# ABSTRACT

SCHMIDT, MICHELLE LYNN. Simulating the Selection of Municipal Water Supply Portfolios to Assess Vulnerability in a Seniority-based Water Rights Program. (Under the direction of Dr. Emily Berglund).

Municipalities in a shared water basin invest in cost-effective and reliable water supply sources to provide water for municipal demands. Municipalities may build water supply portfolios using sources that include permitted surface water, purchased water, groundwater, and recycled wastewater. Demand management strategies, such as indoor and outdoor water conservation programs, can also be included in municipal water portfolios. In several western states, surface water is allocated to municipal, agricultural, and industrial users using a seniority-based water rights program; in such a program the diversions of permit-holders are prioritized following a “first in time, first in right” rule. Climate change and urbanization stress water resources, and municipalities with more recently awarded permits may not receive water as expected. Seniority-based permit programs, therefore, can create municipal surface water shortages.

A shared river basin has characteristics of a complex adaptive system, as autonomous municipal actors interact through a common water resource and adapt decentralized water management practices in response to the environment and behaviors of other actors. This research simulates a shared river basin as a complex adaptive system using an agent-based model (ABM). Municipal agents apply conventional, permit-based adaptive, and supply-based adaptive water management strategies to build a water supply portfolio. Municipal agents meet demands using a combination of surface water, groundwater, purchased water supplies, recycled wastewater, and conservation measures. The ABM is coupled with the Water Rights Analysis Package (WRAP). WRAP simulates a seniority-based water permit

system and municipal agents receive feedback about their surface water supplies and water shortages from WRAP. Using a conventional water management approach, a set of heterogeneous municipal agents identify least-cost water supply portfolios using a linear programming model. Using adaptive water management strategies, municipal agents that experience water shortages deviate from their least-cost water supply portfolios; municipal agents do this in an effort to improve the reliability of their water portfolios.

The ABM framework is demonstrated for the Guadalupe River Basin, Texas. Ten municipalities and other users hold surface water permits that, in total, exceed the mean annual stream flow of the Guadalupe River. Future scenarios of hydrologic change and population growth are simulated and factors that influence vulnerability to water shortages, including hydrology, location in the basin, and permit seniority, are examined. In addition, tradeoffs between water portfolio cost and reliability are explored. Simulation results indicate that municipal agents in the upper and middle portion of the basin are more vulnerable to water shortages, especially for dry and historic hydrology scenarios. Municipal agents that hold junior permits are also more susceptible, and vulnerability to water shortages is exacerbated by population growth in the basin. Adaptive water management, however, is shown to effectively reduce the frequency and magnitude of municipal water shortages in the basin. This modeling framework can be applied to study decentralized water management strategies and water resources dynamics in other river basins.

Simulating the Selection of Municipal Water Supply Portfolios to Assess Vulnerability in a Seniority-based Water Rights Program

by
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## BIOGRAPHY

Michelle received her Bachelor of Science in Integrated Science and Elementary Education from Grand Valley State University. After she graduated, she moved to Durham, North Carolina, and she taught 1st – 3rd grade for three years at a public Montessori school. Michelle decided to pursue a career as an environmental engineer because of the dynamic and rigorous nature of the field. The fields of elementary education and environmental engineering are distinctly different, however, Michelle's career goal has remained the same; she wants to improve people's quality of life. She is particularly interested in developing innovative solutions for the growing pressures on water resources and she plans to use what she has learned from her graduate studies to support sustainable water management practices.

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# CHAPTER 1: INTRODUCTION AND OBJECTIVES

## 1.1 Motivation

Municipalities compete with agricultural, industrial, and other water users for limited water resources in arid river basins. Climate change is predicted to affect the spatial and temporal availability of water resources (IPCC, 2013), which will intensify the competition for water in a shared river basin. Rapidly growing populations and water demands are expected to further complicate municipal water management decisions (Vorosmarty et al, 2000). A municipality can build a portfolio of water supply sources and demand management strategies to provide water for and to reduce growing demands. A municipal water portfolio may include permitted surface water, groundwater, purchased water, recycled wastewater, and water conservation measures. Municipalities can adapt their water portfolio decisions in response to population dynamics and fluctuations in the costs of water sources and conservation practices.

In the eastern U.S., municipalities gain access to water rights through riparian laws, which state that landowners whose property is adjacent to a body of water have the right to make reasonable use of it as it flows through or over their property. In western states, however, water rights are defined following the law of Prior Appropriation, which states that the first actor to withdraw water from a source for beneficial use has the right to continue to use the same quantity of water for the original purpose (Kaiser, 2002). Seniority-based water permit programs have been developed in a number of states in the western part of the U.S. to allocate water resources following the law of Prior Appropriation.  In these arid regions, high variations in surface water flow can significantly affect the volume of water available for a permit-holder. During periods of drought, senior permit holders may deplete the surface water supply, and junior permit holders may not receive water as expected. The use of surface water permits in a municipal water supply portfolio creates distinct vulnerabilities to unpredictable water shortages, and water availability for many cities may be subject to the surface permit ownership and withdrawals of other municipalities and actors in a river basin. Adaptive municipal water management may prevent water shortages for municipalities that rely on surface water with seniority-based permits in shared river basins. Municipalities can strategically update their water portfolios as they respond to and attempt to prevent water shortages.

Shared river basins exhibit features of a complex adaptive system. Heterogeneous, autonomous municipalities build their water portfolios based on population projections, and water supply and demand management costs. Cities interact through the water right permit system and their collective actions affect the spatial and temporal occurrence of water shortages in a river basin. Municipalities can adjust their water management practices in response to the hydrologic environment and the water management decisions of the other municipalities in the basin. Complex adaptive systems, including a seniority-based water rights permit system, can be simulated using agent-based modeling (ABM), which represents interacting actors in a shared environment as agents that act and react based on a set of mathematical and logical rules.

## 1.2 Objectives

The objectives of the research presented here are to

1. Develop an ABM framework to simulate decentralized municipal water management in a seniority-based water rights permit system,
2. Explore factors of location, hydrology, permit seniority, population growth, and municipal water management strategies on municipal vulnerability to water shortages, and
3. Use simulations of conventional and adaptive municipal water management strategies to develop tradeoffs between water portfolio cost and water reliability.

## 1.3 Summary

This research develops an ABM framework to explore the effect of decentralized municipal water management practices on water availability in a basin that is governed by a seniority-based permit program. Municipalities in a basin are represented as agents that exert water demands as the residential population grows over a long-term planning horizon. Municipal agents use rules to update their water supply portfolios as demands grow and the cost of sources fluctuates. Three versions of the ABM are developed and demonstrated to represent conventional water management and two adaptive water management strategies. The conventional management strategy uses cost information alone and selects water supply sources and conservation measures using a local least-cost optimization algorithm. The adaptive portfolio selection strategies, which are modifications of the original strategy, allow municipal agents to consider past water shortages when planning for the future. In these versions of the model, municipal agents learn from the outcomes of their previous management practices. Agents modify their portfolio selection strategy during the simulation to reduce the likelihood of future water shortages. Population growth and hydrology scenarios are simulated to explore factors that impact municipal vulnerability to water shortages.

# CHAPTER 2: BACKGROUND

## 2.1 Water Portfolio Selection Strategies

Identifying a water supply portfolio by selecting from alternative municipal water sources is a challenging task, due to multiple objectives and uncertainties in water availability. Optimization models have been developed and applied to identify feasible water portfolios and select among alternative portfolios. Characklis et al. (2006) applied objectives of cost and reliability to identify water portfolios that included permanent and leased water supplies. The same objectives were applied to select an urban water management plan that could facilitate projected demand growth (Kirsch et al, 2009). Another study applied cost and reliability optimization models to select portfolios based on robustness, defined as the ability to perform well across a wide range of future conditions (Matrosov, 2012).

Adaptive approaches for selecting water portfolios may be more effective than conventional approaches in maintaining water supply reliability. For example, a municipality may evaluate if their strategy satisfies their objective, such as preventing water shortages. If the current management strategy does not satisfy the objectives, then the municipality can modify the current strategy and evaluate the performance of the new strategy. Several iterations of adapting a water portfolio selection strategy may improve the ability of a water agency to satisfy their planning objectives.

## 2.2 Seniority-based Water Rights

Local water regulations govern the development of water supply portfolios and may limit the options of municipalities in a shared water basin. In several western states, surface water rights are allocated to municipal, agricultural, and industrial water users following the Prior Appropriation Doctrine (Kaiser, 2002), which prioritizes water rights as "first in time, first in right." In a seniority-based water allocation system, users are granted perpetual water rights permits that specify the year of the water right, allowable annual withdrawal, and diversion location.

In some river basins, the total volume of flow allocated through permits exceeds the mean annual stream flow in the basin (Texas Commission on Environmental Quality, 2014b). During a drought, the governing state may temporally suspend junior water rights permits, which may be identified as permits that were issued after a selected date, and municipalities holding recently awarded permits may be vulnerable to surface water shortages (Texas Commission on Environmental Quality, 2014a). For example, water right permits have been identified as a key element that causes municipal water shortages in the Willamette Basin, Oregon (Hersh & Wernstedt, 2002). Permit seniority, therefore, must be considered when examining the likelihood and characteristics of water shortages for municipalities.

Water portfolio planning must take into account the limits imposed by a water rights permit system, and the water portfolio decisions of multiple cities within the basin, since those decisions alter the spatial and temporal occurrence of water shortages in a river basin. For example, a municipality may choose to switch its portfolio from groundwater to surface water because the surface water is less expensive and the city holds relatively senior surface water permits. A junior permit holder may, simultaneously, require more water resources to support rapidly growing municipal water demands; the junior permit holder may need to seek water resources in addition to surface water because their junior rights may be suspended in a dry year due to the priority given to senior permits.

### 2.3 Complex Adaptive Systems and ABM

Complex Adaptive Systems (CAS) are comprised of interconnected entities, or agents, and the microscopic behaviors of agents collectively generate phenomenon at the macroscopic level (Holland, 1992). Agent actions are nonlinear and influence one another's behavior. Furthermore, the preferences and behaviors of the entities in the system are dynamic, and change in response to other agents' behaviors and to the environment. The system dynamics and complex, nonlinear interactions between the entities in the system lead to the emergence of unpredictable phenomenon at the system level (Holland, 1992).

Classic analytical, empirical, and numerical models employ top-down approaches to model system dynamics, and these models are often appropriate tools for studying dynamical systems. These conventional simulation methods do not capture the complexities of CAS because the interactions of the entities are not represented, and a bottom-up approach is more appropriate for studying a CAS. An ABM can be used to simulate a CAS that is comprised of entities, or agents, that share information or resources. Within an ABM simulation, agents act in response to the behaviors of the other agents in the system and to the environment. Agents can act in a reactive or active manner. Reactive agents use information about their current state or experience in the system and change their behavior accordingly. For example, a reactive municipal agent may implement an outdoor watering restriction rule if a drought occurs. Active agents are, conversely, objective-oriented; the active municipal agent may choose to implement incentives for water-efficient appliances in an effort to prevent droughts. Both reactive and active agents are rational and make decisions based on predetermined rules.

ABMs have been applied to study a wide range of topics in diverse disciplines. For example, ABMs have been used to simulate financial markets (Kim & Kim, 2014), political election markets (Yu & Chen, 2012), urban traffic dynamics (Manley et al, 2014), animal movement (Tang & Bennett, 2010), disease and public health risk (Nianogo & Onyebuchi, 2015), and opinion transmission (Rouchier et al, 2014). ABMs have also been developed and applied to study socio-technical water resources systems. Several models have been designed for the purpose of studying water quantity issues at both the municipal and river basin scales. For example, ABMs have been used to simulate residential water demands (Athanasiadis et al, 2005) and to model consumers' water use behaviors following the implementation of water conservation programs (Rixon & Burn, 2002). Another study simulated consumers that adopt water efficient appliances in response to the reservoir drought-stage and their communication with other water consumers (Berglund, 2015). At the river basin level, an ABM has been used to explore strategies for mitigating water resources conflicts (Akhbari & Grigg, 2013). Water quality management problems have also been studied using ABMs. For example, ABMs have been encoded to represent nutrient permit markets, which are used to control nutrient discharges to impaired waters (Berglund 2015;

Xiang et al, 2011), and to identify effective hydrant flushing strategies to respond to contaminants in water distribution systems (Shafiee & Berglund, 2015).

Relatively few works have applied an ABM approach to study local water management strategies and the emergent water resources dynamics in a shared river basin. Decentralized water management was simulated for a hypothetical river basin comprised of autonomous municipal water users and river agents (Yang, 2009). Similarly, ABM was used to study cooperation and collaboration between independent water users in the Zambezi River Basin, Africa (Giuliani & Castelletti, 2013). This research develops and evaluates rules that represent adaptive water management through simulation of rules within an ABM framework. Several municipalities are simulated to simultaneously select water portfolios. Agents use a linear programming model to dynamically optimize decentralized municipal water portfolios using updated water supply costs and reliability metrics. Municipalities share a common water resource and co-adapt their portfolios to improve the reliability of their water supplies.

# CHAPTER 3: METHODS

## 3.1 ABM Framework for a Shared River Basin

An ABM framework is developed to simulate decentralized municipal water management decisions in a shared river basin (Figure 3.1). The ABM is programmed in MASON, a discrete-event multi-agent simulation library core in Java (Luke, 2004). Each municipal agent uses a linear programming model to identify a least-cost portfolio of water supply sources and water conservation practices to provide water for projected municipal demands. Municipal agents plan to use surface water supplies by exercising their own surface water right permits or by purchasing surface water from a river authority agent. If the volume of water allowed by a permit cannot be supplied due to the seniority of a water right, the municipal agent does not receive the water and experiences a water shortage. The river authority agent represents a public utility company that holds a significant amount of surface water rights permits in the river basin. The river authority agent diverts water from the river to sell to the municipal agents.

The ABM is coupled with the Water Rights Analysis Package (WRAP), which simulates a seniority-based surface water rights program in a naturalized hydrologic context. The planned permitted diversions of the municipal agents, river authority agent, and the agricultural and industrial permit holders in the river basin are used as input parameters for WRAP. Municipal agents receive information about their annual surface water supplies and surface water shortages from WRAP. In the adaptive versions of the model, municipal agents learn from these feedbacks, and adapt their water portfolio selection strategy in an effort to choose a more reliable water portfolio for the upcoming year.

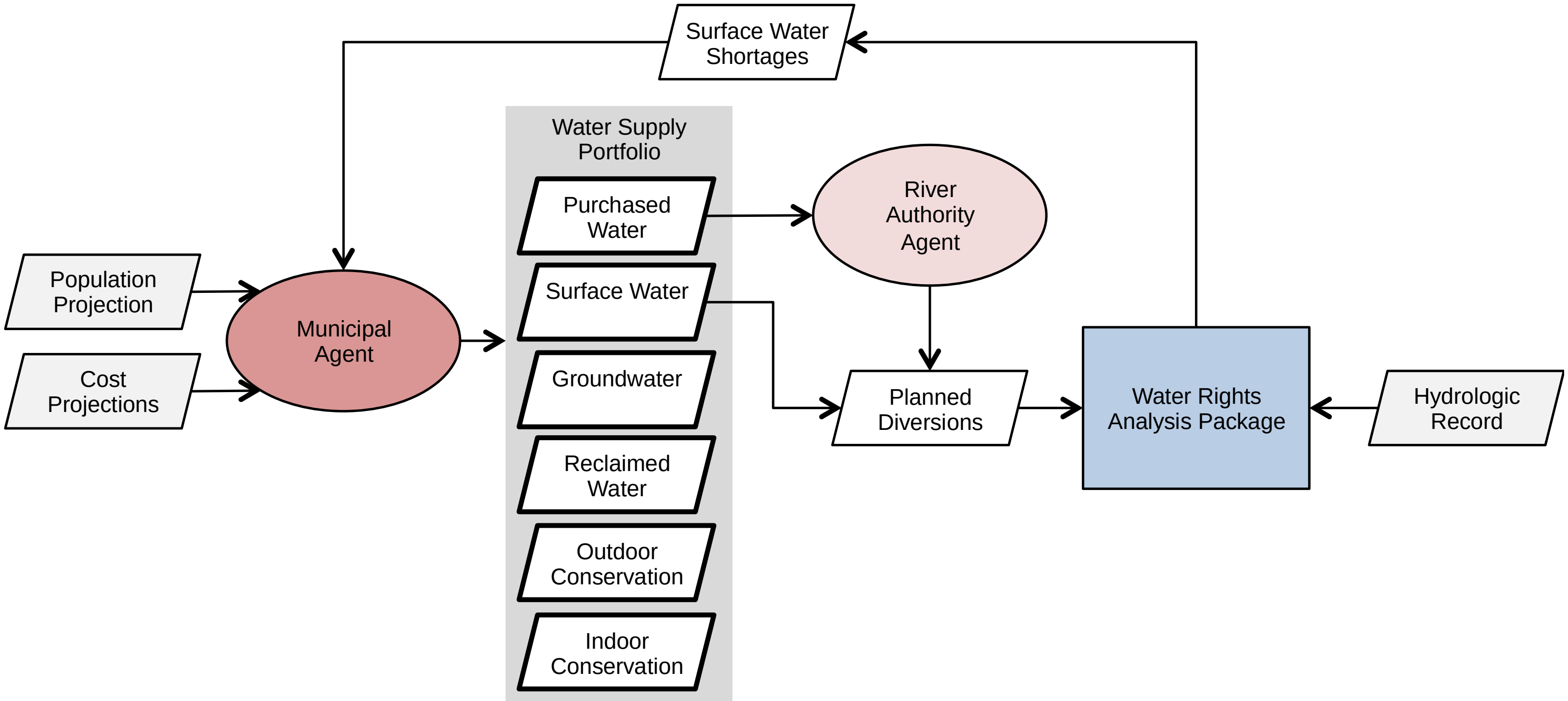



**Figure 3.1** An ABM framework to simulate municipal water portfolio selection strategies in a seniority-based water rights program. Bold parallelograms represent decisions made by municipal agent. Multiple municipal agents may be included in the framework.

The ODD (Overview, Design concepts, Details) was developed as a common method for describing an ABM (Grimm et al, 2006), and the protocol is applied to define the research methods of this study. The Overview describes the model *purpose, state variables* (i.e. agent behaviors and attributes), spatial and temporal *scales*, *process overview* and the model *schedule*. The Design concepts section explains the features of the model that are common among complex adaptive systems. Design concepts that are addressed include *emergence, adaptation, objectives, interaction,* and *observation.* In the Details section, the *initialization* of the model and the model *inputs* are introduced.

### 3.1.1 Overview

The *purpose* of this ABM is to explore factors that may affect municipalities' vulnerability to water shortages; these include (I) hydrology-induced changes in stream flow; (II) location of a municipality in the river basin; (III) water right seniority; and (IV) population growth. In addition, both conventional and adaptive portfolio selection strategies are encoded to explore the extent to which a municipality can effectively reduce its vulnerability to water shortages by evolving its water supply portfolio. Moreover, results from the ABM simulations are used here to analyze tradeoffs between water portfolio cost and reliability.

The *scale* of the model encompasses a large land area, because the ABM is designed to simulate municipalities within a shared river basin. Municipal water decisions are modeled for a long-term planning horizon using an annual time step. Heterogeneous municipal agents have several *state variables* (Table 3.1). The state variables characterize both the behavioral attributes and properties of an agent. Properties are dynamic states of municipal agents, represented by parameter values. For example, population is encoded as a state variable according to the population projections of the municipality. Behavioral attributes represent the choices of the municipal agents and in this model behavioral attributes are used to convey the water supply portfolio selected by a municipal agent each year. In Table 3.1, two behavioral attributes are listed to represent the water supply sources and water conservation practices selected by municipal agents.

The river authority agent sells surface water resources to the municipal agents. The state variables of the river authority agent include a location within the basin, the number and year of surface water permits allowing withdrawal of water from the surface water body, and the market price of water.

**Table 3.1** Properties (P) and behavioral attributes (B) of municipal agents

| State Variable | Brief description |
|---|---|
| *Location (P)* | Geographic position in the river basin |
| *Population (P)* | Municipal population projection used to calculate the municipal water demand |
| *Per capita water demand (P)* | Water demand of each citizen used to calculate the municipal water demand |
| *Surface water permits (P)* | Permits specify the volume, location, and year of right to surface water resources |
| *Groundwater limit (P)* | Maximum volume of groundwater an agent can pump from the underlying aquifer |
| *Water supply costs (P)* | Collective capital, operation, and maintenance cost to a municipality to divert, treat, and deliver a unit of water. Unit costs of surface water, groundwater, purchased water, and recycled water supplies differ |
| *Indoor conservation cost (P)* | Average unit cost of retrofitting residential plumbing fixtures to conserve a set volume of water per year |
| *Outdoor conservation cost (P)* | Average unit cost of alternative residential lawn watering methods to conserve a set volume of water per year |
| *Surface water shortage (P)* | Volume of water an agent did not receive as expected |
| *Percent leakage (P)* | Percent of water leaked by the distribution system |
| *Water supply portfolio (B)* | Volumes of surface water, groundwater, purchased water, and recycled wastewater that the agent uses to deliver water for municipal demands |
| *Water conserved (B)* | Volume of water an agent conserves with indoor and outdoor conservation measures |

The *process overview* and *schedule* of the ABM, which is repeated at each time step, is encoded as follows:

Step 1: Municipal agents evaluate water demands

Each municipal agent applies its projected population and historical per capita water demand to calculate annual municipal water demand as follows:

$$D_{m,i} = P_{m,i} d_m \tag{1}$$

where $D_{m,i}$ is the total water demand of municipality $m$ for year $i$ [ac-ft]; $P_{m,i}$ is the projected population of municipality $m$ for year $i$; and $d_m$ is the per capita water demand of the municipality.

Step 2: River authority agent establishes available water for purchase

The river authority agent sets the amount of water available for purchase as follows:

$$P = \frac{if\ T = 0,\ \ X}{if\ T > 0,\ \ X - T} \tag{2}$$

where $P$ is the amount of water for sale by the river authority agent [ac-ft/yr]; $T$ is the total amount of water that has been purchased by the municipal agents this year [ac-ft/yr]; and $X$ is the surface water rights of the river authority agent [ac-ft/yr].

Step 3: Municipal agents select water portfolio

A municipal agent updates its respective unit costs of surface water, groundwater, reclaimed wastewater, and water conservation measures according to projected values, which are specific to the municipality and year. The river authority shares information about the unit price and availability of water that can be purchased. The amount of water that is for sale is equal to the amount of surface water permits held by the river authority less the amount of water that has been purchased previously by other municipalities in the basin, in that same year (Step 2). The agent applies a linear programming model to identify a least-cost water supply portfolio to provide water for its municipal demand as follows:

$$Minimize \sum_{s=1}^{6} S_{s,i} C_{s,i} \tag{3}$$

*subject to*

$$\sum_{s=1}^{6} S_{s,i} = D_{m,i}$$

$$S_{s,i} \geq 0 \ \ \forall_s$$

$$S_{surface,i} \leq \ W_m$$

$$S_{ground,i} \leq G_{limit,m} A_m$$

$$S_{purchased,i} \leq \ P_i$$

$$S_{indoor\_con,i} \leq I\beta$$

$$S_{outdoor\_con,i} \leq O\alpha$$

$$S_{reclaimed,i} \leq NR_{m,i}(1 - L_m)$$

where $S_{s,i}$ is the amount of source *s* used at year *i* [ac-ft/yr]; $C_{s,i}$ is the cost of source *s* at year *i* [$/ac-ft]; $W_m$ is the surface water permits of municipality *m* [ac-ft/yr]; $G_{limit,m}$ is the groundwater production limit for the major aquifer used by municipality *m* [ac-ft/ac/yr]; $A_m$ is the area of municipality *m* [ac]; $P_i$ is the amount of water for sale by the river authority agent for year *i* [ac-ft/yr]; *I* is the indoor residential demand [ac-ft/yr]; $\beta$ is the maximum percent reduction of the indoor residential demand that can be achieved with plumbing retrofits; *O* is the outdoor residential demand [ac-ft/yr]; $\alpha$ is the maximum percent reduction of the outdoor residential demand that can be achieved with watering restrictions; *N* is the percent of the water supplied for non-consumptive uses; $R_{m,i}$ is the maximum possible inflow to the wastewater facility that year calculated as $S_{surface} + S_{ground} + S_{purchased}$ for municipality *m* for year *i* [ac-ft/yr]; and $L_m$ is the percent leakage of the water distribution system of municipality *m*.

Steps 2 and 3 are scheduled as a cycle. First, the river authority agent sets the amount of water available for purchase equal to its surface water rights permits as indicated in Step 2. Then a municipal agent is selected at random to build its water supply portfolio in Step 3. Before the next agent is selected to build its water supply portfolio, the river authority agent will update the amount of water available for purchase following the rule in Step 2. Step 4 is initiated after all of the municipal agents have selected water supply portfolios.

Step 4: Municipal Agents plan use of surface water permits

A municipal agent attempts to avoid water shortages by exercising its most senior water right permits. A municipal agent ranks its permits in ascending order by the year the permit was issued. For example, consider a municipal agent that was awarded surface water rights permits in 1914, 1952, and 1997 to meet a demand of 700 ac-ft/yr (Table 3.2). The municipal agent selects to use its permits in order from its most senior permit to its most junior permit. This process is terminated when the planned surface water diversion, established in the municipal agent's water supply portfolio, equals the planned permit use. If a municipal agent planned to use 700 ac-ft/yr of surface water and holds permits as shown in Table 3.2, the agent would use 150 ac-ft/yr and 550 ac-ft/yr from its 1914 and 1952 permits, respectfully. The remaining water right permits are not exercised that year.

**Table 3.2.** Permit use strategy of a hypothetical municipal agent that plans to divert 700 ac-ft/yr from the surface water system

| Permit Year | Allocated Diversion [ac-ft/yr] | Planned Permit Use [ac-ft/yr] |
|---|---|---|
| 1914 | 150 | 150 |
| 1952 | 2,000 | 550 |
| 1997 | 600 | 0 |

Step 5: Municipal agents receive information about water shortages

An agent receives information about its annual surface water supply and surface water shortage from the Water Right Analysis Package (WRAP). The sub-model that is executed by WRAP to establish municipal surface water supplies and shortages is described in Section 3.2. In this modeling framework, a municipal water shortage is defined as the volume of surface water that a municipal agent expects to withdraw from the surface water resource but does not receive, as allocated by WRAP, due to seniority-based water right regulations. If a municipal agent experiences a surface water shortage in a particular year, the municipal agent does not supplement the shortage with alternative supply sources or demand management strategies that year.

Step 6: Municipal agents adapt water supply portfolio selection strategy

Using a conventional water management strategy, municipal agents select a least-cost water supply portfolio each year, regardless of if they have experienced recent water shortages, and the agents neglect Step 6. Two adaptive water management rules are developed here to impose additional restrictions on surface water use, based on water shortages in the recent past.

A permit-based adaptive water management strategy limits the amount of surface water that a municipal agent can allocate by adjusting the original surface water constraint in the least-cost programming model. A municipality restricts the amount of surface water that can be used based on the number of permits it holds, minus the recent five-year annual average water shortage:

$$S_{surface,i} \leq W_m - F_m \quad (4)$$

where $S_{surface,i}$ is the maximum amount of surface water that can be used to supply water in year $i$ [ac-ft/yr]; $W_m$ is the surface water permits of municipality $m$ [ac-ft/yr]; and $F_m$ is the average annual surface water shortage over the past five years for municipality $m$ [ac-ft/yr].

Using a supply-based adaptive water management strategy, a municipal agent limits its annual surface water use to the average annual amount of surface water that was supplied over the past five years. This constraint represents that a utility limits is use of surface water permits based on the actual water that was received, and not on the volume of water allowed by the permits.

$$S_{surface,i} \leq J_m \quad (5)$$

where $J_m$ is the annual average volume of water the municipality was supplied from the seniority-based permit system in the past five years [ac-ft/yr].

### 3.1.2 Design Concepts

The ABM is designed to allow a modeler to *observe* the unpredictable spatial and temporal occurrence of water shortages in the river basin. Factors that influence water availability at the municipal and river basin levels are observed as water shortages that emerge during the ABM simulation. *Emergence* of water shortages is collectively and nonlinearly influenced by factors of hydrology, location, permit seniority, population growth, and the decentralized water management decisions of the municipal agents. The municipal agents are *stochastically* selected to build their water supply portfolios because the volume of water available for purchase from the river authority agent is limited. The river authority agent could, for example, sell all of its water supplies to the first few municipal agents. The remaining municipal agents would not have the option to purchase water supplies. This scenario is likely in a competitive water market. Municipal agents *adapt* their water portfolios according to fluctuations in water supply and demand management costs and in response to population dynamics. Using adaptive rules (permit-based and supply-based water management strategies), the agents also *adapt* their portfolios in response to shortages, which are established as the agents *interact* through the surface water permit system. The adaptive municipal water managers are encoded to seek a relatively inexpensive and reliable water portfolio. Agents rationally build their water supply portfolios according to dual *objectives* of cost and reliability.

### 3.1.3 Details

Municipal agents are *initialized* and assigned surface water permits, per capita water demands, and aquifer-based groundwater production limits based on the attributes of the modeled municipalities. The river authority agent is encoded with surface water permits and the associated unit price to sell surface water to the municipal agents. At each time step, the projected municipal population, forecasted water supply costs, and projected water conservation costs of each municipality are used as *input* to the model.

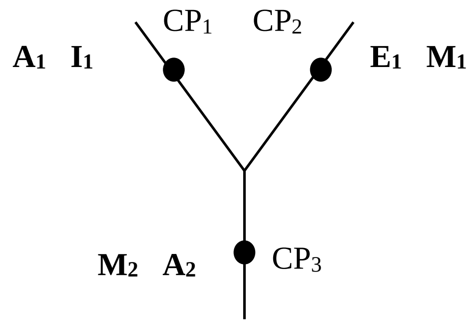
## 3.2 Simulating a Seniority-based Surface Water Rights System

The Water Rights Analysis Package (WRAP) simulates a seniority-based surface water rights permit system in a naturalized hydrologic context, and anthropogenic effects on historic stream flows have been removed. At the start of a simulation, the naturalized stream flow is established at several control points, based on hydrologic data corresponding to the simulation year. The annual surface water target, or planned permit use, of each agricultural, industrial, and municipal water user is used as input to WRAP. These values are then divided into monthly surface water diversion targets using predetermined monthly use coefficients, which are specific to user types, including municipal, industrial, and agricultural users. Municipal coefficients reflect the seasonality observed in city demands. Each diversion target is assigned to a control point in the basin based on the terms of the respective permit. The return flow is calculated as a permit-specific fraction of the water that is diverted from the river. In addition to the diversion-based permits, environmental stream flow permits have been issued for some control points. Environmental permits are allocated to maintain adequate flow in the river to protect the health of aquatic ecosystems and to protect recreational waters.

A hypothetical seniority-based water rights system is used to describe the processes applied in WRAP to establish the water supplies and shortages for the permit holders in the river basin (Figure 3.2). For simplicity, monthly consumable water targets (diversion target less return flow) are used in the example presented here. The water rights permits are ranked first by permit year, and subsequently, permits of the same year are ranked from most upstream to most downstream diversion location. Permitted water diversions are simulated beginning with the earliest, most upstream permit, which is agriculture permit $\mathbf{A_1}$ in this example. The stream flow is reduced at the control point where the diversion occurs and at downriver control points but not at the control points of the other tributaries. This process is repeated for all permits in the system in priority order. Permits experience water shortages when the stream flow at the point of diversion has been depleted.

Given the hydrologic conditions in the basin and behaviors of the permit holders in the system, municipality $\mathbf{M_1}$ experiences a water shortage (Figure 3.2). This shortage occurs because the seniority date of the water right permit held by $\mathbf{M_1}$ is junior to all other permits, and because more senior permit-holder $\mathbf{E_1}$ chose to utilize its permits to divert water from the shared tributary.

The water supplies of $\mathbf{M_1}$ and $\mathbf{M_2}$, 5 and 15 units of water, and water shortages of $\mathbf{M_1}$ and $\mathbf{M_2}$, 2 and 0 units of water, respectively, are calculated by the surface water model (such as WRAP), and the data are passed to the agents (Step 5 of the ABM schedule). The agents ignore this feedback in simulations where the conventional portfolio selection strategy is used. When an adaptive portfolio selection strategy is applied, municipal agents consider the frequency and magnitude of their water shortages when building a water supply portfolio for an upcoming year (Step 6 of the ABM schedule).




| **Permit Holder (ranked by seniority)** | **Permit Year** | **Monthly Consumable Diversion Target [acre/ft/month]** | **Stream flow** | | |
|---|---|---|---|---|---|
| | | | **$CP_1$** | **$CP_2$** | **$CP_3$** |
| | | | 100 | 15 | 130 |
| Agriculture **$A_1$** | 1936 | 15 | 85 | 15 | 115 |
| Agriculture **$A_2$** | 1936 | 12 | 85 | 15 | 103 |
| Industry **$I_1$** | 1950 | 50 | 35 | 15 | 53 |
| Municipality **$M_2$** | 1985 | 20 | 35 | 15 | 33 |
| Environmental Flow **$E_1$** | 2001 | 10 | 35 | 5 | 33 |
| Municipality **$M_1$*** | 2005 | 7 | 35 | 0 | 33 |
| **Water shortage* | | | | | |

**Figure 3.2** A hypothetical simulation of a seniority-based water rights permit system

# CHAPTER 4: CASE STUDY

## 4.1 The Guadalupe River Basin, Texas

The Guadalupe River Basin spans 3,256 $km^2$ across southeast Texas (Figure 4.1). The headwaters of the Guadalupe River begin in Kerr County, Texas, and the river flows southwest, merges with the San Antonio River, and discharges into the Gulf of Mexico at the San Antonio Bay (Yongsheng, 2012). The Guadalupe River Basin was selected as a case study because the collective population of the ten municipalities in the river basin is projected to double before 2060. While municipal water demands are projected to increase, municipal surface water supplies are threatened by climate change-induced droughts and seniority of other permit-holders in the basin.  The water rights permits that have been allocated to the municipal, agricultural, industrial and other water users in the basin, in total, exceed the mean annual stream flow of the Guadalupe River (Texas Commission on Environmental Quality, 2014b). During a persistent drought, it is expected that the Guadalupe River will not be able to supply surface water to all of the existing water rights holders in the river basin (Texas Commission on Environmental Quality, 2014a). The Texas Commission on Environmental Quality (TCEQ) manages the surface water rights in the basin and has the authority to temporally suspend junior water rights when surface water supplies are stressed.

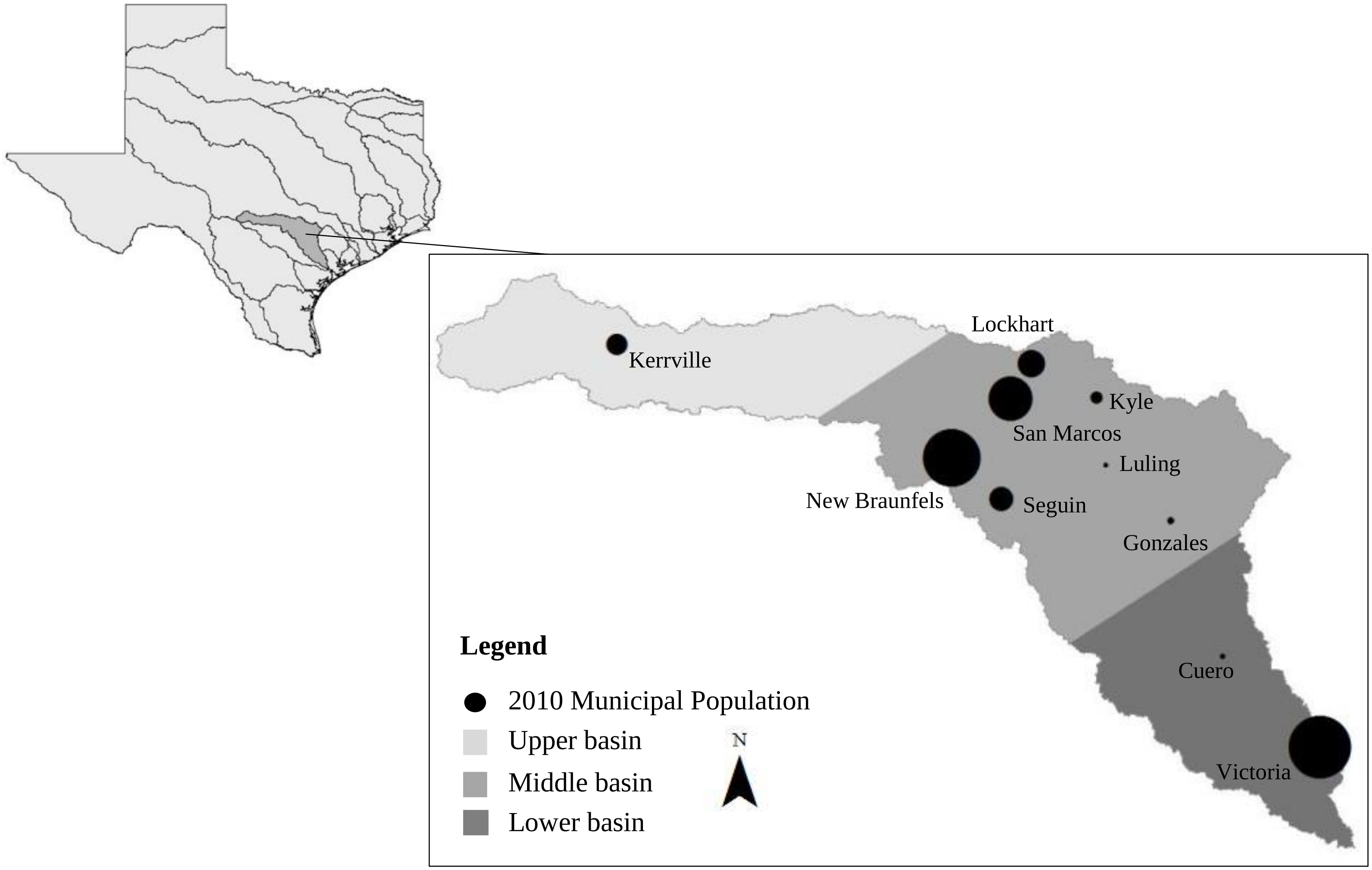



**Figure 4.1** Municipalities in the Guadalupe River Basin, Texas

The water management decisions of the municipalities in the Guadalupe River Basin are simulated using the ABM framework for the planning horizon 2010-2060. Ten municipal agents are created to represent the cities of Victoria, New Braunfels, San Marcos, Kyle, Seguin, Kerrville, Lockhart, Gonzales, Cuero, and Luling. The average 2000-2010 per capita water demand of each municipality (Texas Water Development Board, 2015b) and decadal population projections (Texas Water Development Board, 2015a), which are interpolated to annual values, are applied to model annual municipal water demands (Table 4.1). Projected unit costs of water supply sources and water conservation measures for each municipality (Tables 4.2 and 4.3, respectively), aquifer-based groundwater production limits (Table 4.4), the estimated percent of the water supply for non-consumptive use (70%), the estimated percent of the municipal water demand for residential use (85%), and the estimated percent leakage of each municipal water distribution system were collected from the regional water plan (South Central Texas Regional Water Planning Group, 2010). Each municipal agent is initialized with existing surface water rights (Texas Commission on Environmental Quality, 2014b). The maximum per capita demand reduction that can be achieved by retrofitting plumbing fixtures in residential properties (33% of indoor end-uses) and by limiting residential lawn watering (40% of outdoor end-uses) were applied for the indoor and outdoor water conservation restrictions, respectively (American Water Works Association Research Foundation, 1999).

**Table 4.1** Historic average per capita water demand from 2000-2010 and population projections for municipalities in the Guadalupe River Basin, Texas

| | **Per capita water demand (gpcd)** | **Population** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **2010** | **2020** | **2030** | **2040** | **2050** | **2060** |
| **Victoria** | 154 | 62,592 | 67,787 | 72,496 | 76,201 | 79,501 | 82,211 |
| **New Braunfels** | 176 | 57,740 | 72,982 | 90,609 | 108,532 | 126,546 | 144,500 |
| **San Marcos** | 133 | 44,894 | 71,117 | 84,818 | 101,159 | 120,648 | 143,892 |
| **Kyle** | 103 | 28,016 | 50,808 | 77,050 | 92,000 | 92,000 | 92,000 |
| **Seguin** | 192 | 25,175 | 30,675 | 36,879 | 43,227 | 49,436 | 55,756 |
| **Kerrville** | 173 | 22,347 | 23,319 | 24,209 | 24,736 | 25,258 | 25,633 |
| **Lockhart** | 129 | 12,698 | 15,680 | 19,198 | 22,668 | 26,100 | 29,568 |
| **Gonzales** | 214 | 7,237 | 7,948 | 8,741 | 9,487 | 10,352 | 11,231 |
| **Cuero** | 206 | 6,841 | 7,100 | 7,338 | 7,455 | 7,563 | 7,634 |
| **Luling** | 140 | 5,411 | 6,682 | 8,180 | 9,658 | 11,121 | 12,598 |

**Table 4.2** Projected unit costs [$/ac-ft/yr] of surface water and groundwater supplies for municipalities in the Guadalupe River Basin, Texas

| | Surface Water | Groundwater | | | | | |
|---|---|---|---|---|---|---|---|
| | | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 |
| **Victoria** | 257 | 1,823 | 1,586 | 1,349 | 1,111 | 874 | 637 |
| **New Braunfels** | 249 | 710 | 591 | 472 | 354 | 235 | 116 |
| **San Marcos** | 253 | 687 | 601 | 515 | 430 | 344 | 258 |
| **Kyle** | 259 | 710 | 591 | 472 | 354 | 235 | 116 |
| **Seguin** | 259 | 687 | 601 | 515 | 430 | 344 | 258 |
| **Kerrville** | 260 | 710 | 591 | 472 | 354 | 235 | 116 |
| **Lockhart** | 261 | 678 | 1,062 | 1,062 | 875 | 613 | 634 |
| **Gonzales** | 261 | 687 | 601 | 515 | 430 | 344 | 258 |
| **Cuero** | 261 | 1,823 | 1,586 | 1,349 | 1,111 | 874 | 637 |
| **Luling** | 262 | 687 | 1,085 | 1,085 | 456 | 446 | 776 |

**Annual unit costs were calculated based on 2008 dollars assuming a 6% interest rate and 20 year investment.*

**Table 4.3** Projected unit costs [$/ac-ft/yr] to purchase water from the Guadalupe-Blanco River Authority, reclaim wastewater, and implement indoor and outdoor water conservation practices for municipalities in the Guadalupe River Basin, Texas

| | Purchase Water | Reclaim Wastewater | Indoor Water Conservation Practices | Outdoor Water Conservation Practices |
|---|---|---|---|---|
| **Victoria** | 1,389 | 1,303 | 681 | 524 |
| **New Braunfels** | 1,389 | 1,303 | 681 | 524 |
| **San Marcos** | 1,389 | 1,303 | 681 | 524 |
| **Kyle** | 1,389 | 1,303 | 681 | 524 |
| **Seguin** | 1,389 | 1,303 | 681 | 524 |
| **Kerrville** | 1,389 | 1,303 | 681 | 524 |
| **Lockhart** | 1,389 | 1,303 | 681 | 524 |
| **Gonzales** | 1,389 | 1,303 | 770 | 524 |
| **Cuero** | 1,389 | 1,303 | 770 | 524 |
| **Luling** | 1,389 | 1,303 | 770 | 524 |

**Annual unit costs were calculated based on 2008 dollars assuming a 6% interest rate and 20 year investment.*

**Table 4.4** Aquifer-based groundwater production limits [ac-ft/yr], surface water rights permits (as of 2014) [ac-ft/yr], and estimated percent water leakage in the water distribution systems for municipalities in the Guadalupe River Basin, Texas

| | Groundwater Production Limit | Surface Water Rights Permits | Percent Leakage of Distribution System |
|---|---|---|---|
| **Victoria** | 10,592 | 21,260 | 12.9 |
| **New Braunfels** | 57,600 | 6,947 | 16.2 |
| **San Marcos** | 14,560 | 10,150 | 14.2 |
| **Kyle** | 8,340 | | 14.8 |
| **Seguin** | 6,144 | 7,000 | 14.8 |
| **Kerrville** | 24,336 | 5,916 | 15.0 |
| **Lockhart** | 9,040 | | 15.0 |
| **Gonzales** | 6,528 | 2,240 | 35.1 |
| **Cuero** | 3,200 | | 36.5 |
| **Luling** | 4,400 | | 10.0 |

Four municipalities in the basin do not hold surface water rights permits, including Kyle, Lockhart, Cuero and Luling. These cities are included in the simulation because they have the option to purchase surface water resources from the river authority agent. These diversions alter water availability in the basin and, therefore, can generate water shortages for other municipal water users. The targeted water diversions of the industrial, irrigation, and hydropower permit holders are simulated according to the full authorization of their water rights permits. For example, the water diversion target of an industry that holds a permit for 5,000 ac-ft/yr is simulated as 5,000 ac-ft/yr.

### 4.2 Hydrologic Scenarios

Hydrologic scenarios are developed to explore municipal vulnerability to water shortages with respect to hydrologic uncertainty. A historic hydrology scenario was modeled using the hydrology of the river basin from 1934-1984. Population data and water supply cost data as projected for 2010-2060 are used as input to the ABM (i.e., hydrologic flows from 1934 correspond to population and cost data for 2010, and so forth). A repeated hydrology scenario was created by repeating the hydrologic flows from a single year over a 50-year period. Data were applied from 1934-1984 for a total of 50 repeated hydrology scenarios. For each scenario, the observed naturalized monthly flow at a set of control points, or gaged locations in the river and its tributaries, are used as input.

# CHAPTER 5: RESULTS

## 5.1. Least-Cost Water Management Portfolio Selection Strategy

### 5.1.1 Conventional Municipal Water Supply Portfolios for the Historic Hydrology Scenario

The historic hydrologic scenario was simulated, and all municipal agents use the least-cost rule for selecting water supply portfolios. Municipal agents select diverse water supply portfolios that include permitted surface water, groundwater, purchased water, reclaimed wastewater, and indoor and outdoor water conservation measures to meet growing demands (Figures 5.1(a) and 5.1(b)). The municipal agents often discontinue a water supply source or demand management strategy mid-simulation. For example, the New Braunfels municipal agent discontinues the use of surface water in its water supply portfolio in 2046. The discontinuation of a water supply source or demand management strategy is indicated by a line break in the municipal agent's water supply portfolio.

The municipal agents for New Braunfels, San Marcos, Seguin, and Gonzales use all of their surface water permits when building their water supply portfolios, because surface water is projected to be their least expensive source through almost the entire planning horizon. The San Marcos, Seguin, and Gonzales municipal agents use the maximum volume allowed by their surface water permits by the year 2017, 2041, and 2032, respectively. These three agents select alternative water supply sources to satisfy growing water demands in subsequent years. The Victoria municipal agent relies solely on surface water throughout the simulated planning horizon because surface water remains as the city's least expensive source. Victoria holds water rights permits that allow it to divert up to 21,260 ac-ft/year, which can completely satisfy the water demands through 2060. The Cuero municipal agent, on the other hand, does not hold any surface water permits and uses diverse sources, including the purchase of surface water from the river authority agent.

All of the municipal agents, except the Victoria municipal agent, use groundwater in their water supply portfolios. Groundwater is a relatively inexpensive alternative, and projected fluctuations in groundwater and surface water prices (Table 4.2) cause Seguin (Figure 5.1(a)) and Gonzales (Figure 5.1(b)) municipal agents to completely replace surface water resources with groundwater supplies in the final two years of the simulated period. Water conservation measures are used by six municipal agents, while reclaimed wastewater and purchased water supplies are selected only by the Cuero agent.

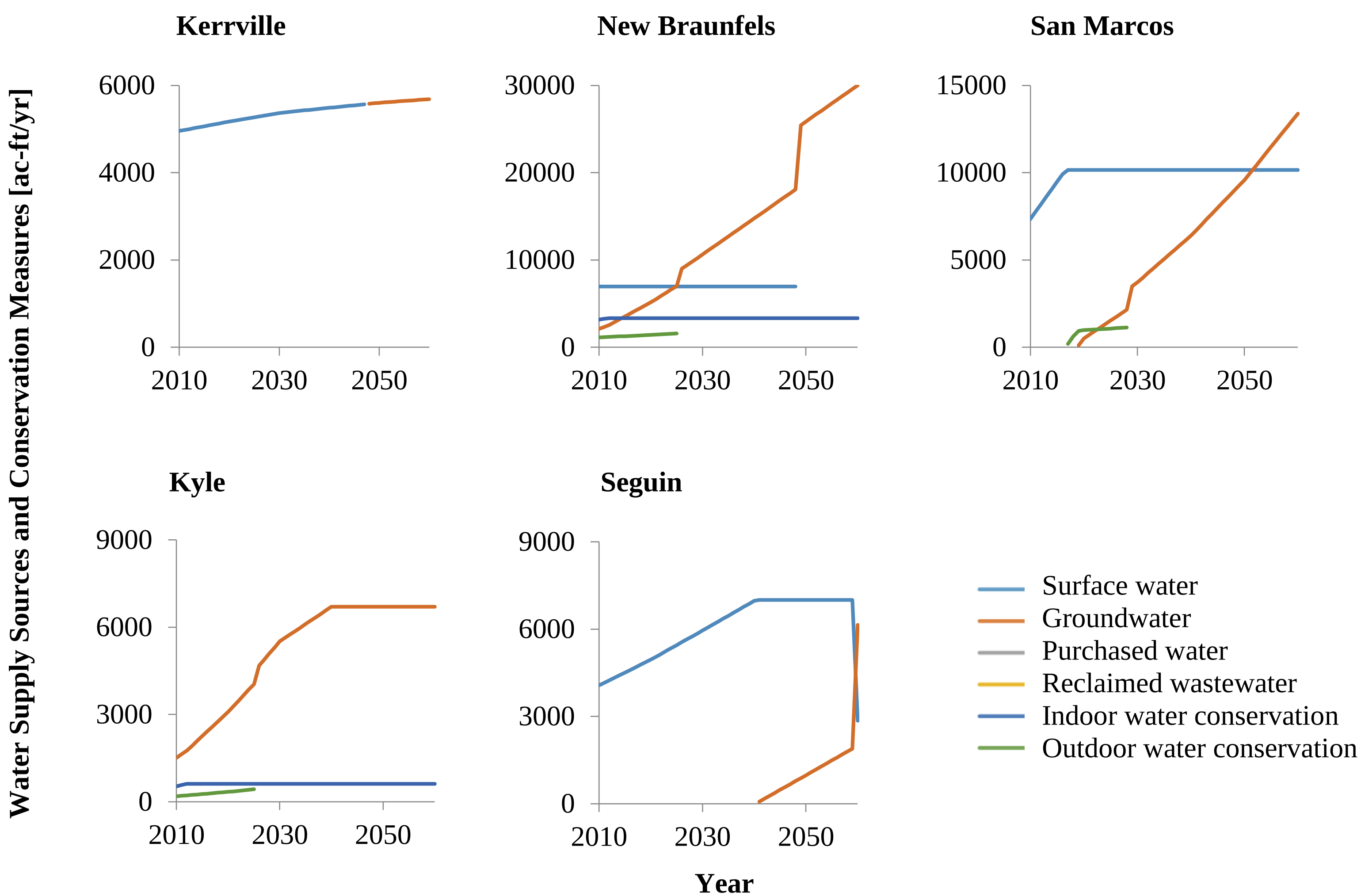



**Figure 5.1(a)** Municipal water supply portfolios from 2010-2060 for the conventional water management strategy for municipalities in the Upper and Middle Guadalupe Basin.

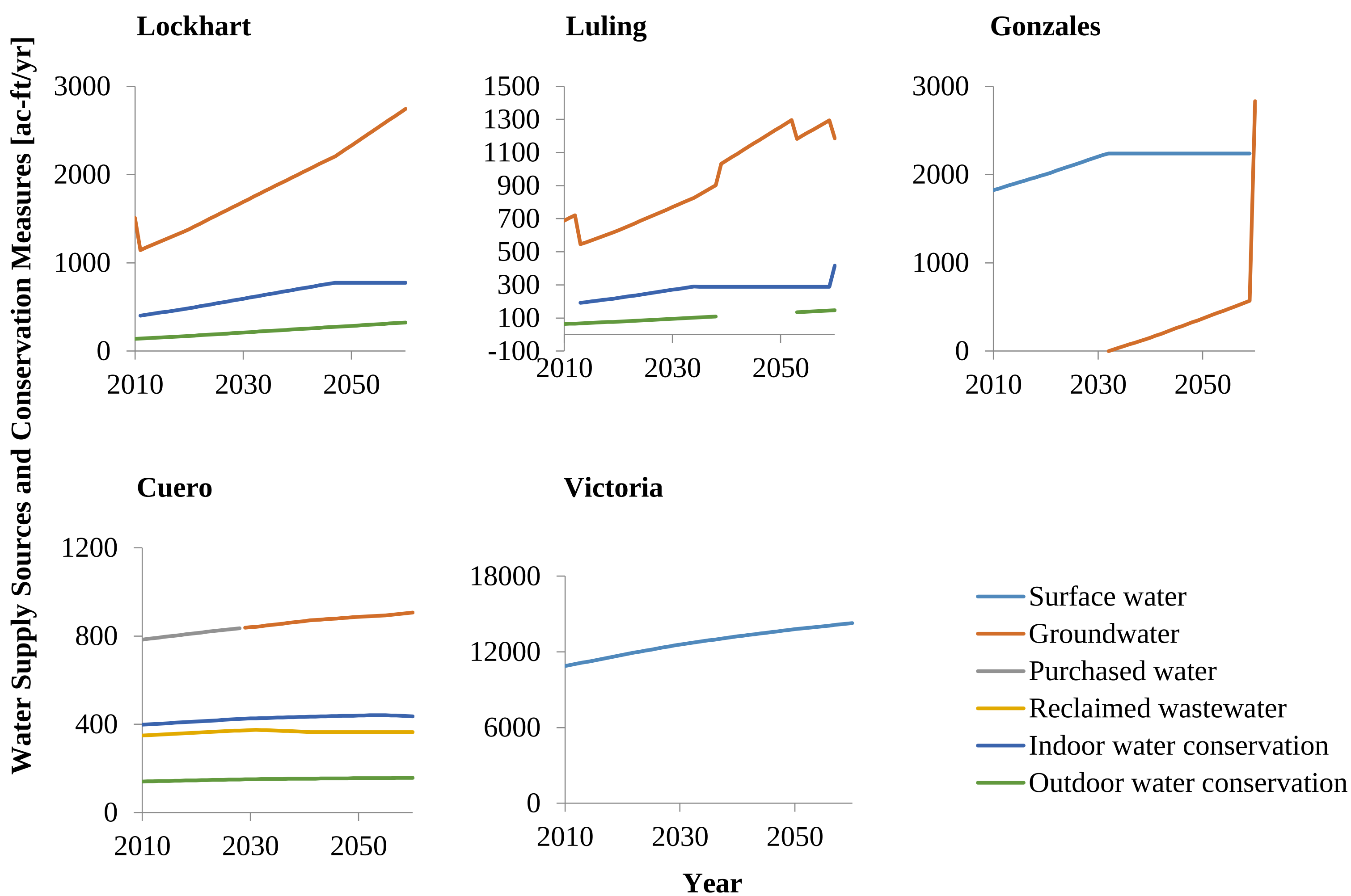



**Figure 5.1(b)** Municipal water supply portfolios from 2010-2060 for the conventional water management strategy for municipalities in the Middle and Lower Guadalupe Basi**n.**

### 5.1.2 Factors that Influence Vulnerability

Fifty repeated hydrology scenarios were simulated to explore the effect of hydrologic flows on municipal vulnerability to water shortages. Municipal water shortages occur most frequently in the month of August for all of the repeated hydrology scenarios, and the flow duration curve for the August flows of the Guadalupe River near Victoria, Texas, is shown in Figure 5.2. The average annual municipal water shortage was calculated for each repeated hydrology scenario as the average of the annual sum of water shortages for all municipalities across 50 years of simulation. For the repeated hydrology scenarios, population and water supply costs change, though the flows in the Guadalupe River remain the same, and as a result, municipal water shortages can vary each year. Average annual municipal water shortages are sorted by the August flow corresponding to the simulation year and are shown on the secondary y-axis of Figure 5.2. Municipal water shortages are severe when the August flow is less than 50,000 ac-ft/month; flows less than this magnitude have a return period of two years. The annual average municipal water shortage does not monotonically increase as flows decrease, due to the complex actions of municipal agents, diversions of the irrigation and industrial water users in the basin, and intra-annual hydrologic variability. The probability of flows in months other than August may not correspond with the exceedence probability of the August flow. For example, in a year with a relatively high flow in August and low flows in other months, municipalities may experience significant water shortages.

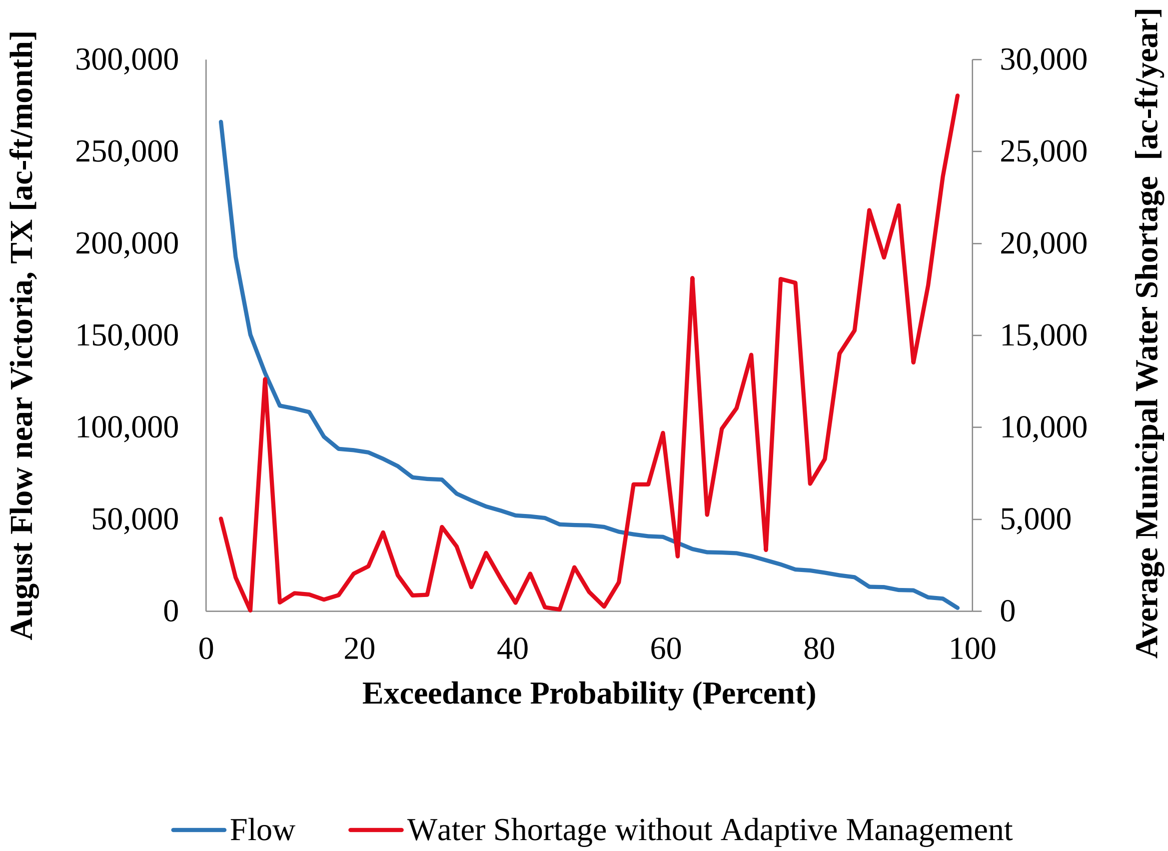



**Figure 5.2** August flow of the Guadalupe River near Victoria, Texas, (ranked by magnitude) for repeated hydrology scenarios and the corresponding average annual municipal water shortage when conventional water management is simulated. Average annual municipal water shortage is calculated as the annual average across 50 years of simulation of the sum of municipal water shortages.

A selected set of scenarios were compared to the historic hydrology scenario to examine the effects of hydrology, location, permit year, and population growth on municipal vulnerability to water shortages (Figure 5.3). Repeated hydrology scenarios for the simulation years of 1979, 1961, and 1956 were selected to represent wet, moderate, and dry hydrology scenarios, respectfully. These hydrologic years were selected because the highest annual flow in the flow data period (1934-1984) was observed in the year 1979, the lowest annual flow in 1956, and the flow observed in 1961 is approximately midway between the 1979 and 1956 flows. As expected, the effect of hydrology-induced changes in stream flow on municipal water shortages is significant. The wet scenario generates few municipal water shortages: the worst shortages occur in the middle region of the basin, and these shortages are infrequent, occurring in less than 9% of the simulated months. In the dry scenario, municipalities located in the upper, middle, and lower regions of the basin experience water shortages in more than 40% of the simulated months.

The effect of the location was also evaluated, and results show that municipalities located in the upper and middle portion of the basin experience more frequent water shortages than municipalities located in the lower portion of the basin (Figure 5.3). This is attributed to the large number of industrial and irrigation permit holders that withdraw water and decrease stream flow in this region of the basin.  The year of water rights permits also affects the water shortages that each municipality experiences. In general, water permits that were issued between 1955-2010 experienced much more frequent water shortages than permits that were issued from 1900-1954. For example, in the historic hydrology scenario, municipalities that hold permits issued between 1955-2010 and are located the middle region of the basin experience water shortages for 40-49% of the simulated months. Municipalities located in the same region that hold permits issued between 1900-1954 experienced less frequent shortages, only 10-19% of the months. Downstream municipalities exhibit the most extreme vulnerability in the basin for the dry hydrology scenario, due to the seniority of water rights. In the dry scenario, senior permit-holders consume scarce surface water supplies, and the Victoria agent, which holds the most junior municipal water right permit and is located in the lower portion of the basin, experiences water shortages. Downstream flows during the moderate hydrology scenario, however, are adequate for the Victoria agent to divert its surface water target. In the moderate and wet hydrology scenarios, some senior permit holders that are located in the upper and middle portion of the basin, including the Kerrville, San Marcos, and Gonzales municipal agents, experience water shortages. Surprisingly, the most junior municipal permit holder that is located in the lower basin, the Victoria agent, does not. This may occur because more senior irrigation and industrial permit holders withdraw surface water resources in the upper basin and effectively reduce stream flow near the Kerrville, San Marcos, and Gonzales municipal agents.

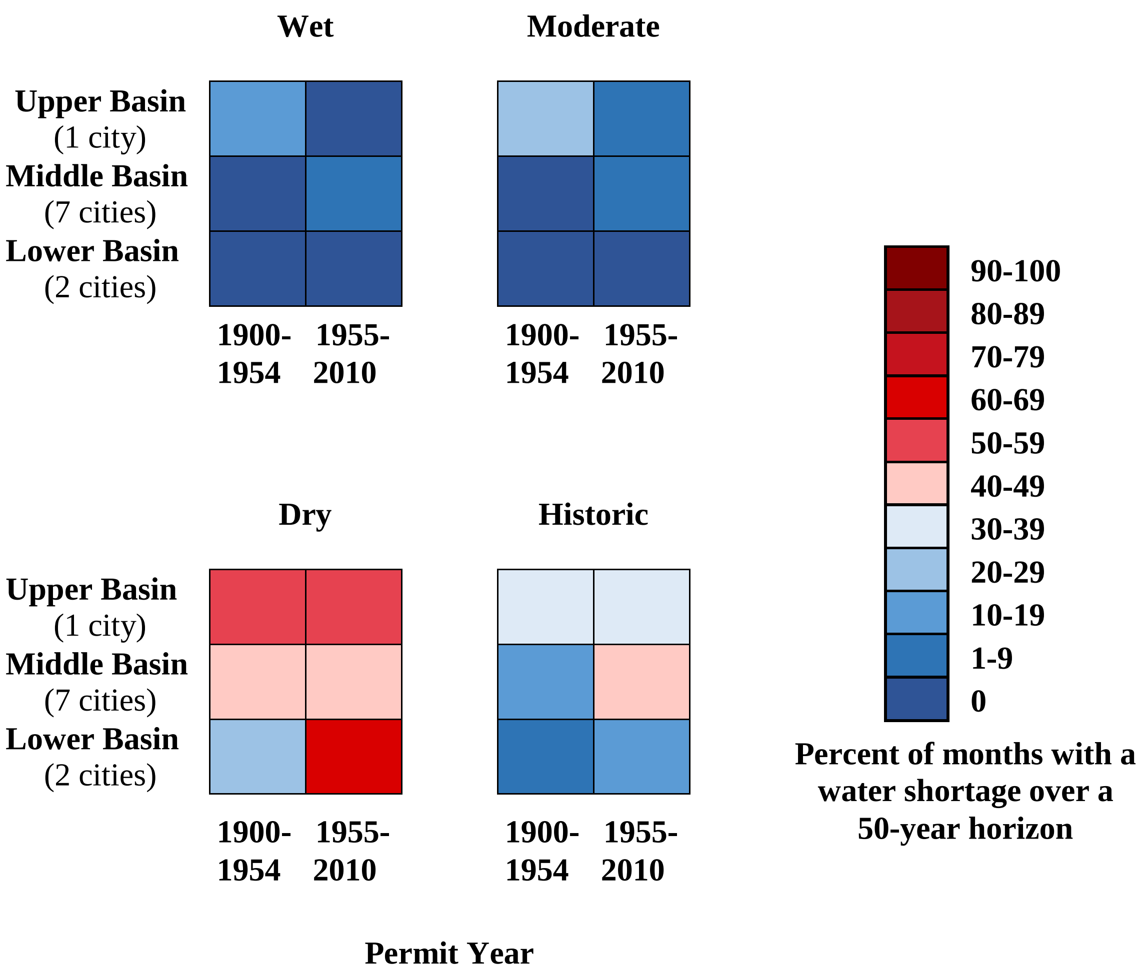



**Figure 5.3** Frequency of municipal water shortages for wet, moderate, dry, and historic hydrology scenarios according to location in the basin and surface water permit year

Population growth is also expected to be a key barrier to sustainable municipal water management in the future. The repetitive hydrology scenarios were applied to examine the effect of population growth on municipal water shortages in the Guadalupe River Basin, which is projected to double in population between 2010-2060. A repeated hydrology scenario was used for this analysis because any fluctuations in municipal water shortages can be attributed to changes in the use of municipal surface water permits and are not caused by fluctuations in surface water flow. Municipal water shortages increase rapidly from 2010-2016 during the dry hydrology scenario, as several of the municipal agents increase the use of their surface water rights permits during this period (Figure 5.4). Water shortages, however, increase at a slower rate during 2017-2060 in the dry hydrology scenario. This is because many of the municipal agents fully utilize their surface water permits and use alternative water resources to meet demands. The rate at which water shortages increase slows because only the Victoria municipal agent continues increasing the use of its permits throughout the entire simulation. Population growth does not exacerbate water shortages in the basin during the wet and moderate hydrology scenarios, as evidenced by the unchanging magnitude of municipal water shortages in the wet and moderate hydrology scenarios across the planning horizon (Figure. 5.4). The surface water supplies in the wet and moderate simulations can adequately provide water for almost all of the planned municipal diversions.

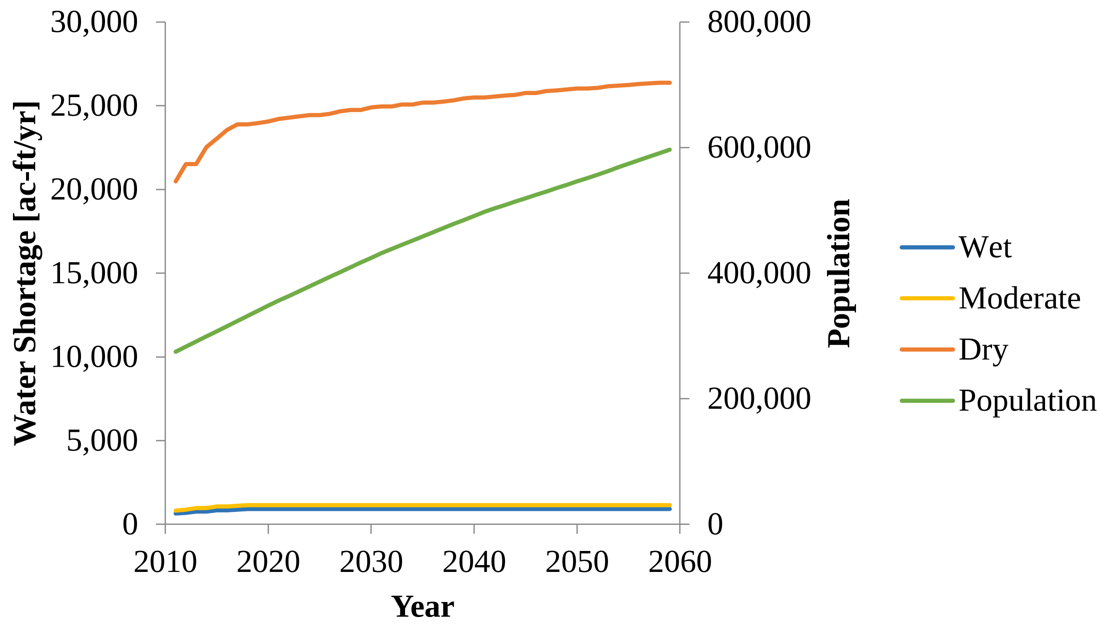



**Figure 5.4** Projected basin-level municipal population and the total annual municipal water shortage for the wet, moderate, and dry repetitive hydrology scenarios.

### 5.2 Permit-based Adaptive Portfolio Selection Strategy

#### 5.2.1 Permit-based Adaptive Municipal Water Portfolios for a Historic Hydrology Scenario

Adaptive municipal management rules were simulated for each municipal agent, where each municipal agent uses a permit-based adaptive strategy to select water supply portfolios. Using this rule, a municipality responds to water shortages by enacting restrictions on its surface water rights permits. The historic hydrology scenario is simulated, and population and cost data are used as described above. The Kerrville and San Marcos municipal agents experience significant water shortages early in the simulation and, in response, enact drastic restrictions on their planned surface water use (Figures 5.5(a) and

5.5(b)). Over the course of the simulation, these municipal agents update their rules and limit their surface water use to reliably meet demands. The San Marcos agent, for example, limits its surface water use to 5,075 ac-ft/yr. This is significantly less than in the conventional management scenario, in which the San Marcos municipal agent fully utilizes its surface water permits, at 10,150 ac-ft/yr. Instead of relying heavily on surface water, the San Marcos agent uses groundwater to supply the majority of its municipal demand. The city is eventually constrained by the aquifer-based groundwater production limit. The growing municipal demand, unreliable surface water supplies, and regulatory constraints on groundwater supplies trigger the San Marcos agent to implement indoor and outdoor water conservation practices in 2050.

The New Braunfels and Seguin municipal agents place modest restrictions on their surface water use because their water shortages are relatively small and infrequent. The Victoria agent is the only municipality that holds surface water permits and implements the same water supply portfolio in the permit-based adaptive strategy as in the conventional case. The Victoria municipal agent experiences water shortages during the historic hydrology scenario, and through the use of the permit-based adaptive strategy, the Victoria municipal agent does not adapt its water portfolio enough to avoid shortages. The magnitude of the Victoria agent's water shortages is a small percentage of its available water rights, which are 21,260 ac-ft/yr, and the total municipal demand is less than 14,180 ac-ft/yr throughout the simulation. In 2030, for example, the Victoria agent's surface water shortage is 6,854 ac-ft/yr, and following the permit-based adaptive rule, the permit use is limited to 14,406 ac-ft/yr in 2031 (21,260 less 6,854 ac-ft/yr). The Victoria agent's projected municipal demand is

12,506 ac-ft/yr in 2031 and, therefore, the rule specifies that the demand should be met using surface water permits alone.

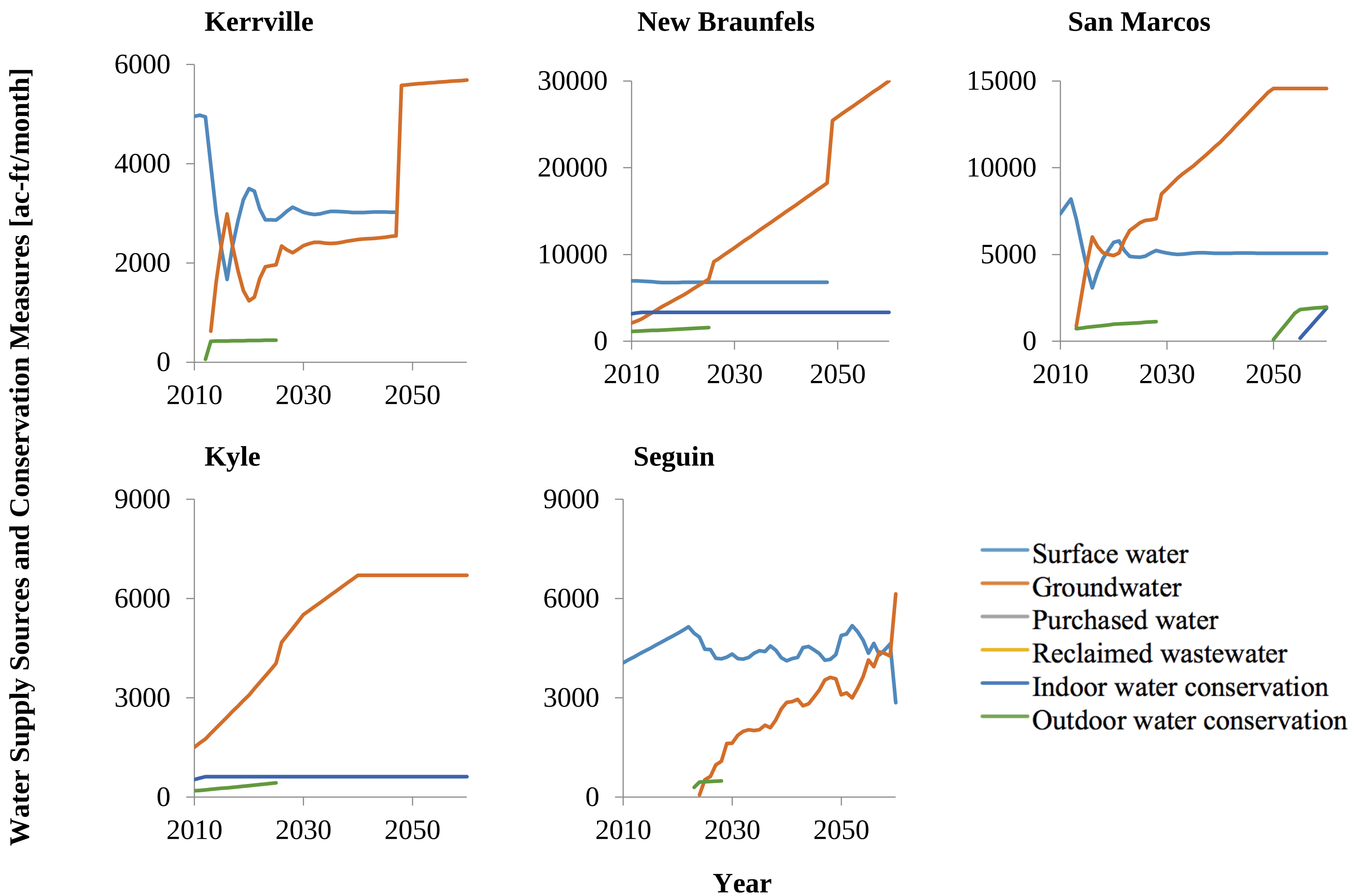



**Figure 5.5(a)** Municipal water supply portfolios from 2010-2060 for permit-based adaptive strategy for municipalities in the Upper and Middle Guadalupe Basi**n.**

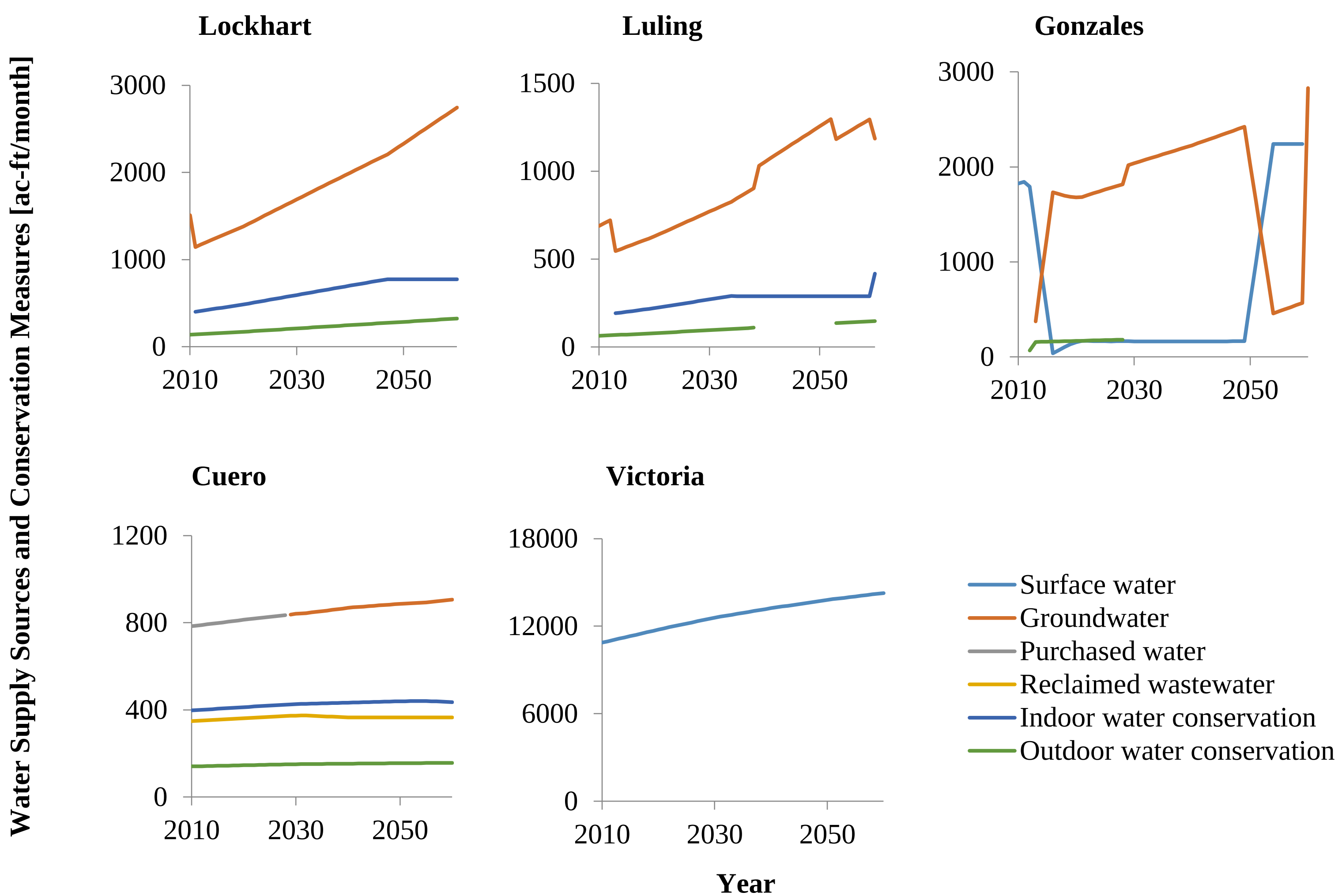



**Figure 5.5(b)** Municipal water supply portfolios from 2010-2060 for permit-based adaptive strategy for municipalities in the Middle and Lower Guadalupe Basin.

### 5.3 Supply-based Adaptive Portfolio Selection Strategy

#### 5.3.1. Supply-based Adaptive Municipal Water Portfolios for a Historic Hydrology Scenario

Municipal agents were simulated using the supply-based adaptive portfolio selection strategy. In response to water shortages, an agent limits its annual surface water use not to exceed the average volume of surface water that was supplied during the most recent five years. The historic hydrology scenario was simulated to assess the performance of the supply-based rule for all agents. The New Braunfels agent builds a similar water supply portfolio for both the permit-based and supply-based strategies (Figure 5.6(a)). Both adaptive rules result in the New Braunfels agent enacting a modest restriction on its surface water use. The Seguin municipal agent also selects a similar portfolio for the two adaptive strategies, although Seguin limits its surface water use to a greater degree when the supply-based adaptive strategy is implemented. For example, in 2050 the Seguin municipal agent has a water demand of 7,973 ac-ft/yr, and the surface water use is limited to 4,890 ac-ft/yr and 3,490 ac-ft/yr when the permit-based and supply-based strategies are used, respectively.

The Victoria municipal agent relies exclusively on surface water when the least-cost and permit-based adaptive strategies are applied. Using the supply-based adaptive strategy, however, the Victoria municipal agent implements a diverse water portfolio (Figure 5.6(b)). Victoria incorporates groundwater, reclaimed water, indoor and outdoor conservation measures into its portfolio as it progressively limits its surface water use to a reliable amount, at approximately 5,400 ac-ft/yr.

The Kerrville, San Marcos, and Gonzales municipal agents select distinctly different water portfolios for the three management approaches. Surface water is the prominent source of water for each of these cities when the least-cost management rule is used. Each city reduces its surface water use in response to water shortages when the permit-based adaptive strategy is applied. Groundwater resources and conservation practices are utilized to supplement their surface water use reductions. By mid-simulation of the supply-based adaptive strategy, these city agents no longer include surface water in their water supply portfolios. The Kerrville and Gonzales agents then elect to fully supply their municipal demands with groundwater and conservation measures, and the San Marcos agent utilizes reclaimed water in addition to these sources.

For both the permit-based and supply-based adaptive portfolio selection strategies, many of the municipal agents supplement unreliable surface water supplies with groundwater, reclaimed wastewater, purchased water, and indoor and outdoor water conservation measures. Use of these alternative water sources and demand management strategies are constrained by aquifer-based groundwater production limits, wastewater supply, water supplies made available for purchase by the river authority agent, and the maximum percent water savings that can be achieved by installing water-efficient fixtures in residential properties and by implementing outdoor watering restrictions (refer to Eq. 3 for the approach used to calculate these constraints). It is important to reiterate that reliability metrics were not developed for these water sources and demand management strategies; these are considered completely reliable in this study. A municipal agent will only restrict its use of groundwater, reclaimed water, purchased water, and water conservation practices due to cost or the restrictions on availability. In reality, these sources are not fully reliable and municipalities will likely consider the reliability of all water sources and demand management strategies when building a water portfolio.

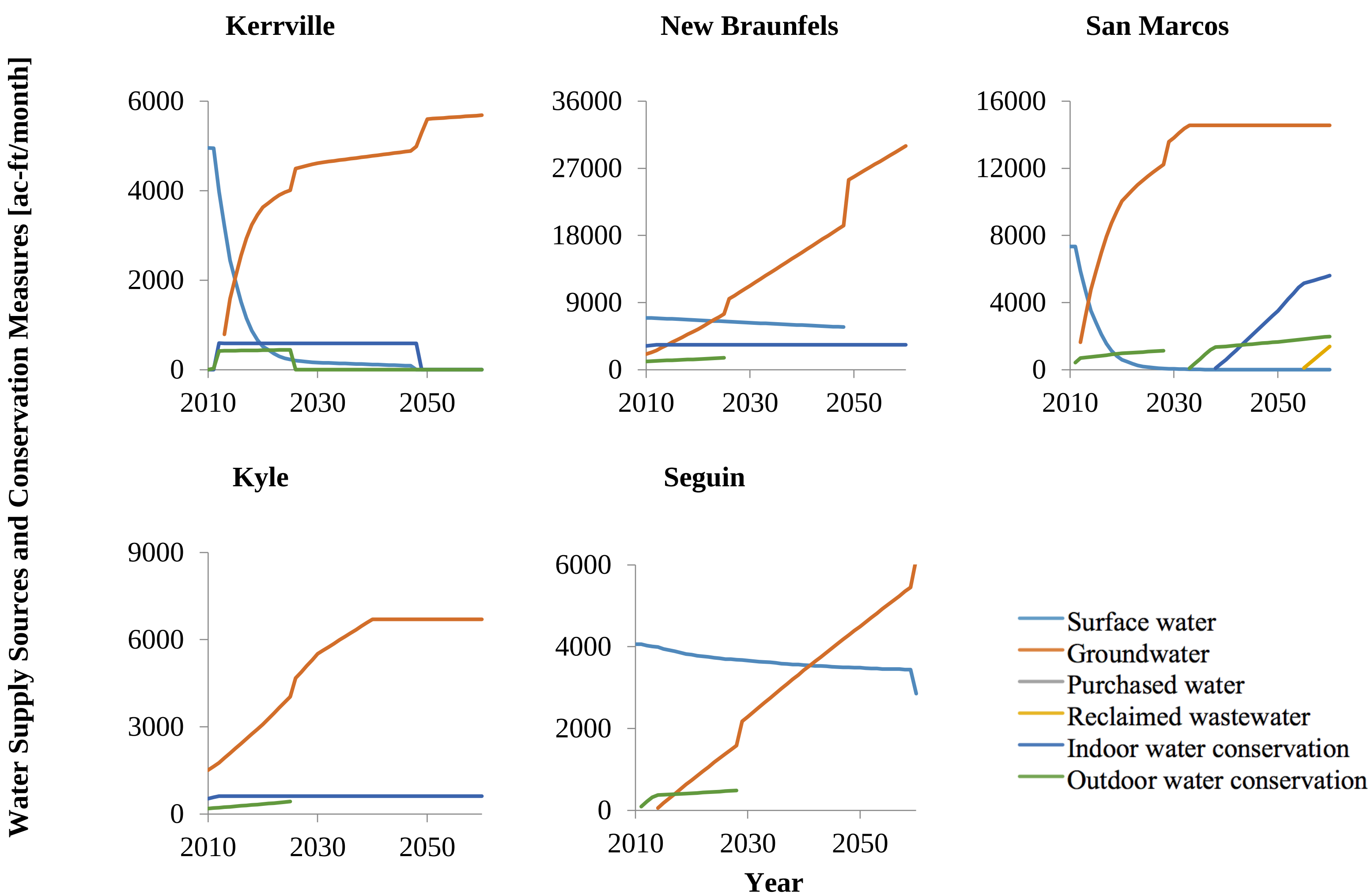



**Figure 5.6(a)** Municipal water supply portfolios from 2010-2060 for supply-based adaptive strategy for municipalities in the Upper and Middle Guadalupe Basin.

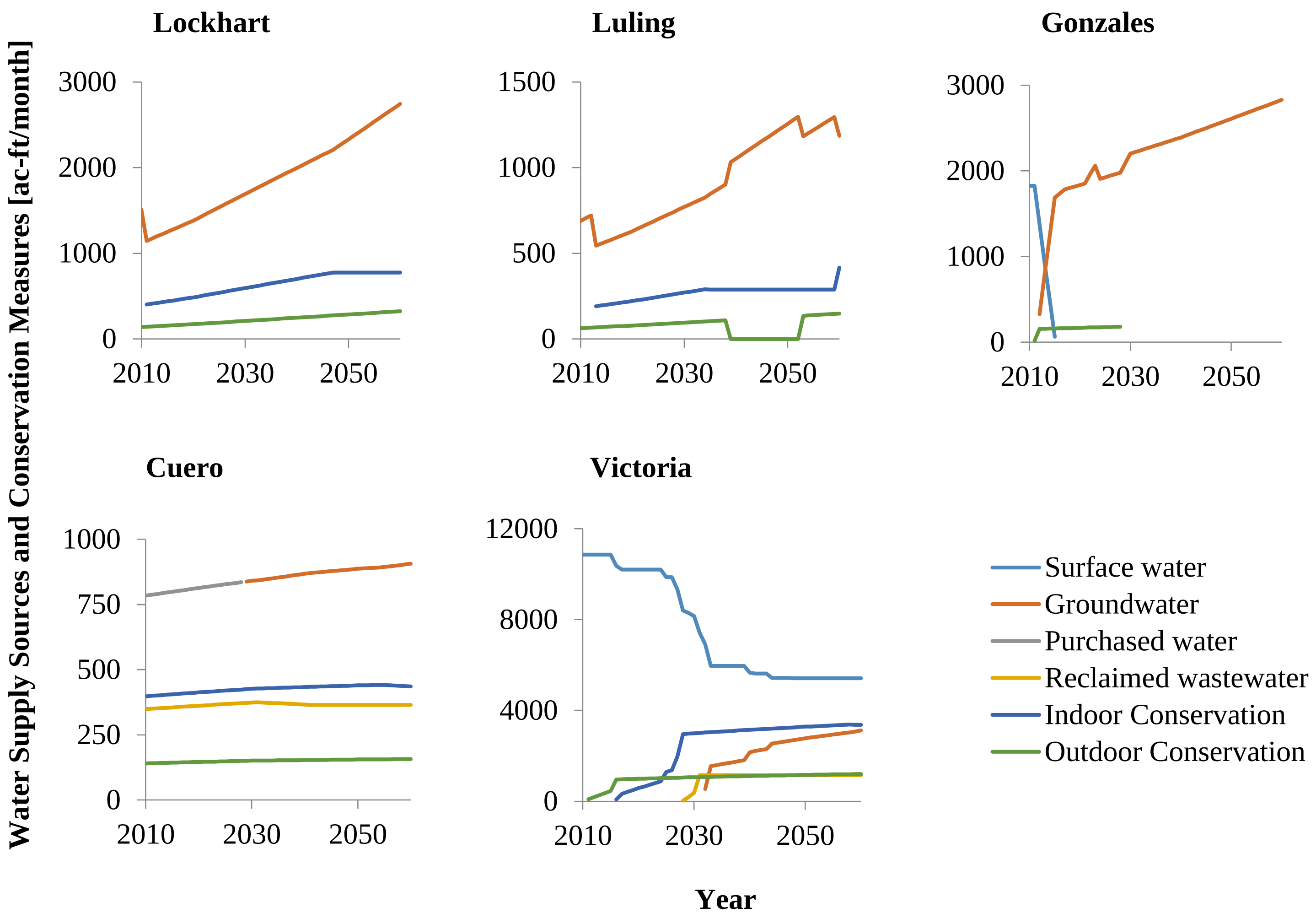



**Figure 5.6(b)** Municipal water supply portfolios from 2010-2060 for supply-based adaptive strategy for municipalities in the Middle and Lower Guadalupe Basin.

## 5.4 Comparison of Conventional and Adaptive Water Management

In comparison to the least-cost water management strategy, the adaptive water management strategies effectively reduce water shortages in the simulations of the Guadalupe River Basin (Figures 5.7(a) and 5.7(b)). The supply-based adaptive strategy is more effective at improving water reliability than the permit-based adaptive strategy. For example, the maximum water shortage in the basin was reduced by 50%, from approximately 900 to 450 ac-ft/yr, for both the wet and moderate hydrology scenarios, when the permit-based adaptive strategy was implemented. Water shortages were reduced to approximately zero for these hydrology scenarios when the supply-based adaptive strategy was simulated.

The most significant basin-wide municipal water shortage occurred in 2032 for the historic hydrology scenario. The water shortages corresponding to the least-cost, permit-based adaptive, and supply-based adaptive strategies are 31,159 ac-ft/yr, 22,774 ac-ft/yr, and 9,880 ac-ft/yr, respectively. This result indicates that both adaptive strategies are effective at mitigating water shortages that arise during severe drought periods. The adaptive strategies also prevent the occurrence of water shortages; in the historic hydrology scenario, shortages were observed in 2046 with the least-cost management rule, but do not appear when the adaptive rules are enacted.

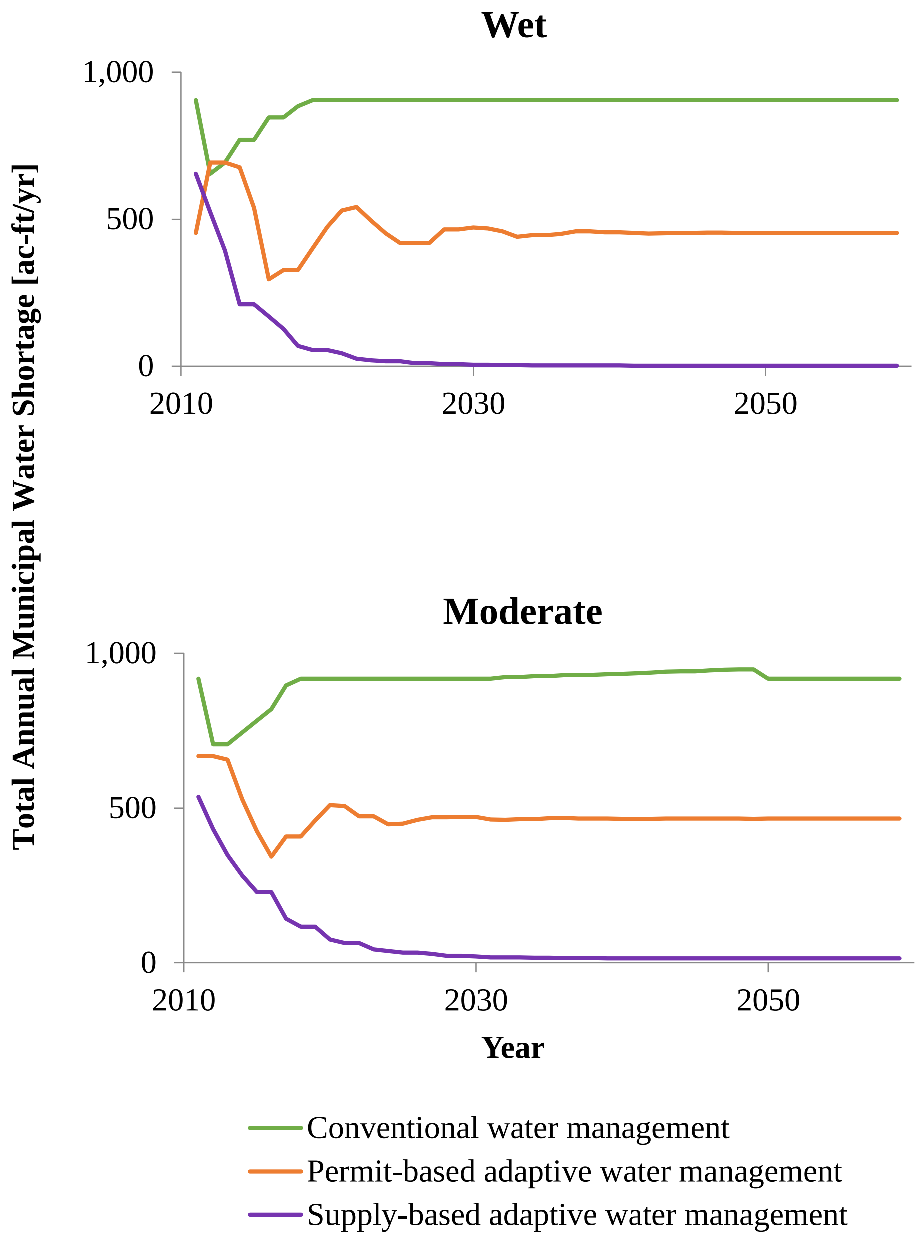



**Figure 5.7(a)** Total annual municipal water shortage during wet and moderate hydrology scenarios for conventional and adaptive water management strategies

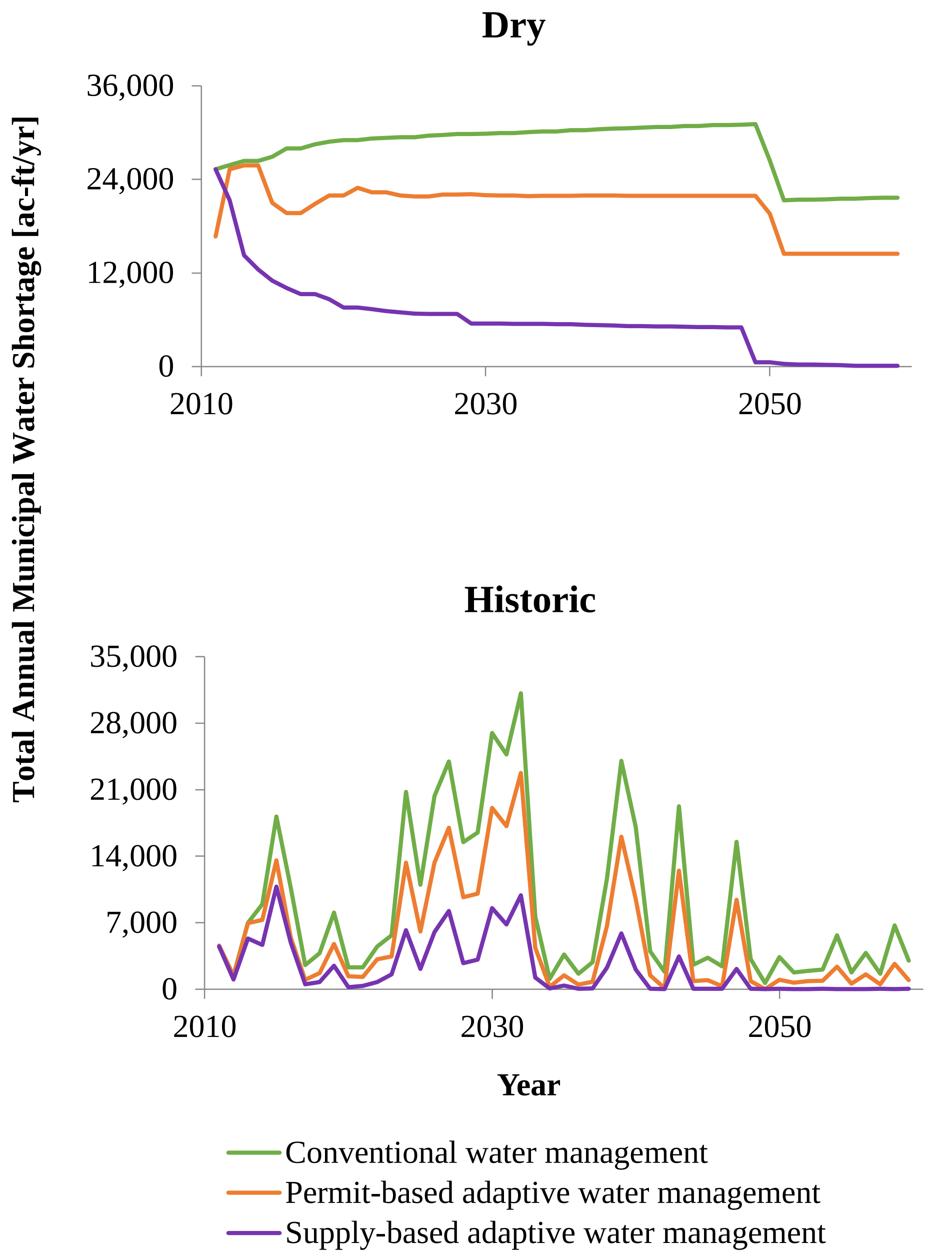



**Figure 5.7(b)** Total annual municipal water shortage during dry and historic hydrology scenarios for conventional and adaptive water management strategies

The adaptive rules were simulated for all 50 repeated hydrology scenarios, and the annual average municipal water shortage was calculated by summing the water shortages of all of the municipalities in the basin (Figure 5.8). For the least-cost management approach, water shortages increase across the Guadalupe River Basin when the August flow falls below 50,000 ac-ft/month (Figure 5.2). Water shortages, however, are less severe for adaptive municipal portfolio planning strategies. For example, the annual average municipal water shortage can be compared for a flow of 11,609 ac-ft/yr, which has a 10-year return period and a 90% exceedance probability. Water shortages are 22,074, 15,924, and 8,235 ac-ft/yr for the least-cost, permit-based adaptive, and supply-based adaptive strategies, respectively.

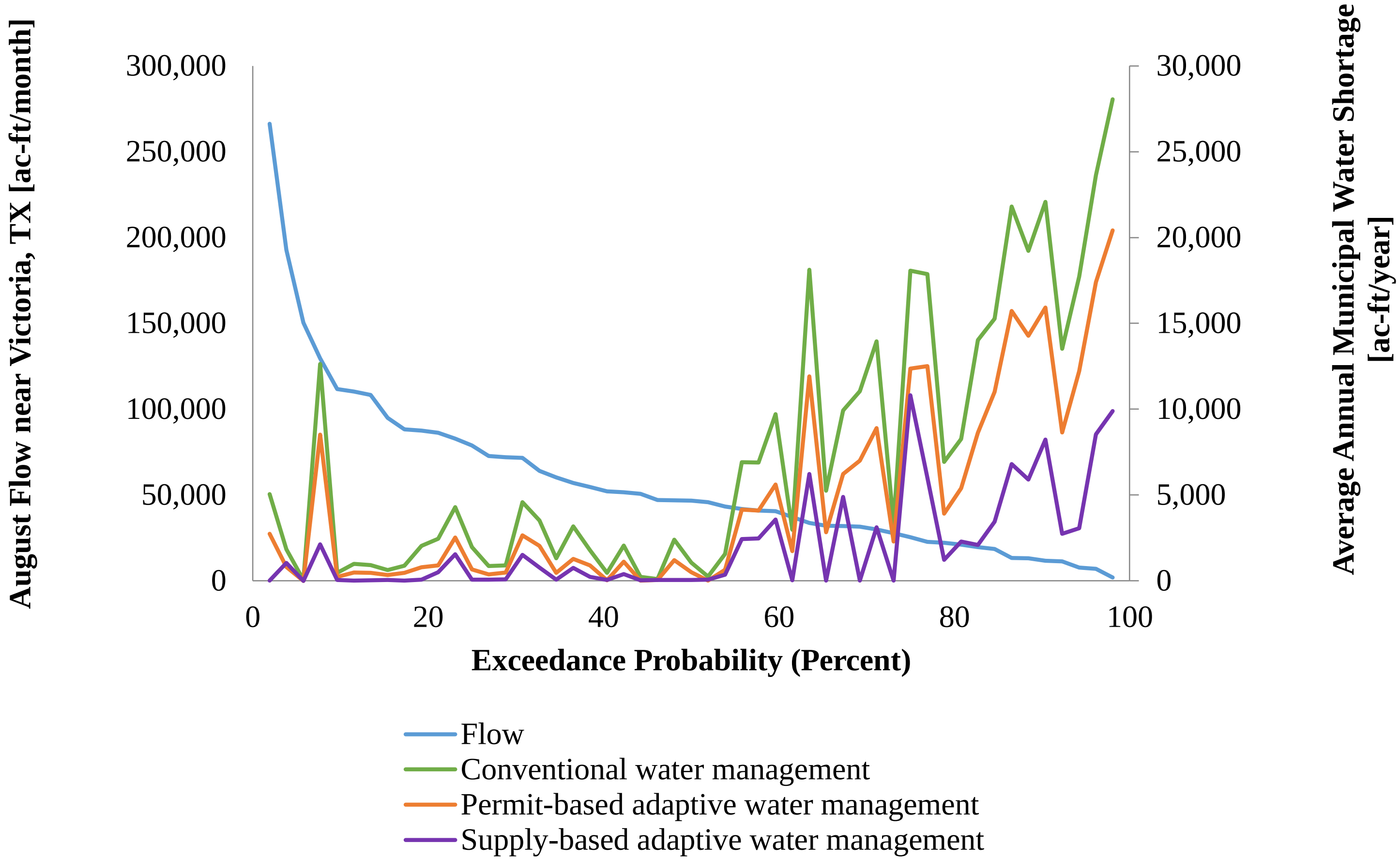



**Figure 5.8** August flow of the Guadalupe River near Victoria, Texas, (ranked by magnitude) for repeated hydrology scenarios and the corresponding average annual municipal water shortage when conventional, permit-based adaptive, and supply-based adaptive water management strategies are simulated. Average annual municipal water shortage is calculated as the annual average across 50 years of simulation of the sum of municipal water shortages.

### 5.5 Tradeoffs between Cost and Reliability

Adaptive water management strategies can reduce municipal vulnerability to water shortages, as shown above; however, the cost of a reliable water supply portfolio will exceed the least-cost water supply portfolio and may be impractical to implement. Cost and reliability tradeoffs are explored for municipalities in the river basin that utilize surface water in their portfolios (Figure 5.9). These municipal agents include Victoria, San Marcos, New Braunfels, Gonzales, Seguin, and Kerrville. The Kyle, Lockhart, Luling, and Cuero municipal agents did not include surface water in their portfolios, and the reliability metrics reported here are based on the provision of surface water resources. Cost and reliability tradeoffs, therefore, are not applicable for these four cities.

Results from the three water management strategies for the historic hydrology scenario are used to explore tradeoffs for municipal agents that utilize surface water resources in their portfolios. The cost metric is calculated as the sum of the cost of annual water supply portfolios across the 50-year simulation for each municipal agent. Similarly, the reliability metric is the sum of annual water shortages across the 50-year simulation.

The New Braunfels and Seguin municipal agents identify reliable water supply portfolios using adaptive management strategies with only a slight increase in portfolio costs, compared to the least-cost portfolio. The cost of using a permit-based adaptive strategy for the New Braunfels and Seguin municipal agents is < 1% and 14% more than the least-cost strategy, respectively. For these municipal agents, the permit-based and supply-based adaptive strategies achieve similar levels of reliability, while the permit-based strategy results in a lower cost. The Seguin agent, for example, selects water supply portfolios that exhibit similar levels of reliability at costs of \$98M (permit-based adaptive strategy) and \$106M (supply-based adaptive strategy). The Gonzales municipal agent selects portfolios at costs of \$49M (permit-based adaptive strategy) and \$122M (supply-based adaptive strategy).

The remaining municipal agents, Kerrville, San Marcos, and Victoria, show significant tradeoffs between cost and reliability (Figure 5.9). Preferences of decision-makers and public officials must be considered during water supply planning. The Victoria municipal agent, for example, must increase the cost of its water supply portfolio by 81% in order to reduce its water shortages by 46%. Similarly, the Kerrville and San Marcos agents must double their planned costs to prevent water shortages.

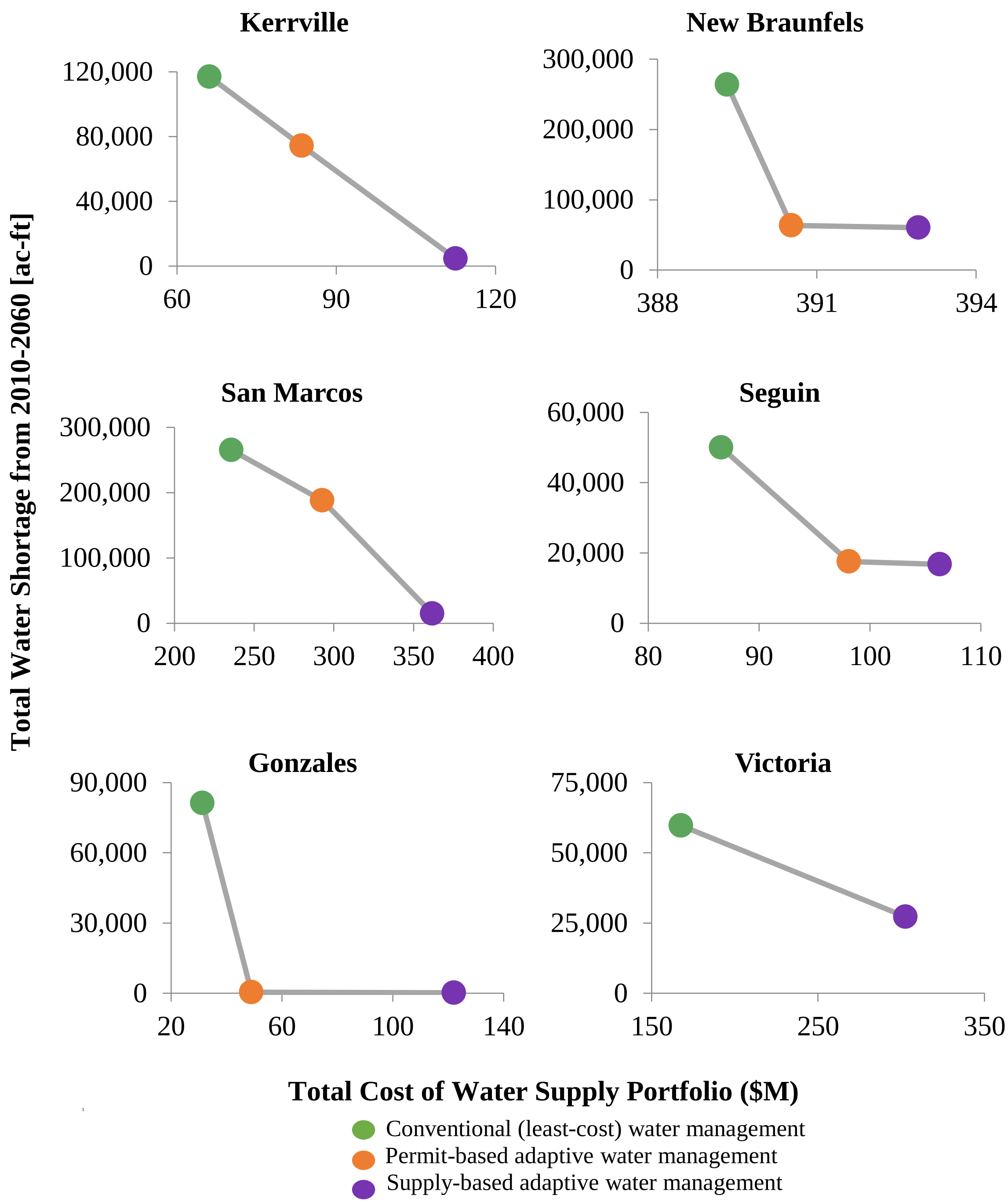



**Figure 5.9.** Tradeoff between the total cost of a municipality's planned water portfolios and the municipality's total water shortage over the 50-year simulation. Results are shown for conventional (least-cost) and adaptive water management strategies assuming a historic hydrology scenario.

**The cost and reliability of Victoria's permit-based adaptive strategy is the same as the least-cost strategy.*

# CHAPTER 6: DISCUSSION

The water portfolios selected by the municipal agents using conventional and adaptive water management strategies are compared to historic municipal water management practices (Tables 6.1-6.10). The Texas Water Development Board provides information about the sources that municipalities used to supply water for demands between 2000-2010 (Texas Water Development Board, 2015(b). Additional information about historically implemented water conservation practices was collected directly from city public utility departments (City of Kerrville, Texas, 2015; New Braunfels Utilities, 2015; City of San Marcos, 2015; City of Kyle, 2015; City of Seguin, 2014; City of Lockhart, 2015*)*. Finally, historic and modeled water portfolios are compared to recommended future water management practices. The South Central Regional Water Planning Group examined projected water demands (2010-2060) in the Guadalupe River Basin and recommended water supply sources and conservation measures for many cities in the basin.

The modeled portfolios are similar to the historic and recommended portfolios for several of the cities in the basin, including Kyle, Lockhart, Luling, Gonzales, and Victoria (Tables 6.1-6.10). The modeled portfolios, therefore, are representative of real management strategies that may be used during 2010-2060 by these cities. Many of the cities that experienced significant water shortages during the model simulations have historically implemented diverse water portfolios. For example, San Marcos, New Braunfels, and Seguin have used surface water, groundwater, purchased water, reclaimed water, and water conservation between 2000-2010. It is evident that these cities recognize their vulnerability to water shortages and have developed their portfolios accordingly.

Purchased water has historically been a popular water supply choice for several of the municipalities in the Guadalupe River Basin, and it has also been recommended that New Braunfels, Lockhart, and Luling purchase water supplies in the future. Purchased water, however, was not a common water supply choice for the municipal agents in the simulation framework. This was due to the fact the projected unit cost of purchased water supplies was relatively expensive. If the future cost to purchase water is less than the modeled projected cost, cities may choose this option more frequently, which will influence their water portfolio costs and vulnerability to shortages.

Water shortages limit residential, commercial, and industrial activities that rely on water and can significantly reduce the revenue of the municipal water supply system. The South Central Texas Regional Water Planning Group reported that water shortages between 0-30% of the municipal demand range in unit cost from \$730 - \$2,040 per acre-foot and water shortages between 30-50% of the municipal demand range in unit cost from \$2,040 - \$10,970 per acre-foot. These values were used to develop a set of linear regression equations that estimate the unit cost of a water shortage as follows:

If $\omega < 30$

$$U = 45.17\omega + 684.83 \tag{6}$$

If $\omega \geq 30$

$$U = 446.50\omega + 1593.50 \tag{7}$$

Where $U$ is the unit cost of a water shortage [$/ac-ft] and $\omega$ is the water shortage as a percentage of the total demand (e.g. for a water shortage that is 10% of the municipal demand, $\omega = 10$).

The cost of the municipal water portfolio can then be adjusted to include the cost of a water shortage as follows:

$$P_a = P_p + V(U - S) \tag{8}$$

Where $P_a$ is the water shortage adjusted cost of the municipal water portfolio [$]; $P_p$ is the planned cost of the municipal water portfolio [$]; $V$ is the volume of the surface water shortage [ac-ft]; $U$ is the unit cost of a water shortage as calculated in Eqs. 6 and 7 [$/ac-ft]; and $S$ is the unit cost of surface water [$/ac-ft], which is subtracted from the original portfolio cost because this volume of surface water was not diverted from the river.

Planned costs and water shortage adjusted costs for the conventional, permit-based adaptive, and supply-based adaptive water management strategy simulations are shown in Figure 6.1. The planned cost is calculated as the sum of the water portfolio costs of the municipal agents. The water shortage adjusted cost is calculated as the sum of the water shortage adjusted costs of the municipal agents, evaluated using Eq. 8. A historic hydrology scenario was applied for all of the water management strategy simulations.

The planned costs of the permit-based adaptive and supply-based adaptive strategies are on average 8% and 32% higher than the planned cost of the conventional strategy. This occurs because some of the municipal agents supplement surface water resources with more expensive, alternative water resources during the adaptive simulations. The water shortage adjusted cost is on average 4.5 times higher than the planned cost when a conventional water management strategy is simulated. The water shortage adjusted costs for the conventional, permit-based adaptive, and supply-based adaptive strategies are on average $117,219,836, $116,700,595, and $68,798,401 per year. The supply-based adaptive strategy significantly lowers the water shortage adjusted costs incurred by the municipal agents. Furthermore, the planned cost is a close representation of the water shortage adjusted cost when the supply-based adaptive strategy is used, but not when the conventional or permit-based adaptive strategies are used. When using the supply-based adaptive strategy the municipal agents can effectively curtail the cost of water shortages.

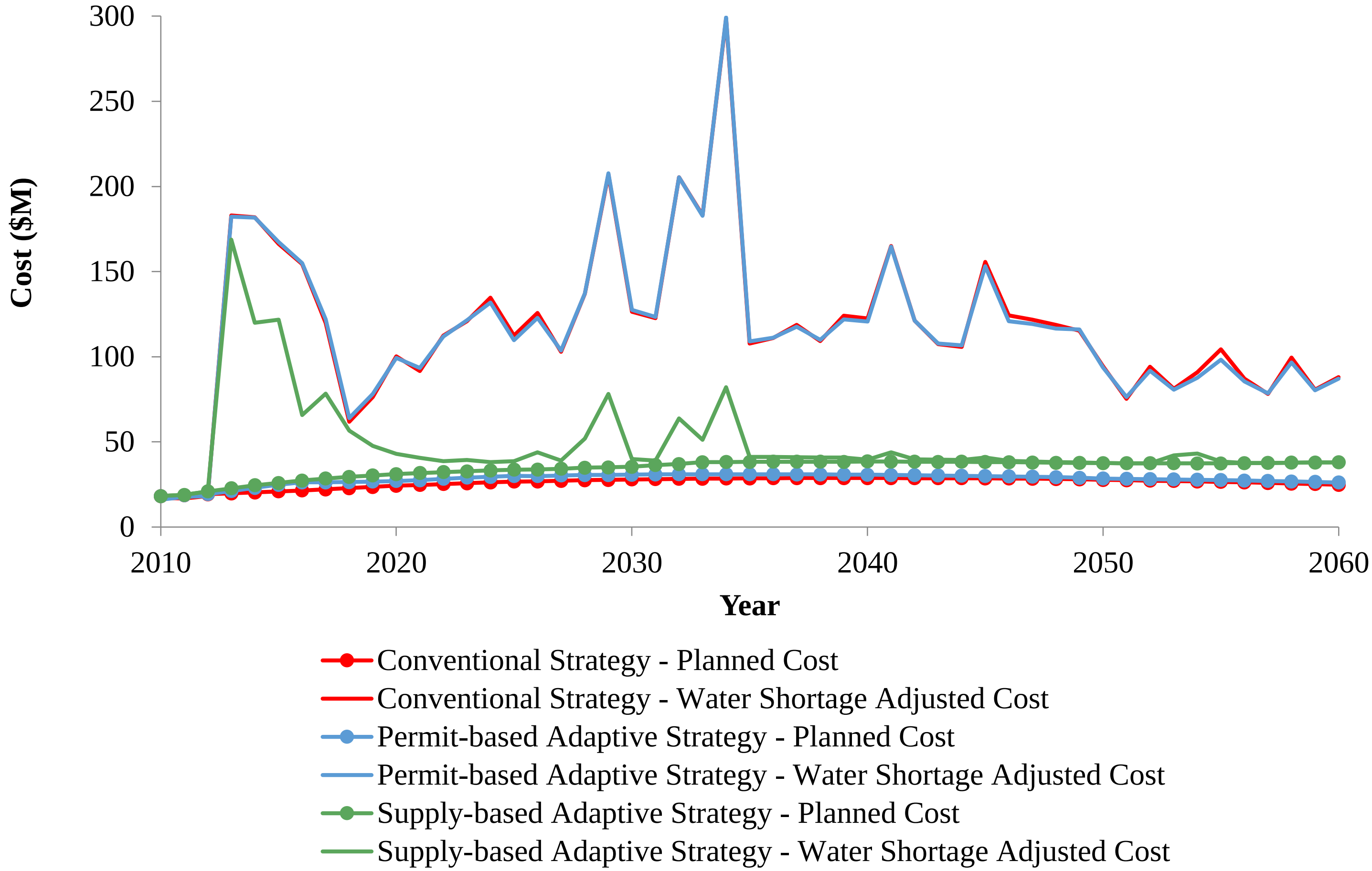



**Figure 6.1** Annual planned and water shortage adjusted costs when conventional, permit-based adaptive, and supply-based adaptive water management strategies are simulated.

The projected costs of water supply sources and demand management strategies are a source of uncertainty in this modeling approach. The costs to utilize surface water, groundwater, and reclaimed wastewater may fluctuate in response to technological advancements or in response to changes in water quality regulations. The cost to purchase water supplies from the Guadalupe-Blanco River Authority may also vary from the projected value. For example, the Guadalupe-Blanco River Authority may raise or lower the market price of water if there is a change in either supply or demand. Another component of model uncertainty is that the municipal agents are simulated as rational entities, and in reality, municipal water managers may act subjectively and use value judgments when making decisions. A municipal water manager may choose a water portfolio based on experiences, opinions, and beliefs, rather than mathematical optimality. The water portfolios municipal water managers will chose and implement in the future is unpredictable. Lastly, reliability metrics were developed for surface water and the alternative water sources and conservation strategies were assumed fully reliable; these sources may not be fully reliable and, therefore, this assumption adds a source of uncertainty to the model results. Groundwater resources, for example, may be less reliable than assumed in the model. Groundwater use was constrained by aquifer-based groundwater production limits, which the regional planning agency expects to be sustainable through the 2060 planning-horizon (South Central Texas Regional Water Planning Group, 2010). The groundwater production limits, however, may not be unsustainable and excessive pumping from the underlying aquifers may result in dry wells and municipal groundwater shortages. Demand management strategies may not be fully reliable because water conservation programs depend on public participation. The actual water savings achieved with a municipal water conservation program may differ from the expected water savings due to the collective watering behaviors of the citizens.

**Table 6.1** Historic, recommended, and modeled water portfolios for Kerrville, Texas

| | Historic Management* (2000-2010) | Recommended Management[t] (2010-2060) | Conventional Water Management Strategy | Permit-based adaptive strategy | Supply-based adaptive strategy |
|---|---|---|---|---|---|
| **Surface water** | | | | | |
| **Groundwater** | | | | | |
| **Purchased water** | | | | | |
| **Reclaimed water** | | | | | |
| **Water conservation** | | | | | |

**Texas Water Development Board, 2015(b); City of Kerrville, Texas, 2015*
*[t]Kerrville was not included in the South Central Texas Regional Water Planning Group, 2010*

**Table 6.2** Historic, recommended, and modeled water portfolios for New Braunfels, Texas

| | Historic Management* (2000-2010) | Recommended Management[t] (2010-2060) | Conventional Water Management Strategy | Permit-based adaptive strategy | Supply-based adaptive strategy |
|---|---|---|---|---|---|
| **Surface water** | | | | | |
| **Groundwater** | | | | | |
| **Purchased water** | | | | | |
| **Reclaimed water** | | | | | |
| **Water conservation** | | | | | |

**Texas Water Development Board, 2015(b); New Braunfels Utilities, 2015*
*[†]South Central Texas Regional Water Planning Group, 2010*

Not selected Selected Information not available

**Table 6.3** Historic, recommended, and modeled water portfolios for San Marcos, Texas

| | Historic Management* (2000-2010) | Recommended Management[†] (2010-2060) | Conventional Water Management Strategy | Permit-based adaptive strategy | Supply-based adaptive strategy |
|---|---|---|---|---|---|
| **Surface water** | | | | | |
| **Groundwater** | | | | | |
| **Purchased water** | | | | | |
| **Reclaimed water** | | | | | |
| **Water conservation** | | | | | |

**Texas Water Development Board, 2015(b); City of San Marcos, Texas, 2015*

*[†]South Central Texas Regional Water Planning Group, 2010*

**Table 6.4** Historic, recommended, and modeled water portfolios for Kyle, Texas

| | Historic Management* (2000-2010) | Recommended Management[†] (2010-2060) | Conventional Water Management Strategy | Permit-based adaptive strategy | Supply-based adaptive strategy |
|---|---|---|---|---|---|
| **Surface water** | | | | | |
| **Groundwater** | | | | | |
| **Purchased water** | | | | | |
| **Reclaimed water** | | | | | |
| **Water conservation** | | | | | |

**Texas Water Development Board, 2015(b); City of Kyle, 2015*

*[†]South Central Texas Regional Water Planning Group, 2010*

Not selected Selected Information not available

**Table 6.5** Historic, recommended, and modeled water portfolios for Seguin, Texas

| | **Historic Management* (2000-2010)** | **Recommended Management† (2010-2060)** | **Conventional Water Management Strategy** | **Permit-based adaptive strategy** | **Supply-based adaptive strategy** |
|---|---|---|---|---|---|
| **Surface water** | ■ | ■ | ■ | ■ | ■ |
| **Groundwater** | ■ | | ■ | ■ | ■ |
| **Purchased water** | ■ | | | | |
| **Reclaimed water** | ■ | | | | |
| **Water conservation** | ■ | ■ | | ■ | ■ |

**Texas Water Development Board, 2015(b); City of Seguin, 2014*

*†South Central Texas Regional Water Planning Group, 2010*

**Table 6.6** Historic, recommended, and modeled water portfolios for Lockhart, Texas

| | **Historic Management* (2000-2010)** | **Recommended Management† (2010-2060)** | **Conventional Water Management Strategy** | **Permit-based adaptive strategy** | **Supply-based adaptive strategy** |
|---|---|---|---|---|---|
| **Surface water** | | | | | |
| **Groundwater** | ■ | ■ | ■ | ■ | ■ |
| **Purchased water** | ■ | ■ | | | |
| **Reclaimed water** | | | | | |
| **Water conservation** | ■ | ■ | ■ | ■ | ■ |

**Texas Water Development Board, 2015(b); City of Lockhart, 2015*

*†South Central Texas Regional Water Planning Group, 2010*

☐ Not selected ■ Selected ▒ Information not available

**Table 6.7** Historic, recommended, and modeled water portfolios for Luling, Texas

| | Historic Management* (2000-2010) | Recommended Management† (2010-2060) | Conventional Water Management Strategy | Permit-based adaptive strategy | Supply-based adaptive strategy |
|---|---|---|---|---|---|
| **Surface water** | | | | | |
| **Groundwater** | | | | | |
| **Purchased water** | | | | | |
| **Reclaimed water** | | | | | |
| **Water conservation** | | | | | |

**Texas Water Development Board, 2015(b)*

*†South Central Texas Regional Water Planning Group, 2010*

**Table 6.8** Historic, recommended, and modeled water portfolios for Gonzales, Texas

| | Historic Management* (2000-2010) | Recommended Management† (2010-2060) | Conventional Water Management Strategy | Permit-based adaptive strategy | Supply-based adaptive strategy |
|---|---|---|---|---|---|
| **Surface water** | | | | | |
| **Groundwater** | | | | | |
| **Purchased water** | | | | | |
| **Reclaimed water** | | | | | |
| **Water conservation** | | | | | |

**Texas Water Development Board, 2015(b)*

*†South Central Texas Regional Water Planning Group, 2010*

Not selected    Selected    Information not available

**Table 6.9** Historic, recommended, and modeled water portfolios for Cuero, Texas

| | **Historic Management* (2000-2010)** | **Recommended Management† (2010-2060)** | **Conventional Water Management Strategy** | **Permit-based adaptive strategy** | **Supply-based adaptive strategy** |
|---|---|---|---|---|---|
| **Surface water** | | | | | |
| **Groundwater** | ■ | ■ | ■ | ■ | ■ |
| **Purchased water** | | | ■ | ■ | ■ |
| **Reclaimed water** | | | ■ | ■ | ■ |
| **Water conservation** | | ■ | ■ | ■ | ■ |

**Texas Water Development Board, 2015(b)*
*†South Central Texas Regional Water Planning Group, 2010*

**Table 6.10** Historic, recommended, and modeled water portfolios for Victoria, Texas

| | **Historic Management* (2000-2010)** | **Recommended Management† (2010-2060)** | **Conventional Water Management Strategy** | **Permit-based adaptive strategy** | **Supply-based adaptive strategy** |
|---|---|---|---|---|---|
| **Surface water** | ■ | ■ | ■ | ■ | ■ |
| **Groundwater** | ■ | | | | ■ |
| **Purchased water** | | | | | |
| **Reclaimed water** | | | | | ■ |
| **Water conservation** | | ■ | | | ■ |

**Texas Water Development Board, 2015(b)*
*†South Central Texas Regional Water Planning Group, 2010*

□ Not selected ■ Selected ▒ Information not available

# CHAPTER 7: CONCLUSIONS

This research presented an ABM framework that can be used to simulate decentralized municipal water decisions in a shared river basin. Optimization algorithms have been applied to identify municipal water supply portfolios (Characklis et al, 2006; Kirsch et al, 2009; Matrosov, 2012), and a linear programming algorithm was implemented in this framework. Rational municipal agents select least-cost water portfolios to satisfy their annual demands from portfolio options that include permitted surface water, groundwater, purchased water, recycled wastewater, and conservation practices. The municipal agents interact through the water rights model, WRAP, which simulated a seniority-based water rights permit system to calculate annual surface water supplies and shortages of permit-holders in the basin. Adaptive water management was modeled to represent municipalities that modify their portfolios in response to water shortages. The research presented here develops a new approach to explore municipal water management by simulating adaptive portfolio selection strategies for many municipalities that manage their water portfolios simultaneously in a shared river basin.

A set of hydrology scenarios were modeled to explore water availability dynamics in the Guadalupe River Basin for historic flows and repeated hydrologic records for wet, moderate, and dry years. A municipality's vulnerability to water shortages is collectively and nonlinearly influenced by internal and external factors; these include location-based effects, permit seniority, population growth, basin hydrology, water management decisions of the municipality itself, and the decisions of the other municipalities in the basin. Location affects municipal vulnerability to surface water shortages in the Guadalupe River Basin;

municipalities in the upper and middle portion of the basin were more vulnerable, especially for the dry and historic hydrology scenarios. This may occur because there are prominent agricultural water users in this region of the basin. Furthermore, many of the agricultural water right permits were established in the early 1900s, and these permits are given priority over some of the municipal water permits.

Permit seniority has been shown to influence vulnerability to water shortages in the western U.S. (Hersh & Wernstedt, 2002) and the findings of this study support that idea. Municipalities in the Guadalupe River Basin that were allocated water permits after 1955 experienced more frequent water shortages than municipalities with more senior permits that are located in the same region of the basin.

Municipal agents co-evolve water portfolios when adaptive water management strategies are modeled. The use of adaptive management strategies significantly reduces the magnitude of water shortages in the basin, and prevents water shortages in some years. When each municipal agent limits its annual surface water diversion to the average amount of surface water it had been supplied in the previous five years (the supply-based adaptive rule) water shortages were infrequent and negligible. Costs to progressively mitigate water shortages in the basin ranged for different cities: the cost of an adaptive strategy is twice as much as the least-cost strategy for some cities, whereas other cities could significantly reduce water shortages with minor increases in their budgets. The permit-based adaptive water management strategy simulated municipal agents that limited the use of their surface water permits based on the water shortages that they had experienced in the previous five years. This strategy was less restrictive and was generally effective at balancing cost and reliability objectives. A few cities could gain highly reliable water portfolios through small increases in water budgets.

Municipal agents significantly reduced their surface water diversions when the adaptive water management strategies were modeled. In lieu of surface water, municipalities primarily met demands with groundwater supplies in the model simulations. Groundwater has historically been a prominent source of water for all ten cities in the Guadalupe River Basin and, therefore, the cities may continue to pump groundwater resources from the underlying aquifers. Although municipal groundwater pumping is constrained by aquifer-based groundwater production limits, such stress on the groundwater supply may not be sustainable. This framework should be extended to examine conjunctive surface and groundwater management; this could be accomplished by combining a similarly designed ABM with a coupled surface and groundwater model.

In many seniority-based permit systems, surface water rights ownership is transferable. Municipal, agricultural, and industrial water users can lease, buy, or sell their surface water permits. Although the diversion location and water use application may change, the priority year of a permit remains the same if it is transferred between two water users. It is possible, therefore, for a municipality to reduce its vulnerability to water shortages by acquiring senior water rights permits. Municipalities should consider the costs associated with purchasing senior permits when building a water supply portfolio. Furthermore, water permit transactions, which alter permitted diversion locations, may affect the spatial and temporal availabilities of water resources in the river basin. The existing ABM framework could be extended to include permit transfers to further examine water availability dynamics.

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