Article

Modeling as a Tool for Transboundary Aquifer Assessment Prioritization

Ashley E. P. Atkins [1,*], **Saeed P. Langarudi** [2] **and Alexander G. Fernald** [1,2]

1   New Mexico Water Resources Research Institute, Las Cruces, NM 88003, USA; afernald@nmsu.edu
2   College of Agricultural, Consumer and Environmental Sciences, New Mexico State University, Las Cruces, NM 88003, USA; lang@nmsu.edu
*   Correspondence: apage@nmsu.edu

Abstract: Transboundary aquifers are critical global water supplies facing unprecedented threats of depletion; existing efforts to assess these resources do not adequately account for the complexities of transboundary human and physical system interactions to the determinant of the impact of assessment outcomes. This study developed a system dynamics model with natural, human, and technical system components for a section of the transboundary Mesilla Basin/Conejos-Médanos aquifer to evaluate the following dynamic hypothesis: how and when information from a transboundary aquifer assessment is reported and perceived, in scenarios where two countries follow identical and different timeframes, dynamically impacts the behaviors of the shared aquifer. Simulation experiments were conducted to quantitatively assess the dynamics of transboundary aquifer assessment information reporting and perception delays. These critical feedbacks have not previously been incorporated practically in simulation and analysis. Simulation results showed that the timing and content of reporting can change the dynamic behavior of natural, human, and technical components of transboundary aquifer systems. This study demonstrates the potential for modeling to assist with prioritization efforts during the data collection and exchange phases to ensure that transboundary aquifer assessments achieve their intended outcomes.

Keywords: transboundary aquifers; human and natural systems; assessment; system dynamics modeling

1. Introduction

International groundwater depletion jeopardizes the well-being of groundwater-dependent natural and human systems, as well as the global populations that rely on agriculture and other critical exports from regions impacted by these water scarcity trends [1–4]. The challenges associated with groundwater depletion are exacerbated for the world's 592 identified transboundary aquifers and groundwater bodies [5,6]. Transboundary groundwater systems, which exist in nearly every country, serve as critical water supplies for populations with distinctive characteristics, histories, and priorities [7,8]. Successful transboundary groundwater management necessitates data and information produced through efforts such as assessments [9]. Collecting and exchanging data to increase understanding regarding these shared resources has emerged as a foundational component of assessments [10].

While recognition has grown regarding the importance and structure of transboundary aquifer assessments, constraints exist that impede their success. Assessments are funded with finite resources and conducted by a limited number of professionals with capacity limits related to the amount of information and analysis they can produce. Logistical challenges, resulting from things such as a lack of data and meta-data standards and conflicting binational priorities and structures, further complicate exchange and coordination. Transboundary aquifers are part of complex, interconnected natural and human systems. Determining what steps an assessment can take to achieve its objectives requires

consideration of not just what information it produces, but how and when this information is communicated and perceived within these complex systems. Given these realities, where should assessment resources be directed to produce the most impactful results? This study investigated modeling as a tool to assist with the prioritization of efforts within the data collection and exchange phase of transboundary aquifer assessments, hypothesizing that for scenarios in which two countries follow either identical or different timeframes, how and when information from a transboundary aquifer assessment is reported and perceived can dynamically impact behaviors of the shared water system. It should be noted that, while this study looks at a scenario for an aquifer shared between two countries, many transboundary aquifers are shared by more than two countries.

This research utilized system dynamics modeling [11] because the foundational structure of system dynamics maintains inherent similarities to hydrologic structures and the non-linear feedback characteristic of human and natural systems [12]. Similar to all models, the model developed in this study is only an abstract simplification of the problem [13]. The model in this study represents a simplification of interconnected natural and human components of a transboundary groundwater system to help make sense of its complexities. The model development process for this research was guided by the acknowledgment of the dominant influence of human behavior, executed through human decision-making, on hydrologic systems. This acknowledgment is the central driver of this study, which attempts to progress understanding of the complexities of human decision-making in innovative ways to understand hydrologic trends within the Anthropocene for transboundary systems.

The model explored the potential role of reporting and perception delays of water availability information in a transboundary groundwater system, positing that researchers can use modeling to understand interconnected human and natural processes to analyze the systemic impact of potential transboundary aquifer assessment efforts [14]. The model investigated the potential role of reporting and perception delays of water availability information in a transboundary groundwater system. This research addressed the following questions: Should assessments focus solely on the type of information they aim to produce and exchange? Or does how and when that information is reported and perceived necessitate prioritization? How do similarities and differences between nations regarding information reporting and perception delays manifest within a transboundary system? This study examined the dynamic hypothesis that how and when information from a transboundary aquifer assessment is reported and perceived, in scenarios where two countries follow identical and different timeframes, impacts the behaviors of the shared water system. A dynamic hypothesis is a logical explanation that relates the feedback structure of a complex system to its dynamic behavior [15].

Simulation experiments were conducted that investigate different reporting and perception delay realities in scenarios where two countries that share an aquifer system pursue identical and different transboundary aquifer assessment timeframes. Results that display oscillations indicate instability in the system. As an example, throughout the COVID-19 pandemic, oscillatory trends have persisted as decision-makers attempted to react to rapidly reported and perceived information and find a balance between heightening or loosening social-distancing related restrictions [16]. These oscillatory behaviors are not unique to the COVID-19 pandemic or to transboundary groundwater decision-making. The presence of these oscillatory behaviors indicates the need for policy optimization to achieve more stable outcomes.

2. Materials and Methods

The study site for this model encompasses the internationally neighboring communities of Sunland Park and Santa Teresa in New Mexico, United States (U.S.) and Anapra and San Jerónimo in Chihuahua, Mexico. These populations utilize a portion of the Mesilla Basin/Conejos-Médanos, which is one of four priority transboundary aquifers along the U.S.–Mexico border designated through the Transboundary Aquifer Assessment

Program [17]. The U.S. and Mexico manage the Mesilla Basin/Conejos-Médanos separately. The aquifer supports the populations that live within the area of the Mesilla Basin/Conejos-Médanos; additionally, these resources supply water for industrial operations on both sides of the border. In Mexico, water from the Mesilla Basin/Conejos-Médanos is pumped to meet the growing demands of neighboring Ciudad Juárez. A map of the study site is available in the Supplementary Materials. See [18] for further background about this study site. The model developed for this research depicts simplified natural, human, and technical components to better understand system behaviors and outcomes (Figure 1). Core behaviors and interconnections for this transboundary region have been modeled previously [18,19]. This study expands on the assumptions from those past efforts, which is explained in the subsections below, to facilitate the quantitative analysis of reporting and perception delays within a transboundary aquifer assessment process. While the model is based specifically on a section of the Mesilla Basin/Conejos-Médanos, the applicability of core behaviors to other transboundary systems makes the findings from the dynamic results insightful for arid and semi-arid regions with transboundary aquifers.
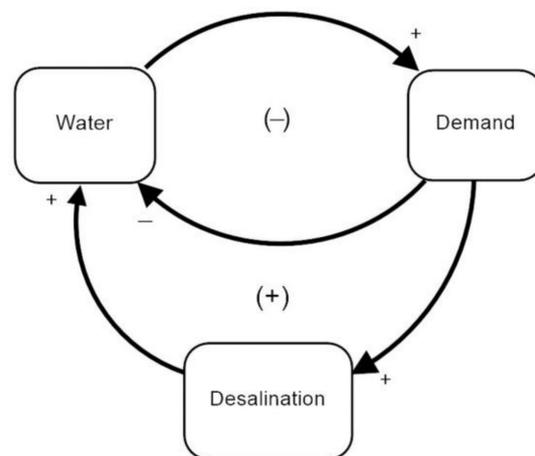

Figure 1. Showcases a simplified representation of the relationships between the model's three primary components.

The model developed for this study has three primary components, water, demand, and desalination (Figure 1), that are detailed in their correspondingly titled subsections. In Figure 1, the (+) indicates a positive or reinforcing loop, and the (−) indicates a negative or balancing loop; this structure was validated in water resources research modeling [20,21]. The water module contains hydrologic dynamics, the demand module contains components relating to the dynamics of water demand, and the desalination module contains components relating to the dynamics of desalination infrastructure and operation. Each module's subsection has a figure, referred to as a stock and flow diagram, that depicts its key components. These stock and flow diagrams are simplifications and do not include all the information needed to recreate the model. The stock and flow diagrams were developed in Stella Architect. Full model documentation is available in the Supplementary Materials section. Information about how to access an online version of the model that allows users to view and experiment with the model is included in the Supplementary Materials. The following standard system dynamics confidence building tests were utilized in the development of this model: boundary adequacy, structure assessment, dimensional consistency, parameter assessment, extreme conditions, integration error, behavior anomaly, surprise behavior, and sensitivity analysis [15]. From these tests, we confirmed that the feedbacks (see [18] for exogenous, endogenous, and excluded parameters) were necessary and aligned with the established hydrologic and decision-making theory. The dimensions were determined to be consistent, and the model underwent rigorous tests under extreme scenarios to ensure that it responded appropriately and logically.

2.1. Water

The quantity and quality-related water dynamics for this study were all rigorously validated through the standard system dynamics confidence building tests discussed in Section 2 [18]. They align with key hydrologic research findings for the Mesilla Basin/ Conejos-Médanos [22–28]. This region of the Mesilla Basin/Conejos-Médanos relies almost solely on groundwater for their drinking water supply. As such, the model only investigates groundwater dynamics. Many transboundary aquifers around the world have intrinsic though not fully understood connections to surface water [29]. While these realities do not apply in the study area for this research, the dynamics of surface water and groundwater connectivity should be accounted for when trying to understand the impact of transboundary aquifer assessments on behaviors for regions dependent on both supplies.

The stock and flow diagrams for each module use standard system dynamics modeling representation. Stocks, depicted in Figure 2 as rectangles, are a fundamental part of system dynamics modeling. They are measurable quantities, such as the brackish water stock in Figure 2. System dynamics models allow users to pursue an analysis that accounts for ranges of stock quantities, which reflects the uncertainty that oftentimes exists regarding quantities of freshwater in aquifers. Model stocks change based on model inflows and model outflows. In the model, freshwater withdrawal is a model outflow from freshwater and a model inflow to withdrawn water. The symbology utilized for freshwater withdrawal represents a flow, and it is used throughout the model to depict flows. As an example, a well that pumps freshwater from an aquifer represents a model outflow that decreases the aquifer's freshwater stock, but a model inflow increases the stock of water withdrawn from the aquifer. Converters are components of the system that indirectly affect stocks by directly impacting other converters or flows that are connected to stocks. Circles are used to show converters in this study; stored water availability serves as an example of a converter (Figure 2). Stocks and converters outlined with dotted lines differentiate components that come from a different module, such as the demand or desalination module in the context of Figure 2. Solid black arrows portray connections from stocks to converters, flows to flows, converters to converters, and converters to flows.
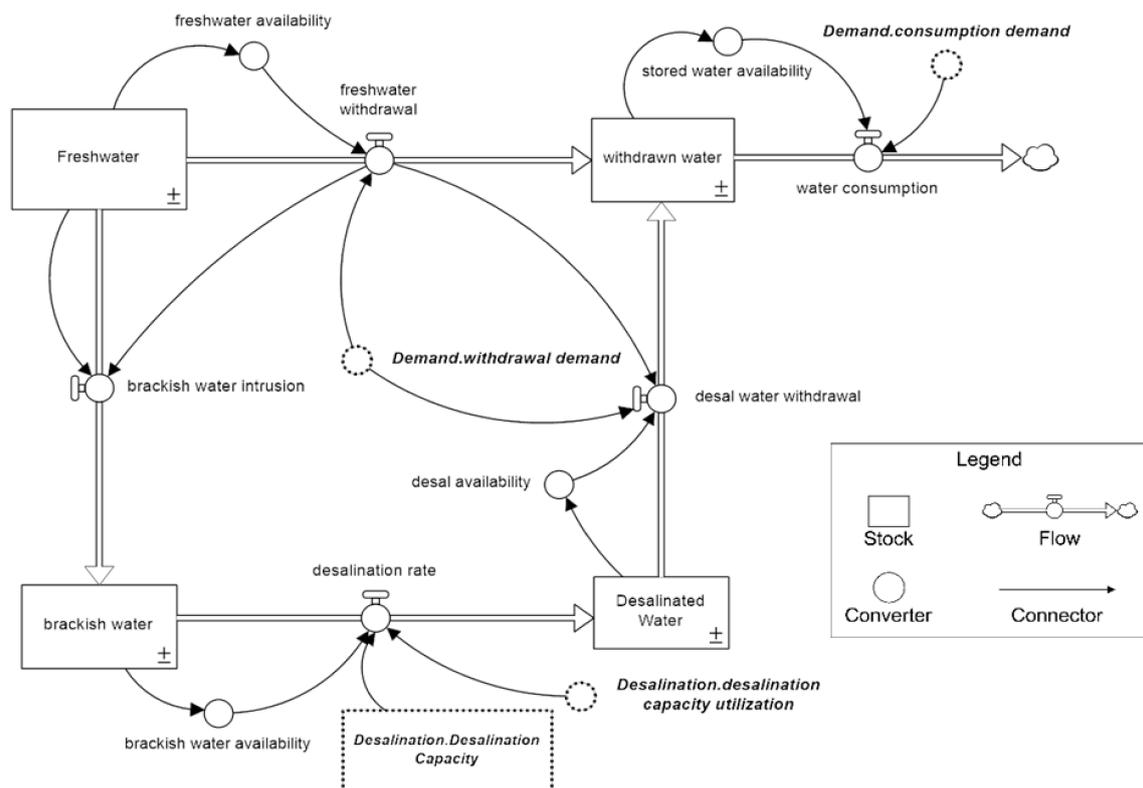

Figure 2. A simplification of the model's water component.

2.2. Demand

The demand module (Figure 3) explores human decision-making dynamics within the context of water demand. It centers around the understanding that perceptions of water availability and the water demand gap are key drivers of water demand [18]. This module was developed based on assumptions rooted in historical water demand trends and system interconnections. In this model, reported demand gap influences are perceived as a water demand gap [18]. While it is commonplace for water models that incorporate demand to calculate demand based primarily on population growth, data from the U.S. Geological Survey (USGS) shows that population increases to do not mean water usage will increase [30]. Our model does not calculate water as a function solely tied to population growth; in this model, the reported demand gap influences the perceived water demand gap [18]. Despite population growth, water use in the United States by 2010 was less than it was in 1970 [31]. This model relies on the assumption that perceptions of water availability have a critical influence on water demand. For example, perceptions of abundant groundwater availability led Albuquerque, New Mexico residents to use a peak of 272 gallons per person per day in 1989 [32,33]. Data instead revealed trends of groundwater depletion from a finite aquifer. In response, the city reduced its per capita water use to approximately 121 gallons per day by 2019, to reflect its updated perceptions of water availability [34–37]. Similar examples on different scales are abundant throughout history.

Figure 3. Key components of the demand module.

The reported demand gap is not instantaneously produced, and in this model, variations in reporting delay realities impact this timeline. The Results and Discussion section describes the context of reporting delay realities in further detail. Reported information does not become perceived by the system or understood in a way that dynamically impacts perceptions of water demand and availability immediately. The study also evaluates varying perception delays timelines.

Both Country A and Country B in the model have identical demand modules. Figure 3 demonstrates the demand module for Country A. The generic names Country A and County B were chosen to reflect the transferability of this study outside the Mesilla Basin/Conejos-Médanos. The demand divide between both countries, however, is not identical. This model explores a scenario where Country A is a majority water user. Coun-

try B uses 20% of the water that Country A does. The water use divide reflects approximate water use distributions in the studied section of the Mesilla Basin/Conejos-Médanos [18]. Uneven divides between water use or the spatial distribution of transboundary aquifers across borders is a common reality. For example, approximately 90% of the Genevese Aquifer is in Switzerland, while approximately 10% is in neighboring France [38].

The model assumes that, to minimize a demand gap, demand must be decreased, or supply must be increased. Decreasing demand and increasing supply can occur simultaneously in this model. Increasing the water supply was investigated in this model through the implementation of inland desalination, which is discussed further in the desalination subsection below. The conservation effect in this study is an aggregate decision rule that acts based on water supply and demand. When the demand gap increases, the conservation effect accounts for scenarios where there is a collective response to reducing water demand. In Figure 3, the collective response comes from Country A. We assume that demand gap does not immediately impact the conservation effect decision rule. An anchoring and adjustment process takes place to produce a normal demand gap [39]. This module considers bounded rationality by taking this anchoring and adjustment heuristic (rule of thumb for decision-making) into account [40].

2.3. Desalination

The desalination module (Figure 4) reflects the reality that water decision-makers implement policies in the present to meet future needs. Policies that involve changes to built and natural environments, such as the implementation of desalination, have binding characteristics and cannot be easily adjusted. Desalination represents an alternative water supply option that can be pursued to increase freshwater supply in this study site. Inland desalination has specifically received attention as a potential policy for this region, as well as other arid and semi-arid inland regions. Pursuing desalination will impact the built and natural environments; including it as a policy option in the model provides insight into its dynamics for this and other inland regions considering desalination. The model simplifies the options decision-makers have available to decrease demand or increase supply to lessen the demand gap. The reported demand gap from both countries impacts the total demand gap. The policy perception delay represents the time between when reported information was perceived in a way that impacts society's perceptions of water availability and policies that reflect those perceptions were implemented. In the simulation experiments conducted in this study, the policy perception delay remains set at a constant 2 years for all runs. Differing political structures between countries that share transboundary aquifers likely means differing policy implementation timelines. Variations in this delay for transboundary aquifers need further investigation. The desalination component of the model was rigorously assessed [18].

2.4. Simulation Experiments

Both countries maintain equivalent reporting and perception delays in Runs 1–3 (Table 1). In Run 1, there is a 1-year reporting delay and a 2-year perception delay. In this scenario, water availability information was collected, analyzed, and reported within the span of 1 year. The reported information is understood and contributes to the public perception of water availability in the system, 2 years into the entire process. A 2-year policy perception delay exists in every run in this study. This delay accounts for the time between the information being perceived and implemented as policy. In Run 2, both countries exhibit a 5-year reporting delay and a 6-year perception delay. Similar to Run 1, there is a 1-year delay between the reporting delay and the perception delay. This 1-year delay remains consistent across all runs in the study. Run 3 represents the lengthiest cumulative delay, with a 10-year reporting delay and an 11-year perception delay.
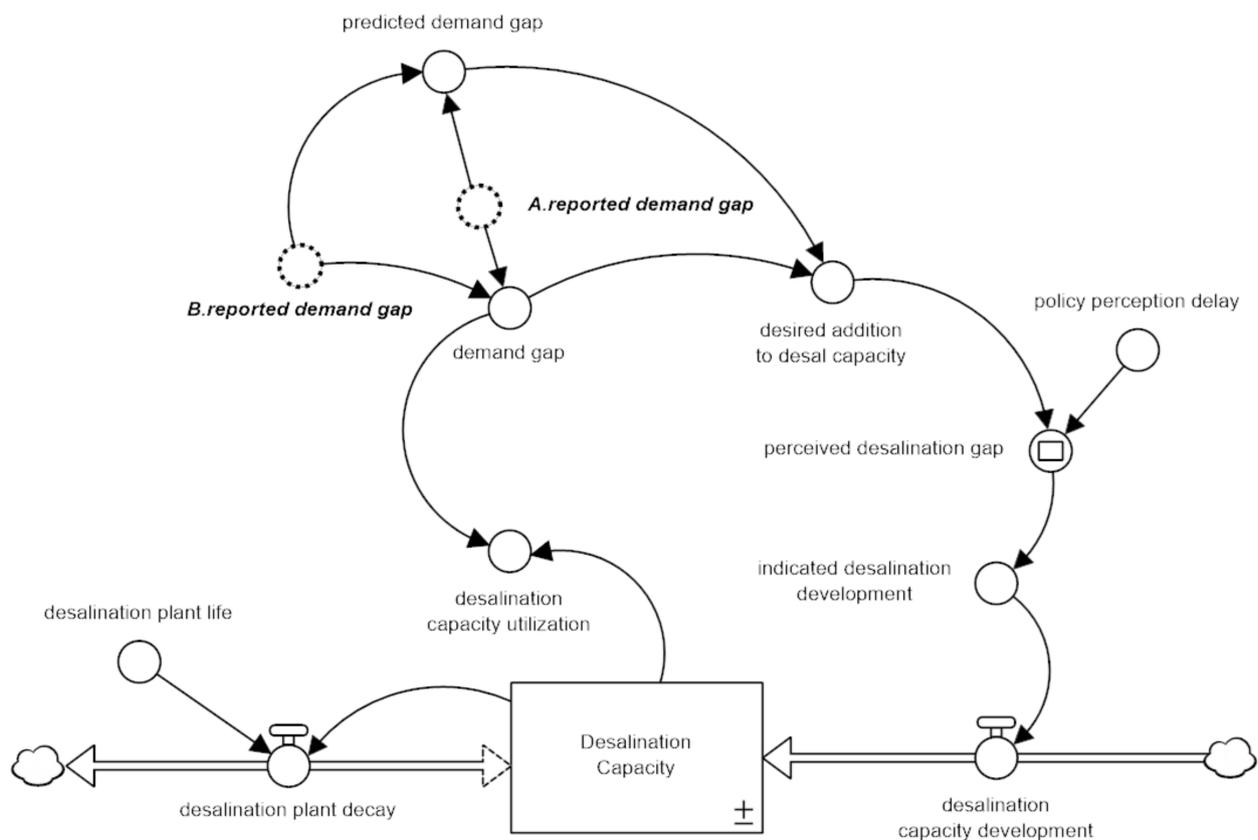
Figure 4. A depiction of the desalination module's core components.

As shown in Table 1, both countries maintain differing reporting and perception delays in Run 4 and Run 5. In each of these runs, one country has the reporting and perception delay from Run 1, while the other country has the reporting and perception delay from Run 2. In Run 4, Country A has a 1-year reporting delay and a 2-year perception delay; Country B has a 5-year reporting delay and a 6-year perception delay. In Run 5, Country A has a 5-year reporting delay and a 6-year perception delay; Country B has a 1-year reporting delay and a 2-year perception delay. In the absence of assessments or agreements, countries that share transboundary aquifers act on their own to develop, process, and implement information. However, in an ideal scenario, scenarios can pursue agreements or assessments together and develop, process, and implement information on the same timeline. This study investigates the impacts of both options: when two countries that share a transboundary groundwater system follow the same and different timelines.

Transboundary groundwater resources can be referred to as common pool resources [41,42]. Rather than homogenously examining the impact of transboundary aquifer assessments through the lens of common-pool resource theory, this study design recognizes that a plethora of dynamics within the system can and have in practice, as witnessed through TAAP, result in delays. The tests selected for this study are a way to empirically evaluate the impact of these heterogeneous delays on the system. A plethora of dynamics can contribute to delays; the delays in this study were chosen based on the assumptions below. The purpose of this study is not to recreate the entire system and examine every possible influencing factor for a delay. Rather, it is to provide dynamic insight into the impact that delays themselves might have on the system and the effectiveness of transboundary aquifer assessments.

The perception and reporting delays explored in Runs 1–5 are compared against different conservation parameters and maximum conservation in Runs 6–18. These parameters control people's response to water shortage in the model as shown by Equation (1), where f(x) is the effect of water shortage on water demand, x is normalized water shortage, m

is maximum conservation, and *p* is conservation parameter. The conservation parameter (*p*) represents people's responsiveness in conservatory reaction to water shortage. The maximum conservation (m) places a limit on the quantity of water that the system can conserve. Equation (1) implies that water demand reacts to water shortage in the opposite direction, but the significance of this reaction depends on m and *p*.

$$f(x) = \max(m, 1 - p\,(x - 1)) \tag{1}$$

Runs 1–15 explore the same runs with different conservation parameters and a constant maximum conservation parameter. The runs with a 0.1 conservation parameter are the least sensitive, and the runs with a 0.9 conservation parameter are the most sensitive. The maximum conservation limit in Runs 1–15 means that water usage can be reduced by up to 50%. In Runs 16–18, the maximum conservation limit is set to reflect an extreme scenario of up to a 90% possible reduction in water usage.

Table 1. Details for each of the runs conducted in this study.

Run	Country	Perception Delay	Reporting Delay	Conservation Parameter	Maximum Conservation Parameter
1	A	1	2	0.5	0.5
	B	1	2	0.5	0.5
2	A	5	6	0.5	0.5
	B	5	6	0.5	0.5
3	A	10	11	0.5	0.5
	B	10	11	0.5	0.5
4	A	1	2	0.5	0.5
	B	5	6	0.5	0.5
5	A	5	6	0.5	0.5
	B	1	2	0.5	0.5
6	A	1	2	0.1	0.5
	B	1	2	0.1	0.5
7	A	5	6	0.1	0.5
	B	5	6	0.1	0.5
8	A	10	11	0.1	0.5
	B	10	11	0.1	0.5
9	A	1	2	0.1	0.5
	B	5	6	0.1	0.5
10	A	5	6	0.1	0.5
	B	1	2	0.1	0.5
11	A	1	1	0.9	0.5
	B	1	2	0.9	0.5
12	A	5	6	0.9	0.5
	B	5	6	0.9	0.5
13	A	10	10	0.9	0.5
	B	11	11	0.9	0.5
14	A	1	2	0.9	0.5
	B	5	6	0.9	0.5
15	A	5	6	0.9	0.5
	B	1	2	0.9	0.5
16	A	1	2	0.1	0.9
	B	1	2	0.1	0.9
17	A	1	2	0.5	0.9
	B	1	2	0.5	0.9
18	A	1	2	0.9	0.9
	B	1	2	0.9	0.9

The run periods were chosen to show differing cumulative reporting and perception delay realities. Beginning a study and producing reporting results within the span of 1 year,

as exhibited in Run 1, is arguably an expedited timeline. The delay between submission and publication of peer-reviewed research alone can span a year or longer [43]. These delays, however, were shortened in the face of extreme circumstances such as the COVID-19 pandemic, which has expedited medical research and publication timelines [44,45]. In the context of extreme water-related local circumstances, such as elevated lead levels in Flint, Michigan and water shortages in Cape Town, South Africa, traditional timelines and procedures have also adapted [46–48]. The National Science Foundation's grants are generally awarded for no more than 5 years; Run 2 showcases behaviors associated with a 5-year reporting delay. The time between identifying an area of research that needs data collection, securing funding and resources, collecting data, analyzing data, and ultimately reporting that data and analysis can take much longer than 5 years. Run 3 shows these realities with a 10-year reporting delay. It should also be noted that reporting and perception delays can also extend well beyond the selected times from these runs, particularly for transboundary regions that face additional coordination challenges.

All simulation experiments in this study are conducted over a 50-year period. This period was selected to reflect a realistic planning horizon for the region. New Mexico and Texas, the two states on the U.S. side of the border that the Mesilla Basin/Conejos-Médanos falls within, either developed or are developing 50-year water plans. Regional and local planning horizons around the world vary; most fall within increments at or under a 50-year period. The 50-year planning horizons were utilized previously in system dynamics water modeling and simulations. While occasionally 100-year horizons are pursued by water managers, plans that extend beyond this are rare.

3. Results and Discussion

3.1. Users with Identical Perception and Reporting Delays

The perception and reporting delays associated with assessment information impact the dynamics of the shared system and lead to different freshwater quantity outcomes (Figure 5). Runs 1–3 showcase scenarios where both countries follow identical timelines; assessment information regarding water availability is reported, perceived, and implemented through policies at the same time for each country. These runs show that even a few years of difference in delays can impact the overall effectiveness of assessments. While these simulation experiments serve as a helpful baseline for understanding transboundary aquifer assessment behaviors and impacts, their level of synced coordination may be difficult to attain in practice, even in regions with established cooperation mechanisms. Therefore, it remains important to investigate the possibility of each county following a different timeline.

3.2. Users with Different Perception and Reporting Delays

The simulation experiments for Runs 4 and 5 show that differences between countries in how and when information from an assessment is reported and perceived ultimately affects outcomes for freshwater resources and system components connected with freshwater resources. Runs 4 and 5 have cumulative delay differences of 4 years between each country; there is a 4-year difference between the perception delays and the reporting delays in Runs 4 and 5 (Figure 5). These simulation experiments are intended to explore the potential impacts of coordinated assessments that progress on divergent timelines. The 4-year difference, while seemingly small compared with the 50-year reporting period, notably impacts the behavior of the system. These simulation experiments show that differences between countries in how and when information from a transboundary aquifer assessment is reported and perceived ultimately affects outcomes for freshwater resources. The reporting and perception delay maintained by Country A, the majority water user, dictates the overall withdrawal behaviors and freshwater behavior of the system as exhibited in the comparison between Run 1 and Run 4 (Figure 5). However, the reporting and perception delays of Country B have an influence on the overall behaviors. Comparing the behavior

of the freshwater supply between Run 2 and Run 5 showcases an example of this minority water user influence (Figure 5).
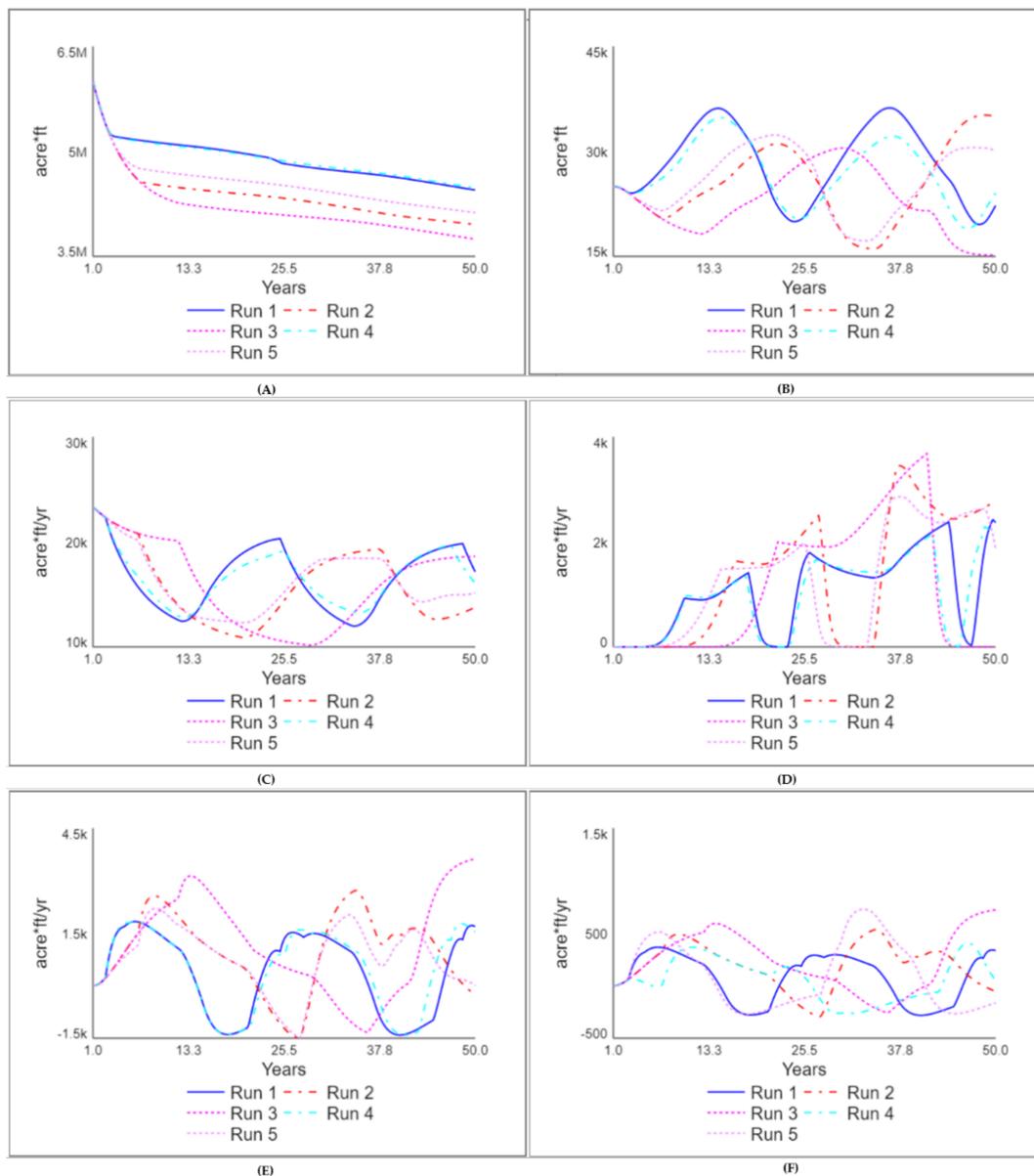

Figure 5. Results of Runs 1–5 for (**A**) freshwater; (**B**) withdrawn water; (**C**) freshwater withdrawal; (**D**) desalinated water withdrawal; (**E**) Country A demand gap; and (**F**) Country B demand gap. The name for each graph corresponds with the name of the selected stock in the model. For example, (**A**) showcases the dynamic quantity of freshwater in the system over the run period of 50 years.

3.3. Practical Implications

An important finding is that all simulation experiments in this study exhibit undesirable behaviors due to the oscillatory behavior of the results, which reflects instability in the system. The decision-makers in Run 1 react most rapidly to changes in freshwater availability and most predictably with almost identical amplitudes and periods for withdrawn water (Table 2). All runs start out on the same freshwater depletion trajectory. Run 1 reacts the most quickly and aggressively to the depletion trend and achieves the best result for the freshwater supply at the end of the 50-year simulation. Run 2 and Run 3 continue the same freshwater depletion trajectory as each other until they begin their staggered responses. The simulations showcase a tradeoff; scenarios with increased delays result in

reduced oscillatory behaviors but lead to a greater use of water resources. Optimizing the runs to reduce volatility by maximizing the period and minimizing the amplitude of an oscillation can result in more stable outcomes. In the context of this study, an optimization of transboundary aquifer assessments would mean that both countries simultaneously receive and perceive water availability information from assessments quickly but react less aggressively and with more foresight for long-term, systemic trends.

Table 2. A description first and second amplitudes and periods for Runs 1–5 for withdrawn water, which is also displayed in Figure 5B.

Run	Amplitude 1	Amplitude 2	Period 1	Period 2
1	16.1	16.2	10	12
2	10.5	15	14	12
3	12.3	15.3	18	18
4	14.3	11.7	12	10
5	15.1	13.3	11	24

3.4. System Sensitivity

Runs 6–15 showcase behaviors for scenarios with a different conservation parameter (p) and a constant maximum conservation (m) (Figure 6). Note that p controls the strength of the negative (balancing) feedback loop in Figure 1, which goes through demand gap, water demand, and withdrawal. We know that negative feedback loops when coupled with significant delays can generate oscillatory behaviors [49]. Higher values of p strengthen this feedback loop and potentially generate greater oscillations. When p is set to 0.5, the model produces relatively large oscillatory behavior (Figure 5). Setting p to 0.9, such as it is in Runs 11–15, strengthens the feedback loop and produces similar dynamic behaviors (Figure 6). When p is set at 0.1 in Runs 6–10, the negative feedback loop is weakened and almost knocked off, and the system becomes insensitive in this case (Figure 6). In the context of this study, an assessment that increases sensitivity above the threshold has a negligible impact on the behaviors of the system. Assessment outputs produced below the threshold will likely not meet their intended outcomes, given the effects of the system's insensitivity.

3.5. Extreme Scenarios

Runs 16–18 test each of these three different p values in an extreme scenario where m is set to 0.9, meaning that the system can reduce water usage up to 90% (Figure 7). Even in this extreme scenario, the behaviors for p at 0.5 and 0.9 are similar, and the behavior for p at 0.1 results in less sensitive and less oscillatory behaviors. These results strengthen confidence in the model as they corroborate our previous knowledge of the systems. They also reveal that a threshold for p exists somewhere between 0.1 and 0.5. Making investments that increase the sensitivity of the system for conservation between the threshold and 0.9 have little impact on the overall behaviors of the system. In the context of a transboundary aquifer assessment, assessment outputs intended to increase system sensitivity can likely have a negligible impact on overall behaviors.

Assessments producing outputs in a system with sensitivity below the threshold likely cannot meet their intended outcomes given the absence of the critical feedback loop between availability and demand that drives behaviors in this scenario. Future research needs to identify the threshold for a system and for a transboundary system, the implications of differing thresholds. These initial results showcase the critical impact that conservation parameters can have on the outcomes of assessments.
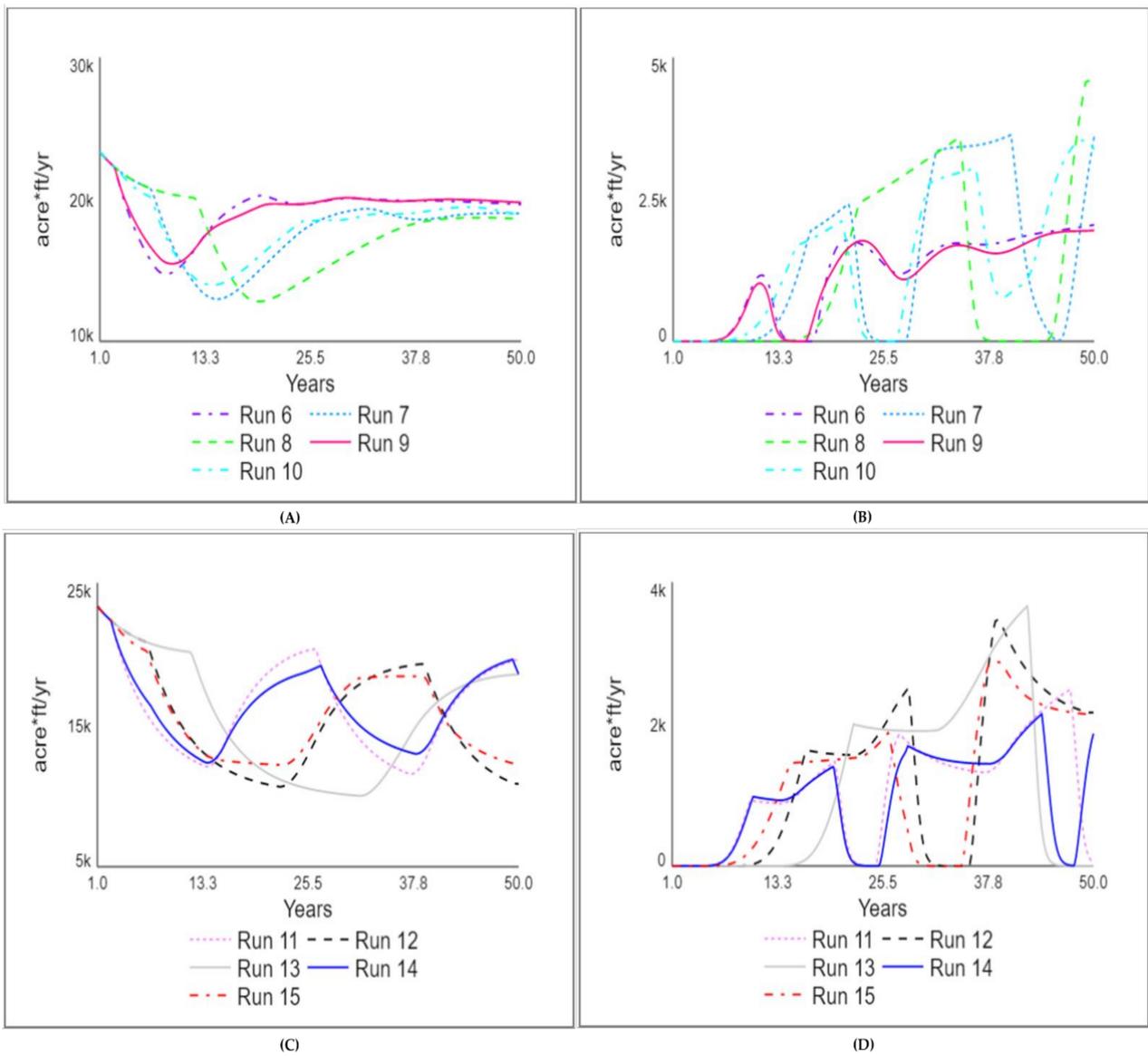
Figure 6. Results of runs 6–10 for (**A**) freshwater withdrawal and (**B**) desalinated water withdrawal. Results of runs 11–15 for (**C**) freshwater withdrawal and (**D**) desalinated water withdrawal.
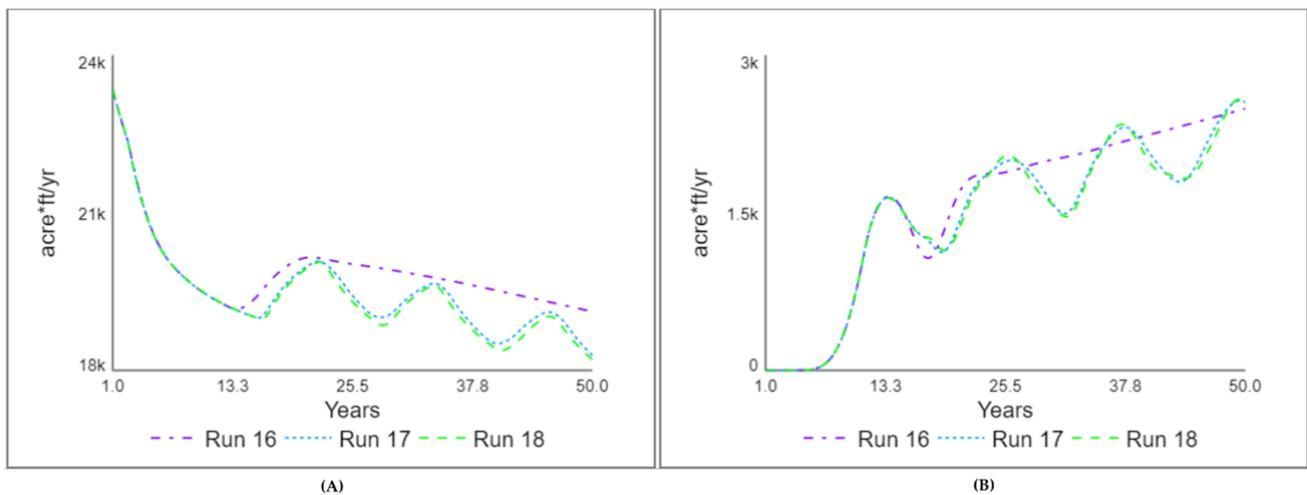

Figure 7. Results of Runs 16–18 for (**A**) freshwater withdrawal and (**B**) desalinated water withdrawal.

3.6. Future Work

Future research needs to identify the conservation parameter threshold for a system and, for transboundary resources, the implications of differing thresholds between countries. The findings regarding the threshold are also widely applicable beyond transboundary systems and should be incorporated more broadly in research investigating the potential impacts of water policies to ensure that decisions can meet their intended outcomes. Additional future work requires exploration into the complex relationships between information reporting, perception, and policy implementation. Langarudi et al. (2021) provides insight into breaking down the information perception process so that its individual components can be analyzed within a system [50]. To carry out our initial investigation, each run in this study had a 1-year gap between the reporting delay and the perception delay and a 2-year gap between the perception delay and the policy delay. These timeframes—and the complex feedbacks that drive them—are not always so straightforward. For example, the science that identified climate change is not new and has been increasing for decades [51,52].

Despite the depth of reported climate change information, decision-making behaviors have not reversed the global warming trends identified in scientific literature. How does the accumulation of reported information affect perceptions? How are policy implementation timeframes impacted by the formulation of divergent perceptions, either within a nation or between nations? These are just some of the questions that may need to be accounted for when pursuing future research. The intricacies of interactions between human decision-making and the hydrologic system might benefit from the innovative application of hybrid modeling that combines system dynamics and agent-based modeling methodologies. While system dynamics models are well-suited for hydrologic structures, agent-based models can allow for a more complex analysis of the rules that govern decision-making behaviors, particularly when studying questions with spatial components [53].

4. Conclusions

This study explored the dynamic hypothesis that how and when information from a transboundary aquifer assessment is reported and perceived impacts the behaviors of the shared water system. The simulation experiments showed a tradeoff; scenarios with reduced oscillatory behavior resulted in greater water use. Based on the evidence of the simulations, we conclude that the explored perception dynamics change the behavior of the transboundary water system. The simulations conducted in this study produced oscillatory behaviors that reflect instability in the system. Optimizing the runs to produce more stable results would mean that both countries receive and perceive water availability information from assessments on the same timeline and react to that information less aggressively and with long-term planning foresight. An optimization that accounts for the sensitivity of a system related to conservation parameters is also a key component in ensuring that the goals of an assessment are met and that investments are made efficiently. Determining how to accomplish this optimization within the complexities of human decision-making behaviors requires further investigation. Transboundary groundwater assessments have been recognized as key components of effective transboundary groundwater management. Understanding what impedes the success of assessments and how assessment characteristics impact the overall system are important areas of exploration to ensure that assessments achieve their intended outcomes. Modeling, as exhibited in this study, serves as a useful tool with the potential to assist with the prioritization efforts within the data collection and exchange phase of transboundary aquifer assessments.

References

1. Famiglietti, J.S. The global groundwater crisis. *Nat. Clim. Chang.* **2014**, *4*, 945–948. [CrossRef]
2. Konikow, L.F.; Kendy, E. Groundwater depletion: A global problem. *Hydrogeol. J.* **2005**, *13*, 317–320. [CrossRef]
3. Siebert, S.; Burke, J.; Faures, J.M.; Frenken, K.; Hoogeveen, J.; Döll, P.; Portmann, F.T. Groundwater use for irrigation—A global inventory. *Hydrol. Earth Syst. Sci.* **2010**, *14*, 1863–1880. [CrossRef]
4. Wada, Y.; Van Beek, L.P.H.; Van Kempen, C.M.; Reckman, J.W.T.M.; Vasak, S.; Bierkens, M.F.P. Global depletion of groundwater resources. *Geophys. Res. Lett.* **2010**, *37*, 37. [CrossRef]
5. IGRAC (International Groundwater Resources Assessment Centre). *Transboundary Aquifers of the World*; UNESCO International Hydrologic Programme; IGRAC: Delft, The Netherlands, 2015.
6. Wada, Y.; Heinrich, L. Assessment of transboundary aquifers of the world—vulnerability arising from human water use. *Environ. Res. Lett.* **2013**, *8*, 024003. [CrossRef]
7. Eckstein, G.; Eckstein, Y. A Hydrogeological Approach to Transboundary Ground Water Resources and International Law. *Am. Univ. Int. Law Rev.* **2003**, *19*, 201–258.
8. Ganoulis, J.; Fried, J. *Transboundary Hydro-Governance: From Conflict to Shared Management*; Springer: Cham, Switzerland, 2018. Available online: https://libezp.nmsu.edu:2176/lib/nmsu/reader.action?docID=5419660&ppg=10 (accessed on 1 February 2021).
9. Albrecht, T.R.; Varady, R.G.; Zuniga-Teran, A.; Gerlak, A.K.; Staddon, C. Governing a shared hidden resource: A review of governance mechanisms for transboundary groundwater security. *Water Secur.* **2017**, *2*, 43–56. [CrossRef]
10. Tapia-Villaseñor, E.; Megdal, S. The U.S.-Mexico Transboundary Aquifer Assessment Program as a Model for Transborder Groundwater Collaboration. *Water* **2021**, *13*, 530. [CrossRef]
11. Forrester, J.W. *Industrial Dynamics*; Productivity Press: Cambridge, MA, USA, 1961.
12. Winz, I.; Brierley, G.; Trowsdale, S. The Use of System Dynamics Simulation in Water Resources Management. *Water Resour. Manag.* **2008**, *23*, 1301–1323. [CrossRef]
13. Sterman, J.D. All models are wrong: Reflections on becoming a systems scientist. *Syst. Dyn. Rev.* **2002**, *18*, 501–531. [CrossRef]
14. Blair, P.; Buytaert, W. Socio-hydrological modelling: A review asking "why, what and how?". *Hydrol. Earth Syst. Sci.* **2016**, *20*, 443–478. [CrossRef]
15. Sterman, J. *Business Dynamics: Systems Thinking and Modeling for a Complex World*; Irwin/McGraw-Hill: New York, NY, USA, 2000. Available online: https://books.google.com/books?id=CCKCQgAACAAJ (accessed on 1 February 2021).
16. Glaubitz, A.; Fu, F. Oscillatory dynamics in the dilemma of social distancing. *Proc. R. Soc. A Math. Phys. Eng. Sci.* **2020**, *476*, 20200686. [CrossRef]
17. Bingaman, J. United States-Mexico Transboundary Aquifer Assessment Act. In *International Groundwater Law and the US-Mexico Border Region*; Brill Nijhoff: Leiden, The Netherlands, 2006.
18. Page, A.; Langarudi, S.; Forster-Cox, S.; Fernald, A. A Dynamic Hydro-Socio-Technical Policy Analysis of Transboundary Desalination Development. *J. Environ. Account. Manag.* **2019**, *7*, 91–118. [CrossRef]
19. Page, A. A Public Policy Modeling Analysis of the Sustainability of Transboundary Desalination within the Sunland Park-Santa Teresa-San Jerónimo-Anapra Hydrologic-Social System. Master's Thesis, New Mexico State University, Las Cruces, NM, USA, 2018.
20. Di Baldassarre, G.; Wanders, N.; AghaKouchak, A.; Kuil, L.; Rangecroft, S.; Veldkamp, T.I.E.; Garcia, M.; van Oel, P.; Breinl, K.; Van Loon, A.F. Water shortages worsened by reservoir effects. *Nat. Sustain.* **2018**, *1*, 617–622. [CrossRef]

21. Di Baldassarre, G.; Sivapalan, M.; Rusca, M.; Cudennec, C.; Garcia, M.; Kreibich, H.; Konar, M.; Mondino, E.; Mård, J.; Pande, S.; et al. Sociohydrology: Scientific Challenges in Addressing the Sustainable Development Goals. *Water Resour. Res.* **2019**, *55*, 6327–6355. [CrossRef]

22. Gates, J.S.; Stanley, W.; Ackermann, H. Availability of fresh and slightly saline ground water in the basins of westernmost Texas. In *Open-File Report*; US Geological Survey: Reston, VA, USA, 1978; pp. 1258–2331.

23. Hawley, J. *Challenges and Opportunities for Brackish Groundwater Resource Development in New Mexico—Prediction Hydro-Science from an Octogenarian Hydrogeologist's Perspective*; White Paper; Hawley Geomatters: Albuquerque, NM, USA, April 2016.

24. Hawley, J.; Kennedy, J.; Creel, B. The Mesilla Basin Aquifer System of New Mexico, West Texas, and Chihuahua—An Overview of Its Hydrogeologic Framework and Related Aspects of Groundwater Flow and Chemistry. In *Aquifers of West Texas*; Angle, E.S., Mace, R.E., Mullican, W.F., III, Eds.; Texas Water Development Board: Austin, TX, USA, 2001; pp. 76–99.

25. Ojeda, G. Aquifer recharge estimation at the Mesilla Bolson and Guaymas aquifer systems, Mexico. In *Isotope Based Assessment of Groundwater Renewal in Water Scarce Regions*; Edmunds, W.M., Ed.; International Atomic Energy Agency: Vienna, Austria, 2001; pp. 23–44.

26. Sheng, Z. Impacts of groundwater pumping and climate variability on groundwater availability in the Rio Grande Basin. *Ecosphere* **2013**, *4*, 1–25. [CrossRef]

27. Texas Water Development Board and New Mexico Water Resources Research Institute. *Transboundary Aquifers of the El Paso/Ciudad Juarez/Las Cruces Region*; US Environmental Protection Agency: Washington, DC, USA, October 1997.

28. Witcher, J.; King, J.P.; Hawley, J.; Williams, J.; Cleary, M.; Bothern, L. *Sources of Salinity in the Rio Grande and Mesilla Basin Groundwater*; WRRI Technical Completion Report 330; New Mexico Water Resources Research Institute: Las Cruces, NM, USA, February 2004.

29. Rivera, A. Transboundary aquifers along the Canada–USA border: Science, policy and social issues. *J. Hydrol. Reg. Stud.* **2015**, *4*, 623–643. [CrossRef]

30. Maupin, M.A.; Kenny, J.F.; Hutson, S.S.; Lovelace, J.K.; Barber, N.L.; Linsey, K.S. Estimated use of water in the United States in 2010. In *Circular 1405*; US Geological Survey: Reston, VA, USA, 2014. [CrossRef]

31. Cooley, H.; Donnelly, K. *Proposed Seawater Desalination Facilities in California*; The Pacific Institute: Oakland, CA, USA, 2012. Available online: http://pacinst.org/app/uploads/2014/04/desalination-facilities.pdf (accessed on 27 January 2017).

32. Selcraig. Albuquerque learns it really is a desert town. *High Country News*, 26 December 1994.

33. Indicators Progress Commission. *City of Albuquerque Progress Report 2004*; City of Albuquerque: Albuquerque, NM, USA, 2004.

34. Indicators Progress Commission. *City of Albuquerque Progress Report 2020*; City of Albuquerque: Albuquerque, NM, USA, 2020.

35. Albuquerque Bernalillo County Water Utility Authority. *2015 Annual Report: Groundwater on the Rebound*; Albuquerque Bernalillo County Water Utility Authority: Albuquerque, NM, USA, 2015.

36. Fleck, J. Aquifer rising despite drought. *Albuquerque Journal*, 6 October 2013.

37. Davis, T. Aquifer on the rebound. *Albuquerque Journal*, 23 August 2019.

38. Cobos, G.D.L. The Genevese transboundary aquifer (Switzerland-France): The secret of 40 years of successful management. *J. Hydrol. Reg. Stud.* **2018**, *20*, 116–127. [CrossRef]

39. Tversky, A.; Kahneman, D. Judgment under uncertainty: Heuristics and biases. *Science* **1974**, *185*, 1124–1131. [CrossRef]

40. Simon, H.A. Bounded Rationality. In *Utility and Probability*; Eatwell, J., Milgate, M., Newman, P., Eds.; Palgrave Macmillan: London, UK, 1990; pp. 15–18. [CrossRef]

41. Roumasset, J.A.; Wada, C.A. Chapter 5—Integrated Groundwater Resource Management. In *Sustainable Economic Development*; Balisacan, A.M., Chakravorty, U., Ravago, M.-L.V., Eds.; Academic Press: San Diego, CA, USA, 2015; pp. 77–89. [CrossRef]

42. Petersen-Perlman, J.D.; Megdal, S.B.; Gerlak, A.K.; Wireman, M.; Zuniga-Teran, A.A.; Varady, R.G. Critical Issues Affecting Groundwater Quality Governance and Management in the United States. *Water* **2018**, *10*, 735. [CrossRef]

43. Björk, B.-C.; Solomon, D. The publishing delay in scholarly peer-reviewed journals. *J. Inf.* **2013**, *7*, 914–923. [CrossRef]

44. Horbach, S.P.J.M. Pandemic publishing: Medical journals strongly speed up their publication process for COVID-19. *Quant. Sci. Stud.* **2020**, *1*, 1056–1067. [CrossRef]

45. Lipworth, W.; Gentgall, M.; Kerridge, I.; Stewart, C. Science at Warp Speed: Medical Research, Publication, and Translation During the COVID-19 Pandemic. *J. Bioethical Inq.* **2020**, *17*, 555–561. [CrossRef]

46. Hanna-Attisha, M.; Lachance, J.; Sadler, R.C.; Schnepp, A.C. Elevated Blood Lead Levels in Children Associated With the Flint Drinking Water Crisis: A Spatial Analysis of Risk and Public Health Response. *Am. J. Public Health* **2016**, *106*, 283–290. [CrossRef] [PubMed]

47. Simpson, N.; Shearing, C.; Dupont, B. Climate gating: A case study of emerging responses to Anthropocene Risks. *Clim. Risk Manag.* **2019**, *26*, 100196. [CrossRef]

48. Visser, W.P. A perfect storm: The hydropolitics of Cape Town's water crisis. *J. Transdiscipl. Res. S. Afr.* **2018**, *14*, 10. [CrossRef]

49. Bradley, J. Morrison and Rogelio Oliva, Integration of Behavioral and Operational Elements Through System Dynamics. In *The Handbook of Behavioral Operations*; Wiley: New York, NY, USA, 2017. Available online: https://papers.ssrn.com/abstract=2997235 (accessed on 1 August 2021).

50. Langarudi, S.P.; Silva, C.G.; Fernald, A.G. Measure more or report faster? Effect of information perception on management of the commons. *Syst. Dyn. Rev.* **2021**, *37*, 72–92. [CrossRef]

51. Arrhenius, S. XXXI. On the influence of carbonic acid in the air upon the temperature of the ground. *Lond. Edinb. Dublin Philos. Mag. J. Sci.* **1896**, *41*, 237–276. [CrossRef]
52. Marx, W.; Haunschild, R.; Thor, A.; Bornmann, L. Which early works are cited most frequently in climate change research literature? A bibliometric approach based on Reference Publication Year Spectroscopy. *Scientometrics* **2017**, *110*, 335–353. [CrossRef]
53. Langarudi, S.; Sabie, R.; Bahaddin, B.; Fernald, A. A Literature Review of Hybrid System Dynamics and Agent-Based Modeling in a Produced Water Management Context. *Modelling* **2021**, *2*, 12. [CrossRef]