Shale Oil Production Expansion and Water-Energy Nexus in North Dakota: A Decentralized Agent-Based Modeling Approach

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Abstract

The expansion of oil industry in the region has led to tremendous increases in the demand for water in western North Dakota where quality water is most scarce. Thus, striking a delicate balance between preserving water resources and expanding oil production at the Bakken is a challenging task. Using a decentralized agent-based model, we posit water depots as "agents" and examine the emergent behavior of water depots under three potential policy scenarios, and these scenarios are then compared to the baseline results to gauge the impacts on water consumption in the North Dakota oil patch. Our results show that restricting industrial use of the Missouri River and Lake Sakakawea waters would reduce a sizable amount of water consumption at the Bakken, but system violations would be prevalent and rendering null the restriction.

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Introduction

Onshore shale oil and gas development has indisputably increased the nation's energy production, but its impact on the natural environment, especially on local water resources, remains poorly understood due to the lack of research and data collection for this new subject area. The Bakken shale formation in western North Dakota is one of the largest unconventional oil fields in the U.S. The expansion of oil industry in the region has led to tremendous increases in the demand for water among other natural, physical, social and economic resources. Demand for water in the western portion of the state where hydraulic fracturing is occurring is where quality water is most scarce. Hence, the water-energy nexus becomes a "policy conundrum" facing North Dakota and the country as a whole (Craig, 2013).

A water depot–based water allocation system has recently emerged to distribute a large quantity of freshwater for hydraulic fracturing at the Bakken Shale. This system has never been examined. A clear understanding of the dynamics of the water depot-based water allocation system and its interactions with regional water resources will help policy and decision makers manage the regional groundwater resources for sustainable use.

This is a pilot study of the water-energy nexus at the Bakken Shale of western North Dakota, using mathematical modeling to gain a better understanding of the complex interactions between the region's human and natural systems that are leading to unprecedented economic development and use of water resources.

The Case of North Dakota

Water in North Dakota is enshrined as a public resource by the 1889 State Constitution and water law in North Dakota follows the doctrine of prior appropriation (Saxowsky, 2015). Any citizens with physical access to an aquifer or surface water in the state can apply to the Office of State Engineer (OSE) for a water permit to put the water into purposed and beneficial uses (Schuh, 2010). First, water permits are granted for the beneficial use of water on the basis of priority date, established by the date of application. Second, competing water permit applications, namely, those filed within 90 days of each other, are given preference by the order of use priority: domestic, municipal, livestock, irrigation, industrial, and recreation, if the water source is insufficient to supply all applicants. Recognizing that the application process takes months to years to complete and that industrial uses rank low (second to last) in the order of use priority, energy companies obtain hydraulic fracturing operation-related water by trucking it from water depots to their oil and natural gas wells in western North Dakota (Kusnetz, 2012; Scheyder, 2013).

A water depot in western North Dakota is a business that 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 supply through successfully acquiring state-issued water permits. Between 1980 and 2007, the state issued just 10 water permits for water depots. In 2014, there were 588 water depots in the state. Tellingly, fracking water use alone accounted for 43% of total water use in the four major oil-producing counties in North Dakota in 2014, up from 0.7% in 2007 (Lin et al., 2015).

North Dakota state law does 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. However, in response to increased water demand in the oil patch by oil companies, the OSE developed a policy granting *yearly temporary* authorization for the holders of existing irrigation water permits to use water for industrial purposes (NDSWC, 2011). In addition, several local towns have also built water depots to sell excess municipal water to increase city's revenue (Kusnetz, 2012).

North Dakota does have a variety of surface and groundwater sources, but most are not suitable for long-term use for various reasons. Much of the state's surface waters and shallow aquifers are fully or nearly fully appropriated (Schuh, 2010). There is overwhelming consensus that Lake Sakakawea and the Missouri River are dependable sources of water that could be used to keep up with demand (Schuh, 2010; Shaver, 2012a). Conflict with the United States Army Corps of Engineers (USACE) over Surplus Water Policy on water distribution from these sources has prevented desired usage of these water sources. Except for the Missouri River and Lake Sakakawea, the storages of surface waters and shallow aquifers are limited and subject to drought condition.

Methodology

For the purpose of this study, we apply an agent-based model for the water allocation system at the Bakken region in western North Dakota. This agent-based model has a number of advantages over a traditional water resources management model or a conventional water demand-supply model. A traditional water resources management model is often fragmented and is more focused on human needs (Yang et al., 2009). A conventional water demand-supply model is based on the framework of "water marketing," a process by which members of the market negotiate voluntarily over "the amount, timing and price of water to be exchanged" (Kaiser and McFarland, 1997, page 888). But water in North Dakota is allocated through prior appropriation rather than market negotiation. The State Engineer assumes responsibilities in water resources regulation and administering the water permit procedure in the order of use priority. As a result of the oil production in western North Dakota, existing irrigation and municipal water permit holders are temporarily allowed to use water for industrial purposes. This process is overseen by the state which determines the number of permits of the amount of water withdrawal allowed.

The agent-based model of our study overcomes these drawbacks by integrating agent interactions with nature and environmental factors within the institutional and policy framework. The model thus allows for the bidirectional relation between individuals and the system and enables us to capture emergent behavior and new patterns in the water allocation system. A set of attributes for the agents is assumed in our model.

Agents are autonomous and self-directed. They are active planners and participants rather than passive responders. Each agent is able to interact with other agents, and each agent will choose an optimal amount of water use subject to the prices of water and a set of environmental, economic and policy constraints. Thus, agents are also dependent upon the environment and their interactions with other agents. They have access and user rights to a stock of water resources owned by the state via water permits and are able to learn and adapt to new environmental and economic changes. While all agents have their own goals in the system, each agent is assumed to be rational and will always choose a course of action that maximizes its own utility (benefits).

This means that agents may violate the terms of the permits to increase their own benefits when regulation is not effectively enforced. A permit violation or over withdrawal of water will negatively affect other permit holders or water users.

Decentralized Optimization Problem

The decentralized algorithm proposed by Yang et al. (2012) is modified to account for priority of water use and water sources in the context of current situation in North Dakota. The objective of an agent is to maximize its benefit subject to the penalty resulting from constraint violations:

$$\max_{x_i} \Pi_i(x_i, \beta_i | \{x_{\sim i}\}) = \max[\beta_i \cdot \pi_i(x_i) - P_i(x_i | \{x_{\sim i}\})], \tag{1}$$

$\forall i \in \mathbb{M} = \{1, \ldots m\}$ agents, where Π_i is the objective function for agent i, x_i is a decision variable for *i* with permits to draw water, β_i is a local interest parameter with $\beta_i > 0$, $\{x_{\sim i}\}$ is a set of decisions or actions by other agents that affect i, π_i is the initial benefit function without penalty assessment, and $P_i(\cdot)$ is the penalty associated with violating any of the constraints in the system. If $P_i(\cdot) > 0$, the agent is penalized for constraint violation and its utility from water use is reduced by $-P_i(\cdot)$; $P_i(\cdot) = 0$ otherwise. While the larger the value of β_i is, the larger the benefit received by agent i. The *a priori* assumption of the specification in equation (1) is that, to maximize its own benefit, agent *i* will select a β_i and avoid violating any constraints.

The environmental constraint facing the system is the water source whose overall availability is determined by nature and involves varying degrees of uncertainty. The policy constraint facing the system is the amount of water appropriation from a water source. We assume that the sum of appropriated water will never exceed the overall water in the watershed.

Local Optimization

For local optimization, we assume that agents seek to maximize their benefits given their interconnection with their neighborhood. The decentralized optimization problem for is defined as:

$$\max_{x_i} \Pi_i(x_i, \beta_i | \{x_{\sim i}\}), \tag{2}$$

with the solution denoted as:

$$[x_i^* | \beta_i, \{x_{\sim i}\}] = \arg\max_{x_i} \ \Pi_i(x_i, \beta_i | \{x_{\sim i}\}). \tag{3}$$

Global Optimization

The penalty function $P_i(\cdot)$ in equation (1) accounts for all constraints associated with x_i in the system, and is given by

$$P_i(x_i | \{x_{\sim i}\}) = P_{li}(x_i) + P_{gi}(x_i | \{x_{\sim i}\}), \tag{4}$$

where $P_{li}(x_i) = \sum_{q=1}^{q_i} P_{li,q}(x_i)$ is the sum of all local constraints associated with x_i, and $P_{gi}(x_i | \{x_{\sim i}\}) = \sum_{s=1}^{s_i} P_{gi,s}(x_i | \{x_{\sim i}\})$ is the sum of all constraints associated with x_i and $\{x_{\sim i}\}$. This second component of (2) is thus the interconnecting penalty function, and equation (4) characterizes the interconnection between agent *j* and other agents.

Thus, the global objective function can be written as

$$\Pi(x, \beta | \{x_{\sim i}\}) = \sum_{i=1}^{m} \left(\beta_i \pi_i(x_i) - \sum_{q=1}^{q_i} P_{li,q}(x_i) \right) - \sum_{s=1}^{s_i} P_{gi,s}(x_i | \{x_{\sim i}\}), \tag{5}$$

where m is the number of agents. Equation (5) yields a global performance metric (İnalhan et al., 2002). More specifically, the sum of the objective functions in equation (5) enables us to measure the benefits of all agents given the permit constraints, while the sum of the global constraints in the equation measures the system violation.

First-Order Necessary Condition and Second-Order Sufficient Condition for Decentralized Optimization

Solving for the optimal solution in (1), and based on İnalhan et al. (2002) and Yang et al. (2009), the first order necessary condition and the second order sufficient conditions are given by equations (6) and (7), respectively:

$$\frac{\partial}{\partial x_i} \Pi_i(x_i^*, \beta_i^* | \{x_{\sim i}\}) = 0, \forall i \in \mathbb{M}, \tag{6}$$

$$\frac{\partial^2}{\partial x_i^2} \Pi_i(x_i^*, \beta_i^* | \{x_{\sim i}\}) < 0, \forall i \in \mathbb{M}, \tag{7}$$

where the negative sign of the second partial derivative in (7) ensures that the second order sufficient condition is satisfied. That is, the solutions to (6) are true maxima.

Equation (6) is the generic form of differentiating equation (1) and setting the derivative equal to zero. The first order necessary condition can also be written as:

$$\frac{\partial}{\partial x_i} \Pi_i(x_i^*, \beta_i^* | \{x_{\sim i}\}) = \beta_i \cdot \frac{\partial \pi_i(x_i)}{\partial x_i} - \frac{\partial P_i(x_i | \{x_{\sim i}\})}{\partial x_i}\Bigg|_{x=x^*, \beta=\beta^*} = 0, \forall i \in \mathbb{M}. \tag{8}$$

Additionally, the penalty function is given by:

$$P_i(x_i|\{x_{\sim i}\}) = \sum_{k=1}^{k_i} \max\{0, g_i(x_i|\{x_{\sim i}\})^2\},$$

(9)

where k_i denotes the number of constraints associated with agent i; $g_i(x_i|\{x_{\sim i}\})$ is squared to ensure second-order differentiability indicated by equation (7), and $g_i(x_i|\{x_{\sim i}\})$ is the constraint function that accounts for agent i's local constraints ($g_{li}(x_i)$) and global constraints ($g_{gi}(x_i|\{x_{\sim i}\})$):

$$g_i(x_i|\{x_{\sim i}\}) = \begin{cases} g_{li}(x_i) \leq 0 \\ g_{gi}(x_i|\{x_{\sim i}\}) \leq 0 \end{cases}.$$

(10)

As the name implies, the global constraints, $g_{gi}(x_i|\{x_{\sim i}\})$, interconnect agent i to other agents within the system.

The purpose of this decentralized agent-based model is not to obtain a system-level optimal solution, because the model assumes that agents do not necessarily have the knowledge of the entire system, and that they do not seek to maximize the total benefits of the system. Rather they seek to maximize their own benefits given their own constraints as well as the overall constraint at the system level.

Water Depots as Agents of Water Distribution in North Dakota

In addition to large privately owned water depots, the key players in the water depot industry also include government-enacted water suppliers and a large number of private, small, temporary water depots. We categorize these depots into nine types from which we define nine agents in our model, each representing one type of water depot. These nine types of water depot are categorized based on their ownership, water permit types and water sources. They are defined in Table 1.

[Insert Table 1]

A water depot has a "perfected" water permit as defined by the state water law if it has been determined by engineers of the OSE that the water depot has put water to beneficial use based on the prescribed conditions, and hence a water right is established. A "perfected" permit or establishing a water right takes a couple of years.

As a result, a large number of temporary permits were granted to alleviate the pressure of increased water demand for industrial use (fracking) in recent years (Shaver, 2012a). A water depot is "temporary" if it has a temporary water permit to begin drawing water from a source. Temporary water permits are limited to a period of 12 months; the permits cannot be modified or transferred.

The historic data of the water consumption and the approved water permits of these water depots during the period of 2007-2014 are summarized in Table 2. Table 3 provides a summary of the notations used in the optimization problems for the agent-based models discussed below.

[Insert Tables 2 and 3]

Agent 1: Industrial - Fox Hills (Type 1 Water Depot)

Agent 1 is a representative industrial water depot that withdraws water from the Fox Hills (FH) aquifer. Water wells that draw water from the FH aquifer are about 1,500 to 2,300 feet deep. Historically, permits to draw water from the FH aquifer for industrial use have been restrictive considering the significance of the more than 500 flowing-head wells to livestock watering in remote pastures in the region. Nevertheless, water has been drawn from this source in recent years. The optimization problem for agent 1 is given below:

$$\max_{x_{1t}} f_1(x_{1t}) = a_1 {x_{1t}}^2 + b_1 x_{1t} + c_1, \tag{11}$$

$$\text{subject to} \begin{cases} x_{1t} - WP_{1t} \leq 0, \\ n_{1t}x_{1t} - FH_t \leq 0, \end{cases}$$

where the subscript 1 denotes agent 1; a_1, b_1 and c_1 are the coefficients of the objective function, which is the benefit function $f_1(x_{1t})$, where x_{1t} is the water consumed by agent 1 in year *t*.

The first constraint in (11) means that agent 1's water consumption must not exceed WP_{1t}, the amount of water permitted in year *t*. In the second constraint, n_{1t} is the number of type 1 water depots. The constraint implies that the total water consumption by all depots in the type 1 category which agent 1 belongs must not exceed the total amount of water available from the FH aquifer in year *t*.

Agent 2: Industrial - Other Groundwater (Type 2 Water Depot)

Agent 2 is a representative industrial water depot that withdraws water from shallow aquifers (GW). While groundwater resources are available, they are limited in quantity and quality at the Bakken. The optimization problem for agent 2 is given below:

$$\max_{x_{2t}} f_2(x_{2t}) = a_2 {x_{2t}}^2 + b_2 x_{2t} + c_2, \tag{12}$$

$$subject\ to \begin{cases} x_{2t} - WP_{2t} \leq 0, \\ n_{2t}x_{2t} + n_{6t}x_{6t} + n_{7t}x_{7t} - GW_t \leq 0, \end{cases}$$

where the subscript 2 denotes agent 2. Thus a_2, b_2 and c_2 are the coefficients of $f_2(x_{2t})$ which is the benefit function for agent 2 to be maximized, where x_{2t} is the water consumed by agent 2 in year *t*.

The first constraint in (12) means that agent 2's water consumption must not exceed the amount of water permitted in year *t*. The second constraint in (12) implies that the total water consumption by all depots in the type 2 category which agent 2 belongs and the sum of the total water consumption by all types 6 and 7 water depots must not exceed the total amount of water available from the shallow aquifers (GW) in year *t*.

Agent 3: Industrial - Lake Sakakawea/Missouri River (Type 3 Water Depot)

Agent 3 is a representative industrial water depot that withdraws water from Lake Sakakawea or the Missouri River (LSMR). Waters from the LSMR are an important and a major source, especially for western North Dakota. Lake Sakakawea, the largest water body in the state, is the third largest man-made lake in the U.S. overseen by the US Army Corps of Engineers (USACE, undated). Contention between the USACE and North Dakota state officials arose in recent years with regard to access to the LSMR waters for industrial use in light of rising water demand from the oil industry. In 2010, the USACE began denying access to the LSMR by industrial water users. While the USACE agreed to issue temporary permits for water usage in mid-2012, contention between the state and federal governing bodies has largely remained (North Dakota State Water Commission, 2012 and 2016).

The optimization problem for agent 3 is given below:

$$\max_{x_{3t}} f_3(x_{3t}) = a_3 {x_{3t}}^2 + b_3 x_{3t} + c_3, \tag{13}$$

$$subject\ to \begin{cases} x_{3t} - WP_{3t} \leq 0, \\ n_{3t}x_{3t} + n_{5t}x_{5t} + n_{8t}x_{8t} - LSMR_t \leq 0, \end{cases}$$

where the subscript 3 denotes agent 3. The benefit function $f_3(x_{3t})$ for agent 3 is to be maximized, where x_{3t} is the water consumed by agent 3 in year *t*.

The first constraint in (13) means that agent 3's water consumption must not exceed the amount of water permitted in year *t*. The second constraint in (13) implies that the total water consumption by all depots in the type 3 category which agent 3 belongs and the sum of the total water consumption by all types 5 and 8 water depots must not exceed the total amount of water available from LSMR in year *t*.

Agent 4: Industrial - Other Surface Water (Type 4 Water Depot)

Agent 4 is a representative industrial water depot that withdraws water from other non-LSMR surface water sources (*SW*). These include creeks, Lake Trenton and Yellowstone River. The optimization problem for agent 3 is given below:

$$\max_{x_{4t}} f_4(x_{4t}) = a_4 {x_{4t}}^2 + b_4 x_{4t} + c_4,$$

$$subject\ to \begin{cases} x_{4t} - WP_{4t} \leq 0, \\ n_{4t}x_{4t} + n_{9t}x_{9t} - SW_t \leq 0. \end{cases} \tag{14}$$

The benefit function $f_4(x_{4t})$ for agent 4 is to be maximized, where x_{4t} is the water consumed by agent 4 in year *t*. The first constraint in (14) means that agent 4's water consumption must not exceed the amount of water permitted in year *t*. The second constraint in (14) implies that the total water consumption by all depots in the type 4 category which agent 4 belongs and the sum of the total water consumption by all type 9 water depots must not exceed the total amount of water available from *SW* in year *t*.

Agent 5: Government-Enacted Water Depots – LSMR (Type 5 Water Depot)

Type 5 water depots are government-backed. North Dakota state legislature enacted regional water authorities to serve the water needs of rural communities in western North Dakota. As the Bakken shale oil production expanded, so was the demand for water in that area.

The optimization problem for Agent 5, which is a representative of type 5 water depots, is given by:

$$\max_{x_{5t}} f_5(x_{5t}) = a_5 x_{5t}{}^2 + b_5 x_{5t} + c_5,$$

$$subject\ to \begin{cases} x_{5t} - WP_{5t} \leq 0, \\ n_{3t}x_{3t} + n_{5t}x_{5t} + n_{8t}x_{8t} - LSMR_t \leq 0^{\cdot} \end{cases} \quad (15)$$

where x_{5t} is the water consumed by agent 5 in year t. The first constraint in (15) means that agent 5's water consumption must not exceed the amount of water permitted in year t. The second constraint in (15) implies that the total water consumption by all type 5 depots and the sum of the total water consumption by all types 5 and 8 water depots must not exceed the total amount of water available from LSMR in year t.

Agent 6: City-Owned Water Depots – Groundwater (Type 6)

Agent 6 represents an average city-owned water depot that has municipal permits transferred from municipal use to industrial use. The agent withdraws water from shallow groundwater aquifers in the region. The optimization problem for this agent is given below:

$$\max_{x_{6t}} f_6(x_{6t}) = a_6 x_{6t}{}^2 + b_6 x_{6t} + c_6,$$

$$subject\ to \begin{cases} x_{6t} - WP_{6t} \leq 0, \\ n_{2t}x_{2t} + n_{6t}x_{6t} + n_{7t}x_{7t} - GW_t \leq 0, \end{cases} \quad (16)$$

where x_{6t} is the water consumed by agent 6 in year t. The first constraint in (16) means that agent 6's water consumption must not exceed the amount of water permitted in year t. The second constraint in (16) implies that the total water consumption by all type 6 depots and the sum of the total water consumption by all types 2 and 7 water depots must not exceed the total amount of water available from GW in year t.

Agent 7: Irrigation Transferred Water Depots – Groundwater (Type 7)

Agent 7 is a representative water depot that represents an average water depot with an industrial use water permit transferred from an irrigation use water permit. The transfer of permit from irrigation to industrial use is temporary and limited to one year. Additionally, a type 7 depot is required to forego irrigation for the year during which water is drawn for industrial use (Shaver, 2012a). Agent 7 draws water from GW in the region as well. The optimization problem for agent 7 is:

$$\max_{x_{7t}} f_7(x_{7t}) = a_7 {x_{7t}}^2 + b_7 x_{7t} + c_7,$$

$$subject\ to \begin{cases} x_{7t} - WP_{7t} \leq 0, \\ n_{2t}x_{2t} + n_{6t}x_{6t} + n_{7t}x_{7t} - GW_t \leq 0, \end{cases} \tag{17}$$

where x_{7t} is the water consumed by agent 7 in year t. The first constraint in (17) implies that the agent's water consumption must not exceed the amount of water permitted in year *t*. The second constraint in (17) implies that the total water consumption by all type 7 depots and the sum of the total water consumption by all types 2 and 7 water depots must not exceed the total amount of water available from GW in year *t*.

Agent 8: Temporary Water Depots – LSMR (Type 8)

Agent 8 is a representative temporary water depot that has a temporary permit to draw water from the LSMR. Unlike agent 3, agent 8's water permit is temporary and expires in one year. The optimization problem for agent 8 is given below

$$\max_{x_{8t}} f_8(x_{8t}) = a_8 {x_{8t}}^2 + b_8 x_{8t} + c_8,$$

$$subject\ to \begin{cases} x_{8t} - WP_{8t} \leq 0, \\ n_{3t}x_{3t} + n_{5t}x_{5t} + n_{8t}x_{8t} - LSMR_t \leq 0. \end{cases} \tag{18}$$

The first constraint in (18) means that agent 8's water consumption must not exceed the amount of water permitted in year *t*. The second constraint in (18) implies that the total water consumption by all type 8 depots and the sum of the total water consumption by all types 5 and 8 water depots must not exceed the total amount of water available from *LSMR* in year *t*.

Agent 9: Temporary Water Depots – SW (Type 9)

An abnormally wet winter in 2009-2010 resulted in increased surface water availability. The State Water Commission began issuing temporary water permits for access to surface waters. Agent 9 is a representative temporary water depot that has a temporary permit to draw water from surface water sources other than the LSMR. Its permit expires in a year, and the optimization problem for agent 9 is given below:

$$\max_{x_{9t}} f_9(x_{9t}) = a_9 {x_{9t}}^2 + b_9 x_{9t} + c_9,$$

$$subject\ to \begin{cases} x_{9t} - WP_{9t} \leq 0, \\ n_{4t}x_{4t} + n_{9t}x_{9t} - SW_t \leq 0. \end{cases} \qquad (19)$$

The first constraint in (19) means that agent 9's water consumption must not exceed the amount of water permitted in year *t*. The second constraint in (19) implies that the total water consumption by all type 9 depots and the sum of the total water consumption by all type 4 water depots must not exceed the total amount of water available from *SW* in year *t*.

Analytical Results and Scenario Analysis

Baseline Results

Assuming no other regulations other than the constraints given in equations (11) – (19), agent *i* optimizes its own objective at a given value of β, and sends the solution to the agents interconnecting with agent *i* iteratively until an optimal solution is reached.

Summing up individual agents' optimal water consumption and the associated benefits they received yields the total water consumption and total benefits for the system. The baseline results are reported in Figure 1. Total water consumption by all depots and the total benefits they received moved in locked steps from 2007 to 2014. The upward trend largely reflects the region's increased oil production during the same period (see Figure 2).

[Insert Figures 1 and 2]

In Figure 3, we present the size of total permit violations (denoted TVio1) and overall system violations (TVio2) as well as the total benefits over time. The two violations dropped significantly after 2009. This result corresponds to the issuance of irrigation transferred water depot permits and temporary water depot permits during a period of time when oil production expanded rapidly. Total benefits for the water depot industry rose as a result.

[Insert Figure 3]

From a policy perspective, we alter the status quo to examine individual agents' response. We consider three scenarios that could affect agents' behavior and their interactions with other agents in the hydrological system:

1. LSMR Constraint: industrial use of LSMR waters is denied due to regulations;
2. GW Constraint: industrial use of GW is severely limited due to drought;
3. SW Constraint: industrial use of SW is severely limited due to drought.

Scenario 1: LSMR Constraint

Under this scenario, access to LSMR waters by water depots with an industrial water use permit is denied, regardless of whether the permit is perfected or temporary. LSMR is the only large and reliable surface water source in western North Dakota. Lake Sakakawea has been used for flood reduction, electricity generation, irrigation, municipal water supply, navigation, recreation, fish and wildlife. While state officials recommended using LSMR waters to meet oil companies' water demand, LSMR waters are managed by the USACE, and it has recommended against industrial access and proposed charging a high fee for water use. Although the USACE has eased its position, access to LSMR waters is still restrictive, and state officials and the USACE remain at odds over the issue.

Scenario 2: GW Constraint

Groundwater from shallow aquifers is not abundant in or near the oil patch, and quality water is scarce. It is also subject to climate uncertainty in the hydrologic system (Shaver, 2012a). Historically, GW sources have been primarily for agricultural and ranching purposes (Shaver, 2012b). Under Scenario 2, access to GW sources for industrial users is severely limited due to drought.

Scenario 3: SW Constraint

While SW sources other than LSMR are available at the Bakken, they are limited, and the availability of SW in any given year is unstable and sensitive to the season of the year as well as the precipitation amount that the region receives. Under Scenario 3, access to SW in the region is severely limited due to drought.

Scenario Results

The impact of each of the three scenarios on total water consumption is displayed in Figures 4a and 4b. In Figure 4a, the total level of water consumption under each scenario is compared against the baseline. The differences in total water consumption levels from the baseline under scenario 1 (LSMR0.0) and scenario 2 (GW0.0) were not readily apparent until

2010. Under scenario 3 (no SW access, or SW0.0) the size of water consumption reduced slightly and gradually after 2011.

Under scenario 1 (in Figure 4b), the total water consumption dropped acutely in 2010 then gradually tapered off. In percentage terms, the size of water use reduction under scenario 1 decreased from 39% in 2010 to less than 20% in 2014, while total water consumption under scenario 3 dropped from 2.5% in 2011 to over 40% in 2014. Under scenario 2, water consumption reduction was between 10 to 34% in 2007-2014. Over time, scenario 2 creates the largest and steadier reduction in water consumption.

[Insert Figures 4a and 4b]

The impacts of the three scenarios on the total benefits of the water depot industry is displayed in Figures 5a and 5b. In Figure 5a, the depots' total benefits track closely with their water use under all three scenarios seen in Figure 4a. Consistent with the changes in water consumption, the effect of no SW access (under scenario 3) on the industry's total benefits became apparent after 2011, while changes in total benefits were visible starting 2010 under the first two scenarios.

In Figure 5b, total benefits under scenario 1 dropped sharply for the industry in 2010; scenario 3 reduced the industry's total benefits gradually and reached -27% in 2014; of the three scenarios, scenario 2 had the greatest impact on total benefits over time.

[Insert Figures 5a and 5b]

At any rate, Figures 4a through 5b show that no access to either one of the three water sources would create a sizable impact on all agents and the entire system. The effect is most pronounced after 2009, and especially after 2010, when oil production began to spike and the demand for water by the oil industry was great. When access to water sources is severely limited and the demand for water is rising, agents would react to the demand by resorting to other available water sources or would violate the permit requirements such as the limit of water use and the permitted source. The violations can be explained by the total benefits associated with expanded water use.

Violations under Scenario 1 (No LSMR Access)

Increased water demand creates incentives for agents to use water resources that are available to increase their own individual benefits. If so, under scenario 1, the agents' behavior would lead to permit and system violations. The total benefits and system violations by all water depots are shown in Figure 6; system violation (TVio2) was prevalent and remained high after 2010.

[Insert Figure 6]

From a system-wide perspective, we broke down the system violations (Tvio2) by the type of water depots. Figure 7 presents the breakdown under scenario 1, in which depots of types 3, 5 and 8, the current LSMR water permit holders, are predominantly the system violators, followed by depots of types 4 and 9, which are temporary SW water permit holders. In response to the restriction under scenario 1, the current LSMR permit holders would violate the restriction by withdrawing from the LSMR to maximize their own benefits. Meanwhile, temporary SW permit holders would seek to fill the void in the industry by violating their own permits, but the role they play would be much smaller.

[Insert Figures 7]

Violations under Scenario 2 (No GW Access)

Under scenario 2, GW access is revoked. In Figure 8, the effects of such restriction on total benefits and system violations are displayed. The system violations dropped sharply while total benefits rose after 2009. Total benefits to the industry was $142 million in 2014, up from $35 million in 2009. In Figure 9, violations are found predominantly among depots of types 2, 6 and 7 who hold GW permits in 2010 through 2014. Prior to 2010, depots of types 3, 5 and 8, the LSMR permit holders were the major violators who tried to capture the market demand for water in the absence of GW sources.

[Insert Figures 8 and 9]

Violations under Scenario 3 (No SW Access)

When SW access is rescinded under scenario 3, violations by water depots dropped markedly after 2009, while total benefits rose from $40 million in 2009 to nearly $140 million in 2014 (Figure 10). The breakdown of the system violations is shown in Figure 11. Between 2007 and 2009, the five types of water depots (types 3, 4, 5, 8 and 9) were the violators, with LSMR permit holders (depot types 3, 5 and 8) being the major ones, and depots of types 4 and 9 (SW permit holders) played a smaller role. However, type 4 and type 9 depots continued to have violations after 2009.

[Insert Figures 10 and 11]

Results Discussions

While the scenarios in our model represent three hypothetical cases, they closely imitate the real world scenarios in North Dakota, and policy implications emerge from the results. We observed that year 2009 was a crucial turning point. Under scenario 1, total violations in the system rose sharply after 2009, while under the two other scenarios, the total violations peaked in 2009 and dropped rapidly after 2009. The results also show that water depots with LSMR permits would mostly likely emerge as violators to the system under all three scenarios. LSMR water depots would most likely fill the void of other depots by increasing their water supply to the oil industry when the two other alternative water sources are not available. But compared to scenario 1, their roles would be much smaller and the magnitude of violations would be less prevalent under scenarios 2 and 3.

From a policy standpoint, completely restricting access to LSMR for industrial use would decrease total industrial water consumption in the region by an average of 20% per year. Compared to the baseline, total benefits would drop by 13% per year during the same period, but system violations would remain prevalent, since there would be incentives to violate as long as the demand for water is there.

Policies restricting industrial use of GW sources would likely see considerably less system violations with an average of 24% per year reduction in water consumption. The economic impact on the industry would be an estimated reduction of total benefits by 16% per year. Additionally, restricting access to SW sources would also see less system violations. But the effect on water consumption reduction would be small at a reduction of less than 10% per year, and the associated reduction in total benefits would be under 6% per year.

In a nutshell, scenario 2 (restricting GW access) would create the largest amount of water conservation and with less violations. The impact of SW constraint on water consumption in the region would be the smallest. While LSMR restriction would reduce a sizable amount of water consumption, system violations would be prevalent and practically rendering null the restriction and defeating the policy altogether.

Conclusions

Striking a delicate balance between preserving scarce water resources and expanding oil production at the Bakken is a challenging task. Uncertainty in the hydrologic system and climate presents another challenge to state policymakers when it comes to allocating water permits and distributing water to oil companies and other users. The state of North Dakota currently relies on water depots as suppliers and distributors of freshwater to oil companies. Positing these water depots as agents, we apply a decentralized agent-based model to examine the emergent behavior of water depots under three potential scenarios, and these scenarios are then compared to the baseline results to gauge the potential impacts on water consumption in the North Dakota oil patch.

Our results suggest that restricting use of LSMR could dent the size of water consumption by the oil industry at the Bakken, but it will likely not strike an adequate, efficacious balance in the water-energy nexus in western North Dakota, since system violations would prevail. The results point to the existing gaps in water and energy policies in the U.S. which arise from a disconnect between the state and federal governments as policymakers and managers of water and energy resources. Policies on water resource management and energy security and independence need to be better intertwined to reflect the strong interdependent relationship of the two resources (Craig, 2013).

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Table 1. Agent definitions for different types of water depot (WD)

Agent	WD type	Definition
1	Industrial – Fox Hills	Privately owned WDs with perfected permits for withdrawing water from the Fox Hills aquifer.
2	Industrial –GW	Privately owned WDs with perfected permits for withdrawing water from shallow groundwater (GW) aquifers.
3	Industrial – LSMR	Privately owned WDs with perfected permits for withdrawing water from Lake Sakakawea (LS) or the Missouri River (MR).
4	Industrial –SW	Privately owned WDs with perfected permits for withdrawing water from surface water sources other than LS or the MR.
5	Government-Enacted – LSMR	Government owned WDs with permits for withdrawing water from LS or the MR.
6	City –GW	City owned WDs with permits transferred from municipal water use permits withdrawing water from shallow GW aquifers.
7	Irrigation transferred – GW	Privately owned WDs with yearly permits temporarily transferred from irrigation permits withdrawing water from shallow GW aquifers.
8	Temporary – LSMR	Privately owned WDs with temporary permits (less than 1 year) withdrawing water from LS or MR.
9	Temporary –SW	Privately owed WDs with temporary permits (less than 1 year) withdrawing water from surface water sources other than LS or MR.

Table 2. Summary of the water consumptions by and approved water permits for different types of water depot (2007-2014)

Agent	WD type	Total water consumption (ac-ft)	Average water consumption (ac-ft)[5]	Water consumption range (af-ft)	Total approved water permit (ac-ft)	Average approved water permit[5] (ac-ft)	Approved water permit range (ac-ft)
1	Industrial – Fox Hills	515.40	16.11	0-60.36	1,040.00	32.50	20-60
2	Industrial – Other GW	10,893.30	42.75	0-230.70	40,696.40	150.50	19.40-1,341.80
3	Industrial – LS/MR	5,713.23	164.14	0-1,946.90	540,728.00	18,231.31	800-18,000
4	Industrial – Other SW	2,789.74	121.39	0-930.40	20,332.00	764.43	50-3,300
5	Government Enacted – LS/MR	18,961.80	1,272.74	201.70-5,854.30	232,315.00	14,731.56	1,130-40,325
6	City – Other GW	3484.76	99.08	0-222.70	12,229.50	304.91	2-265.50
7	Irrigation transferred – Other GW	16801.022	91.65	0-495.40	82,140.10	400.12	20-708
8	Temporary – LS/MR	3441.16	59.60	0-1,013.30	55,268.43	1,086.55	10.31-6,000.00
9[4\]	Temporary – Other SW	15789.574	17.51	0-619.70	103,218.82	109.35	0.46-10,000

Table 3. Notations

x_{it} – Water consumption (ac-ft) for agent *i* in year *t*. This time series represents the annual water consumption *averaged* across one type of water depot that are represented by agent *i* (see Table 1).
f_i – The benefit function (BF) for *i*th agent, which is defined as $f_i(x_{it}) = a_i x_{it}^2 + b_i x_{it} + c_i$, where a_i, b_i, and c_i are BF coefficients for agent *i*.
n_{it} – Total number of *individual* water depots in the category of agent *i* in year *t*.
WP_{it} – *Average* water permit (ac-ft) for agent *i* in year *t*.
FH_t – *Total* water permits approved (ac-ft) for all agents (i.e., Agent 1) that withdraw water from the Fox Hills aquifer (FH) in year *t*.
GW_t – *Total* water permits approved (ac-ft) for all agents (i.e., Agents 2, 6 & 7) that withdraw water from shallow aquifers (GW) in year *t*.
$LSMR_t$ – *Total* water permits approved (ac-ft) for all agents (i.e., Agents 3, 5 & 8) that withdraw water from Lake Sakakawea (LS) or the Missouri River (MR) in year *t*.
SW_t – *Total* water permits approved (ac-ft) for all agents (i.e., Agents 4 & 9) that withdraw water surface water sources other than Lake Sakakawea (LS) or the Missouri River (MR) in year *t*.

Figure 1. Baseline Total Water Consumption and Total Benefits

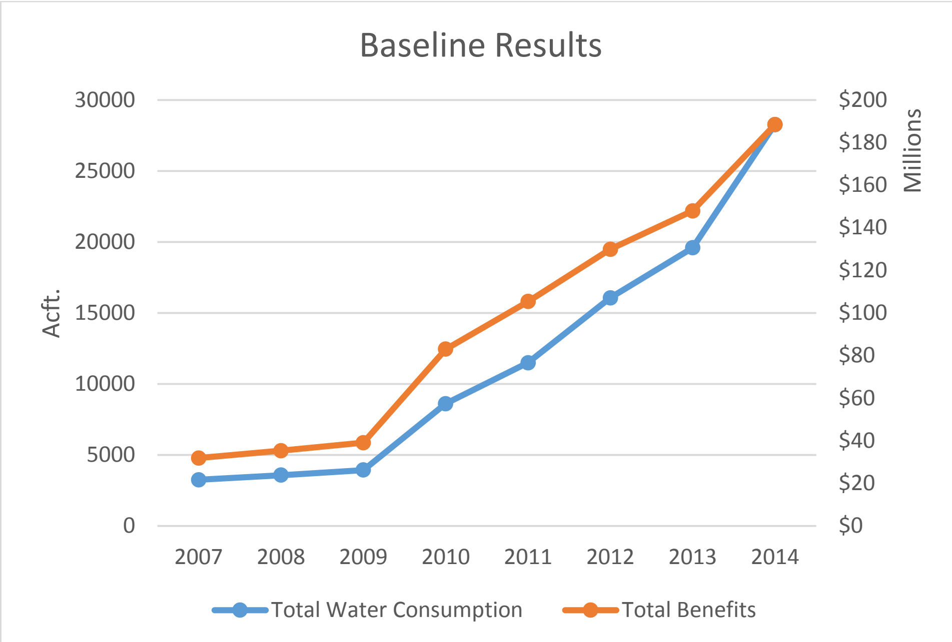
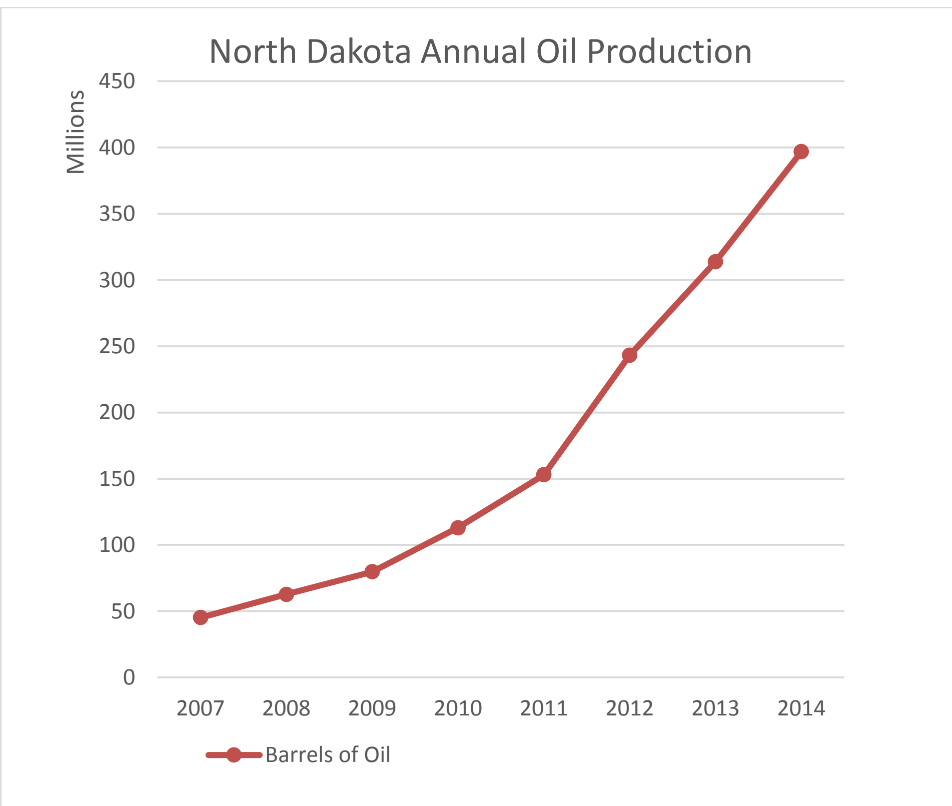


Figure 2. North Dakota Annual Oil Production



Source: North Dakota Department of Mineral Resources

Figure 3. Baseline Permit Violations, System Violations and Total Benefits

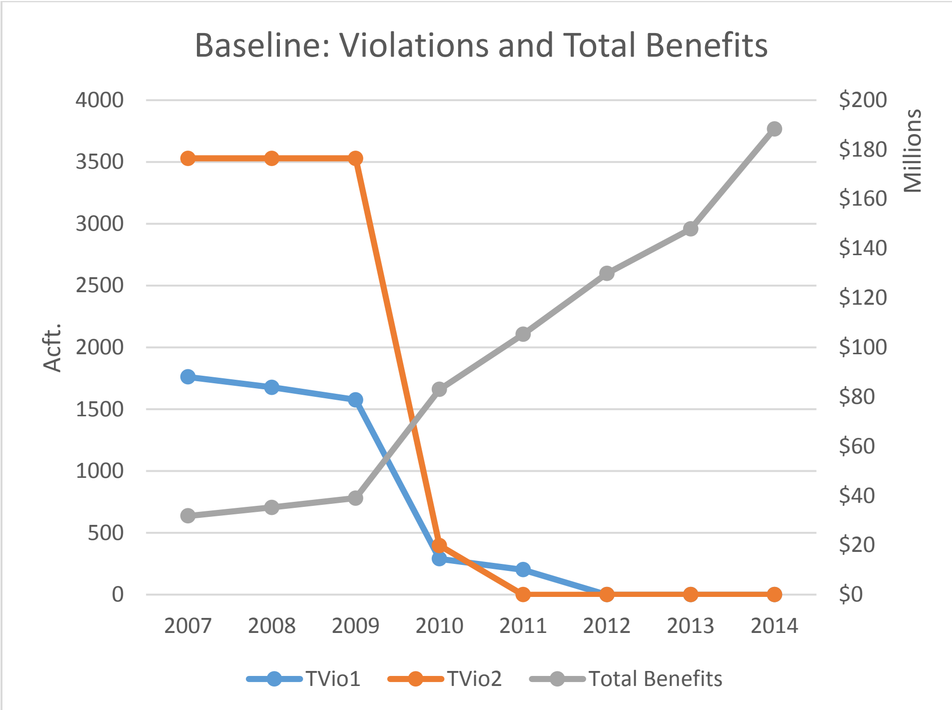
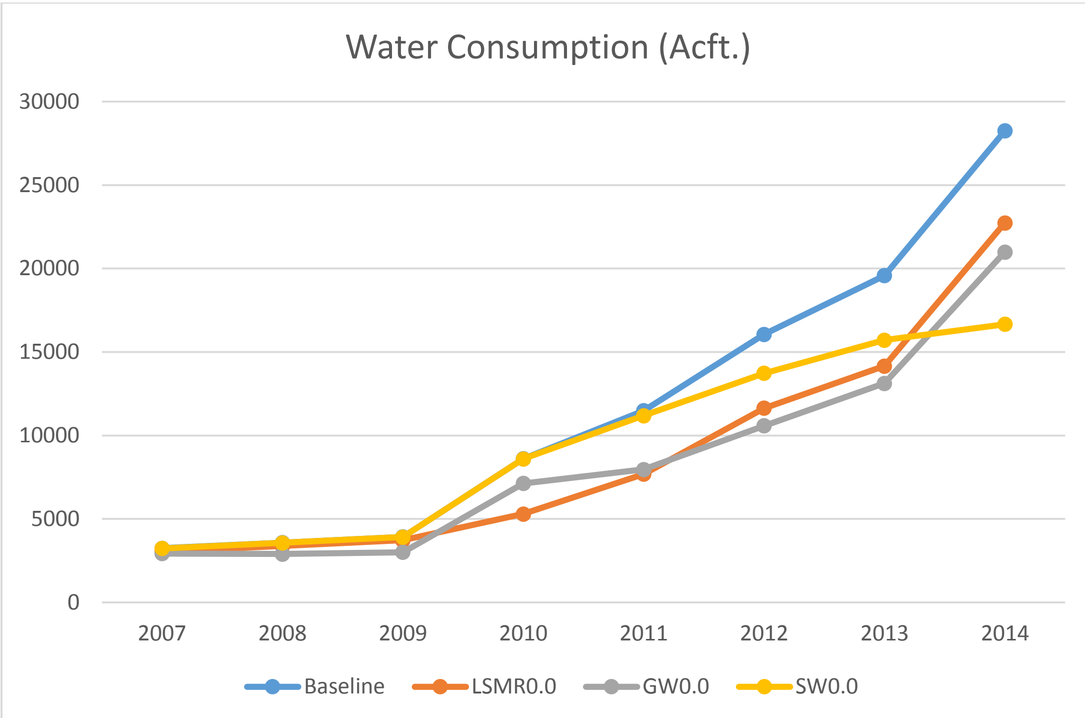


Figure 4. Scenario Analysis: Impact on Water Consumption

a. Total Water Consumption Level



b. Percentage Change in Total Water Consumption

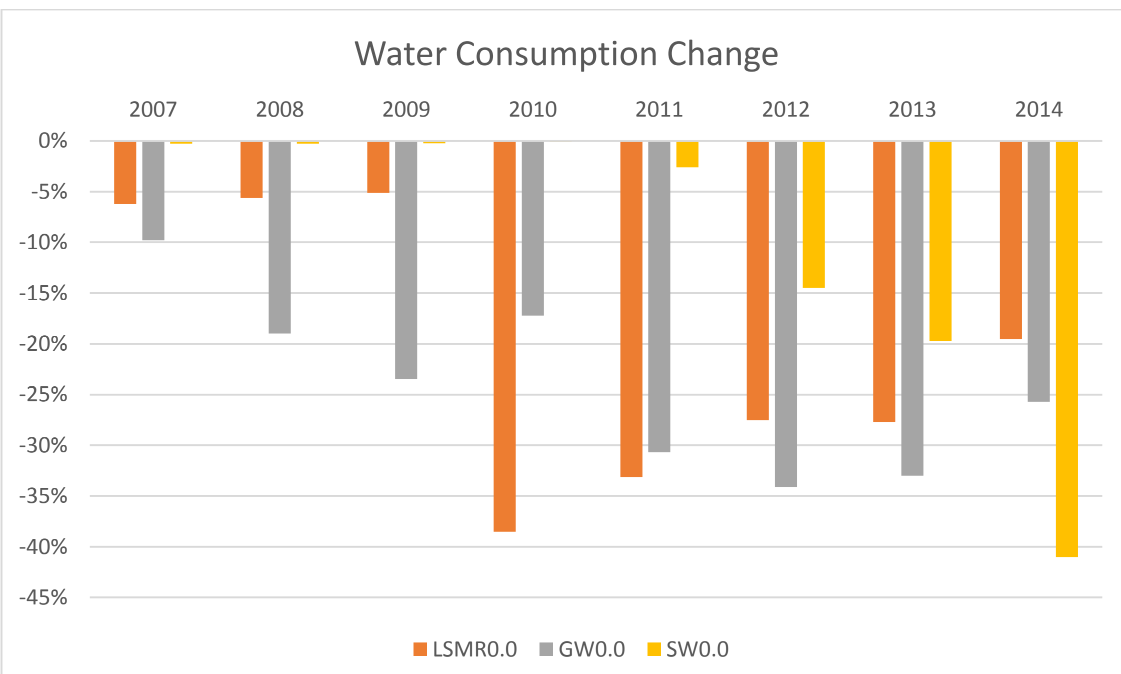
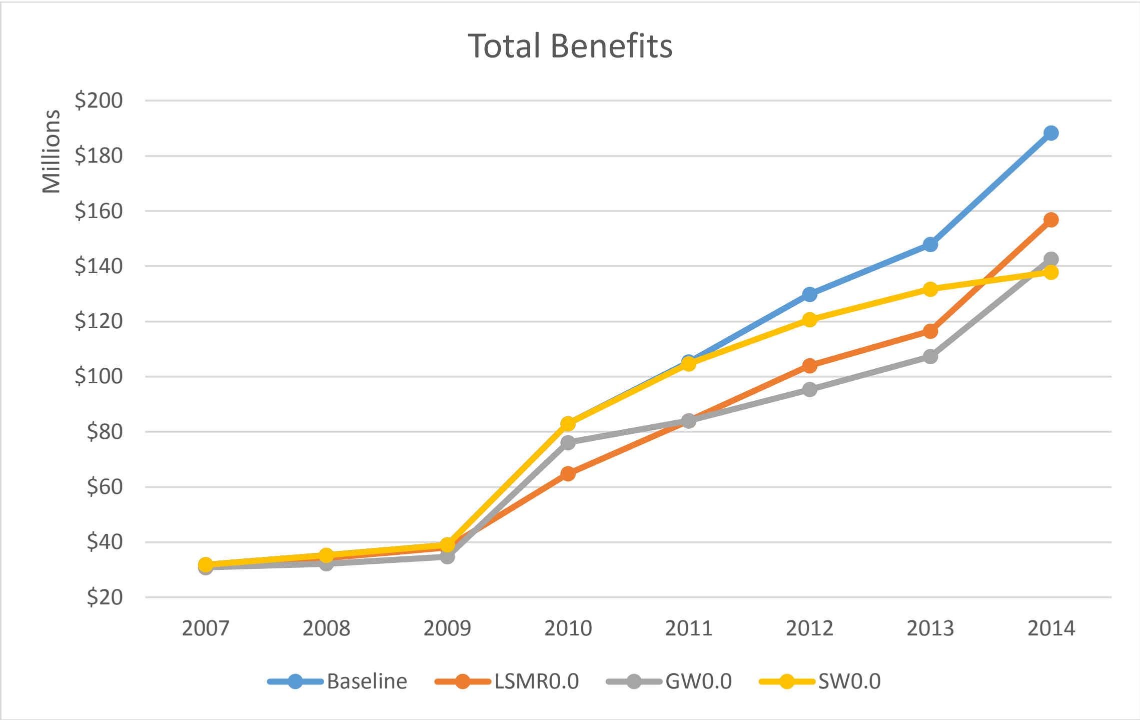


Figure 5. Scenario Analysis: Impact on Total Benefits

a. Total Benefits Comparison



b. Percentage Change in Total Benefits

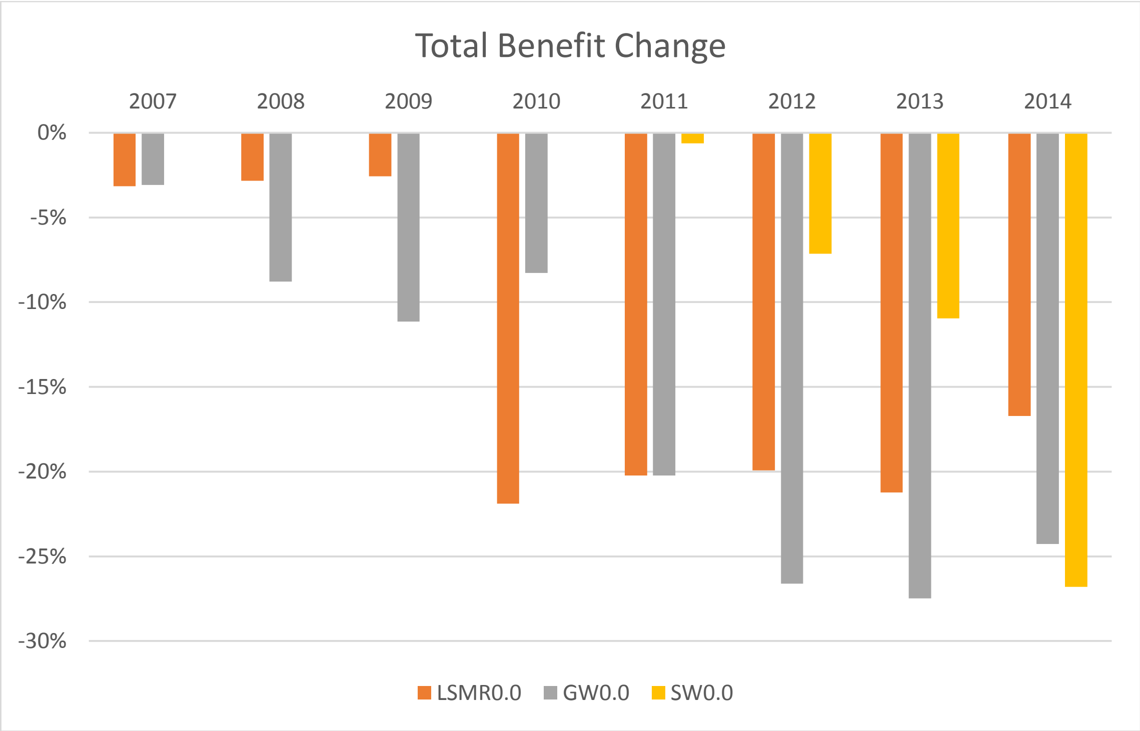


Figure 6. Violations and Total Benefits under Scenario 1

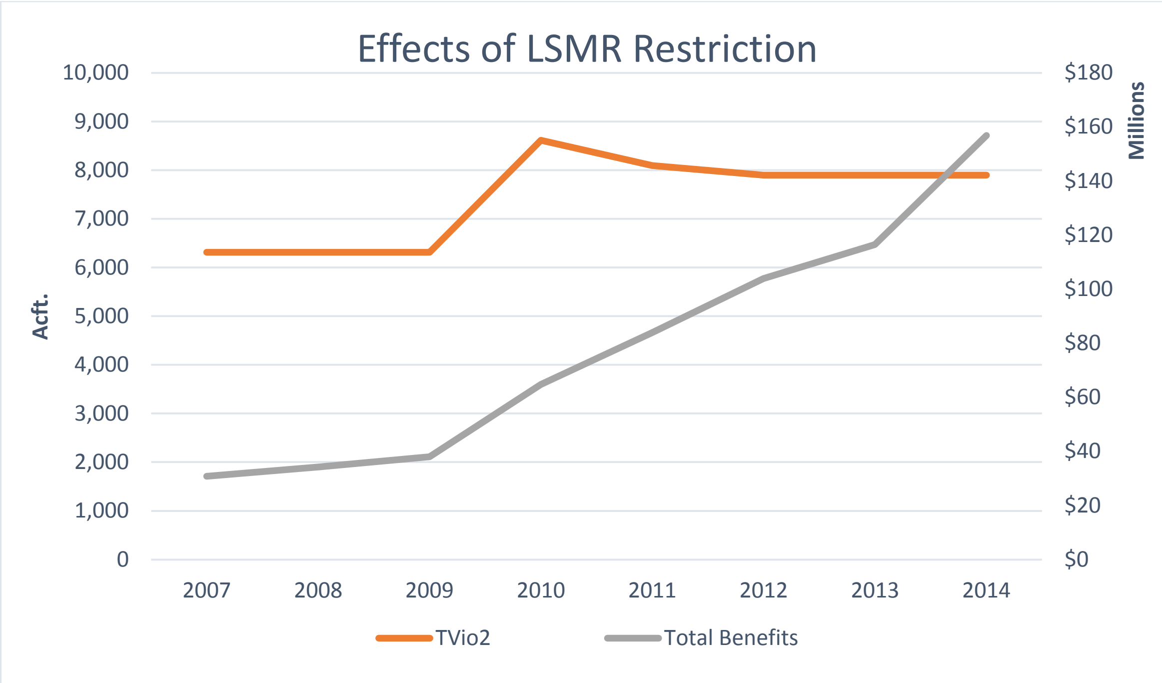


Figure 7. System Violations under Scenario 1

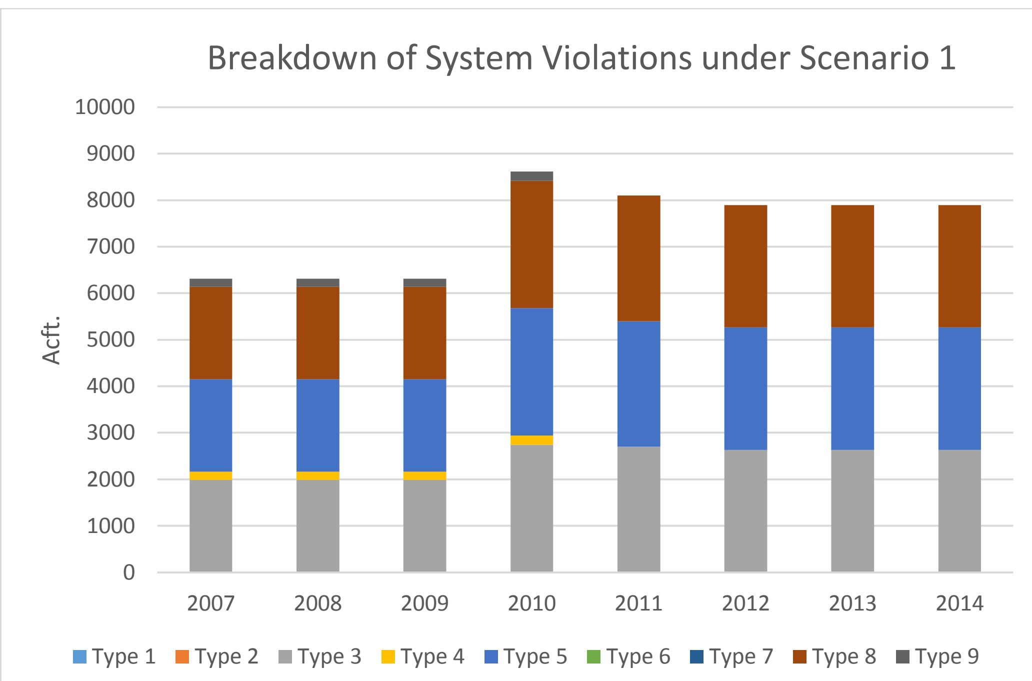


Figure 8. Violations and Total Benefits under Scenario 2

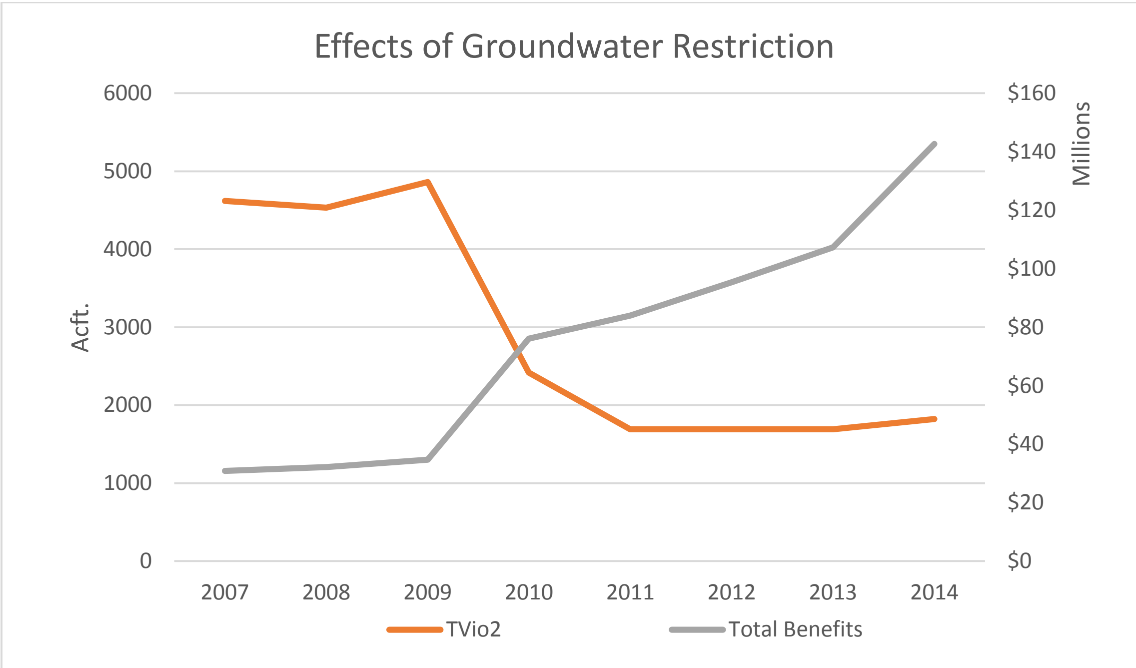


Figure 9. System Violations under Scenario 2

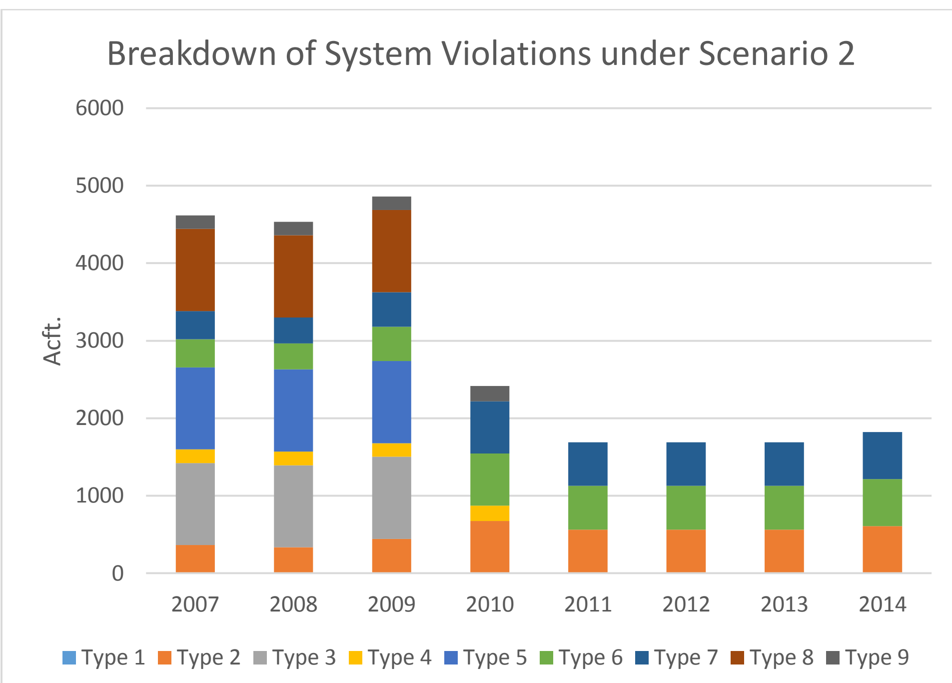


Figure 10. Violations and Total Benefits under Scenario 3

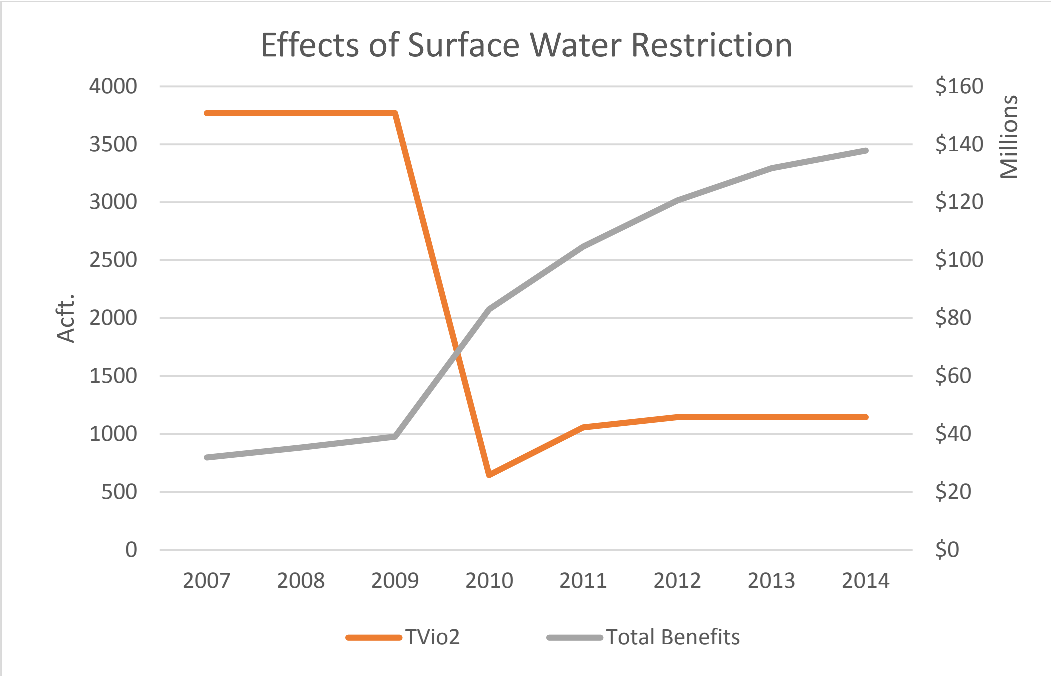


Figure 11. System Violations under Scenario 3