t$ – total water permits issued to all agents in year *t*, which draw water from the Lake Sakakawea and Missouri River (LSMR). OGW_t – total water permits issued to all agents in year *t*, which draw water from other groundwater (OGW) sources. OSW_t – total water permits issued to all agents in year *t*, which draw water from other surface water (OSW) sources.

3.2 Model Calibration

A penalty-based decentralized optimization algorithm (İnalhan et al., 2002), which has been modified by Yang et al. (2009), is applied to solve the problem described in the previous section. The method first tries to find a solution (i.e., annual water use) based on the choices of all individual agents, allowing the violation of some constraints defined in the optimization models for individual agents (Table 2), and then reduces the constraint violation at the system level. The agent-based model was then calibrated against historic annual water use data and the estimated industry water sales during 2007-2014 to adjust the parameter values for a_i's, b_i's, c_i's. First, c_i's were set to be average annual fixed costs associated with the water depots represented by agent i, estimated based on our interviews with the water depot owners in the region. Secondly, the ratios of a_i's and b_i's were adjusted by calibrating the model-simulated water uses against the recorded historical water uses, while the absolute values of a_i's, b_i's, and c_i's were further adjusted by calibrating the model-simulated benefit function values against the estimated ranges of water sales.

3.3 Scenario Analysis

Once calibrated, the agent-based model can be employed to evaluate the importance of the water policies newly adopted to meet the unprecedented water demand from the Bakken oil shale development while safeguarding water resources in the region. Table 3 lists six scenarios including the baseline scenario (i.e., Scenario 0) under which the model was calibrated. Scenarios 1-5 are designed to evaluate the five pieces of water policies. Under each of these scenarios, a particular water-depot agent is eliminated from the model or its water permit is reduced. The water depots represented by agents 5-9 basically originated from the specific water policies adopted to manage the limited water resources in the western part of the state. Therefore, eliminating these agents from the model allows us to examine the potential impacts on hydraulic fracturing water use and water permit violations in the absence of the water policies.

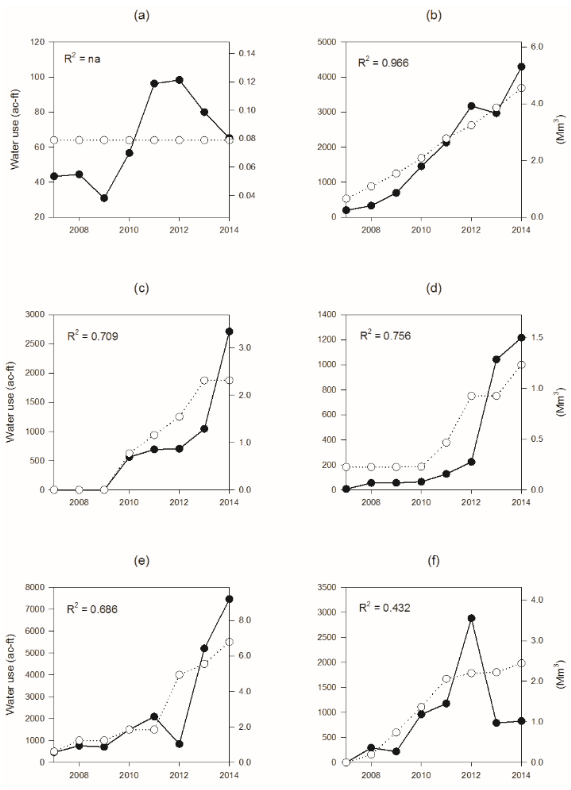
Table 3. Definitions of water management scenarios.

Scenario	Definition	Changes made to the agent-based model
0	Baseline	No changes
1	North Dakota legislature did not authorize the Western Area Water Supply (WAWS) project	The water permit and the number of water depots for agent 5 are reduced to the pre-WAWS level
2	Office of the State Engineer (OSE) did not allow excess municipal water use transferred to industrial use	Agent 6 is eliminated
3	OSE did not adopt the "In-Lieu-Of Irrigation" program	Agent 7 is eliminated
4	U. S. Army Corps of Engineers did not relax its restriction on surplus water from Lake Sakakawea	Agent 8 is eliminated
5	OSE did not issue temporary surface water permits	Agent 9 is eliminated

4 RESULTS AND DISCUSSION

4.1 Model Calibration

Figure 2 compares the water depot water uses recorded by the Office of the State Engineer and those simulated by the calibrated agent-based model during 2007-2014. The model was able to simulate the overall upward trends of water uses by all agents except for agent 1 (Permanent – FHHC, Fig. 2a) and agent 6 (City – OGW, Fig. 2f) which had decreasing water uses after 2012. The model did exceptionally well in simulating the water uses by agent 2 (Permanent – OGW, Fig. 2b), agent 7 (Irrigation – OGW, Fig. 2g), and agent 9 (Temporary – OSW, Fig. 2i), as well as the total water uses by all agents (Fig. 2j), with R^2 greater than 0.96. The model performed reasonably well for agent 3 (Permanent – LSMR, Fig. 2c), agent 4 (Permanent – OGW, Fig. 2d), agent 5 (Cooperative – LSMR, Fig. 2e), and agent 8 (Temporary – LSMR, Fig. 2h), with R^2 ranging between 0.69 and 0.80.



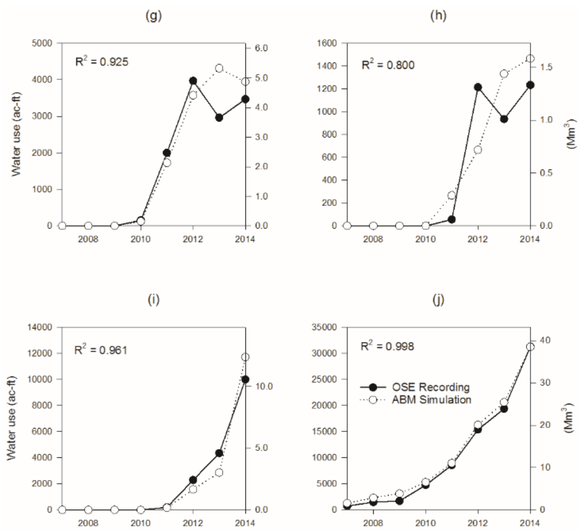
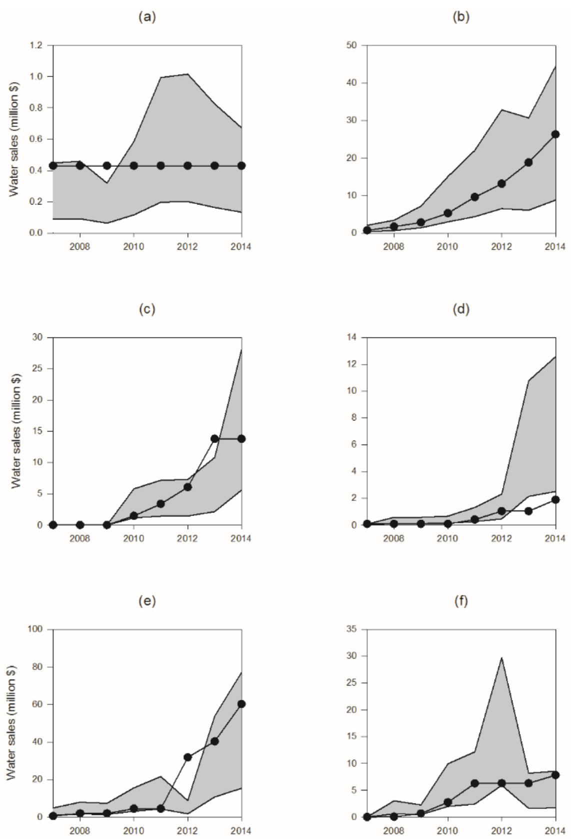


Figure 2. Comparison of the water uses recorded by the OSE (Office of the State Engineer) and those simulated by the ABM (agent-based model) for (a) agent 1, (b) agent 2, (c) agent 3, (d) agent 4, (e) agent 5, (f) agent 6, (g) agent 7, (h) agent 8, (i) agent 9, and (j) all agents in the Bakken region of western North Dakota.



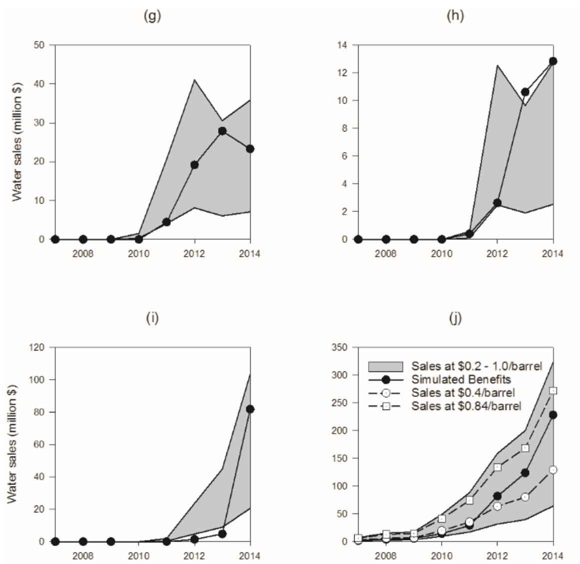


Figure 3. Comparisons of the estimated water sales and the model-simulated benefits for (a) agent 1, (b) agent 2, (c) agent 3, (d) agent 4, (e) agent 5, (f) agent 6, (g) agent 7, (h) agent 8, (i) agent 9, and (j) all agents in the Bakken region of western North Dakota.

We further compared the estimated water sales (in millions of dollars) and the model-simulated benefit function values for all water-depot agents. As shown in Figure 3a-3i, the simulated benefit function values for individual agents were generally within the respective ranges of the estimated water sales.

Fig. 3j shows that the *total* benefits of all agents simulated by the model were within a narrower range of water sales estimated using the prevailing water prices ($0.4-0.84/barrel). It is also shown that the annual industrial water sales in western North Dakota increased from less than $2 million in 2007 to more than $228 million in 2014 by more than 130 times in just eight years.

4.2 Water Use Comparison

Figure 4 compares the recorded and the simulated total water uses during 2007-2014 in terms of water depot type (or agent, Fig. 4a), permit or ownership type (Fig. 4b), and water source (Fig. 4c). In general, the model slightly over-predicted the total water uses for almost all categories, except for agent 9 (Temporary – OSW), whose water use was under-predicted by the model. The model also slightly under-predicted the water uses for agent 1 (Permanent - FHHC) and from the FHHC water source, albeit not visible in the figure (Fig. 4a & 4c). In most cases, the differences between the recorded and the simulated water uses were less than 10%, except for agent 3 (Permanent – LSMR, 14.8%), agent 4 (Permanent – OSW, 29.3%), and agent 6 (City – OGW, 27.3%).

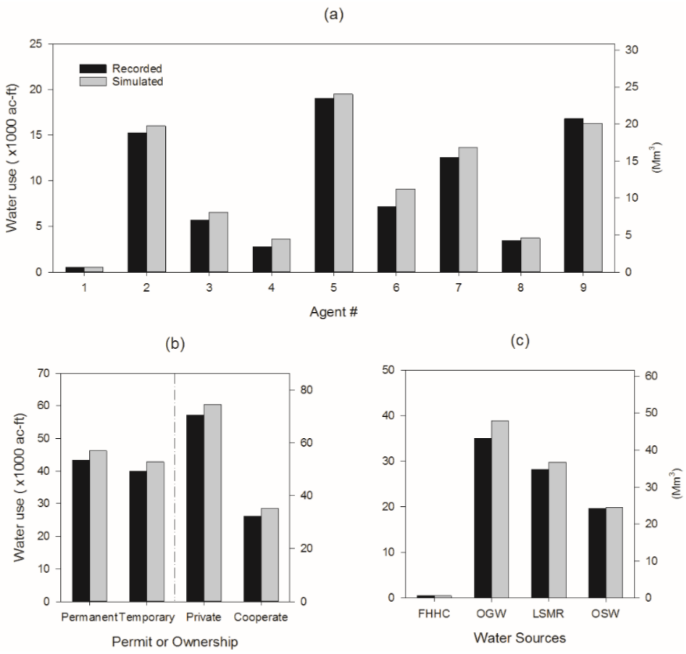


Figure 4. Comparison of the recorded and the simulated water depot water uses in terms of (a) agent, (b) permit or ownership type, and (c) water source. Notes: FHHC – Fox Hills and Hell Creek aquifer; OGW – other groundwater systems, LSMR – Lake Sakakawea and Missouri River, OSW – other surface waters, and Mm^3 – million cubic meters.

A close inspection of Figure 4 also renders a few noteworthy observations. First, the four largest contributors, agent 2 (Permanent – OGW), agent 5 (Cooperative – LSMR), agent 7 (Irrigation – OGW), and agent 9 (Temporary – OSW), accounted for 76.5% of total water depot water use. Second, the permanent and the temporary water depots contributed almost equally to the total water depot water use (Fig. 4b). However, in terms of ownership, the privately owned water depots sold twice as much water as the cooperative-owned water depots did (Fig. 4b). Third, in terms of water source, the shallow glaciofluvial aquifers (i.e., OGW) contributed the largest quantity of water depot water use, followed by Lake Sakakawea and the Missouri River (i.e., LSMR) and other surface waters (i.e., OSW); while the contribution from the Fox Hills and Hell Creek aquifer (i.e., FHHC) was negligible (Fig. 4c).

4.3 Water Policy Evaluation

Scenarios 1-5 are designed to evaluate how elimination of water-depot agents from the agent-based model or the absence of the associated water policies in the field would have affected water depot water uses. The effects of the absence of certain water policies on water depot water uses at the Bakken are illustrated in Figure 5. Except for Scenario 0, each scenario signifies the failure of adopting one specific water policy. Please refer to Table 3 for details on each of the five scenarios. Water shortage is defined as the model-simulated total water uses subtracting those sold by the water depots represented by the nine agents during the recent oil boom at the Bakken. A positive value for water shortage means that the model-simulated water volume is smaller than that actually needed for hydraulic fracturing at the Bakken. We assume there was no water shortage under the baseline scenario or Scenario 0, which has no water-depot agents removed from the model.

Figure 5 shows that Scenarios 1, 3 and 5 would have caused the most water shortage for hydraulic fracturing at the Bakken. These three scenarios respectively correspond to no authorization of the

Western Area Water Supply Project (i.e., water permit reduction for agent 5), no implementation of the "In-Lieu-Of Irrigation" program (i.e., elimination of agent 7), and no accelerated issuance of temporary surface water permits (i.e., elimination of agent 9).

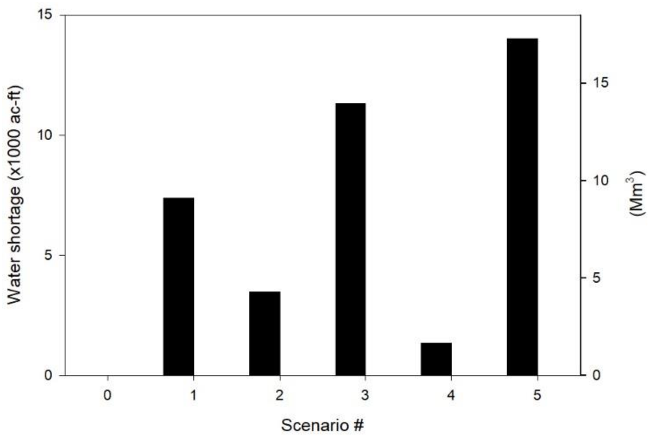


Figure 5. Effects of water policies on hydraulic fracturing water shortage.

Figure 5 also shows that Scenarios 2 and 4 would have caused relatively less water shortage. These two scenarios correspond to no use transfer from excess municipal water permits (i.e., elimination of agent 6) and no temporary relaxation of Lake Sakakawea surplus water restrictions from the United States Army Corps of Engineers (i.e., elimination of agent 8).

5 CONCLUSIONS

A water-depot based water allocation system has emerged in western North Dakota to distribute a large quantity of freshwater for shale oil development activities at the Bakken. We developed an agent-based model for the system, by categorizing more than 600 water depots into 9 agents in terms of types of water permit, ownership and water sources. The model was calibrated against annual water use data recorded by state agency during 2007-2014, with R^2 values ranging between 0.432 to 0.998 for individual or all agents. The benefit functions for individual or all agents also compared favorably against the estimated water sales for the water depot industry in western North Dakota. This agent-based model can be used by policymakers and water management practitioners to evaluate the impacts of water policies and to devise water management strategies in the Bakken shale and other regions in the world facing increased industrial water demands associated with unconventional oil and gas development.

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