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Evaluation of power generation operations in response to changes in surface water reservoir storage

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Abstract
We used a customized, river basin-based model of surface water rights to evaluate the response of power plants to drought via simulated changes in reservoir storage. Our methodology models surface water rights in 11 river basins in Texas using five cases: (1) storage decrease of existing capacity of 10%, (2) storage decrease of 50%, (3) complete elimination of storage, (4) storage increase of 10% (all at existing locations), and (5) construction of new reservoirs (at new locations) with a total increase in baseline reservoir capacity for power plant cooling of 9%. Using the Brazos River basin as a sample, we evaluated power generation operations in terms of reliability, resiliency, and vulnerability. As simulated water storage decreases, reliability generally decreases and resiliency and vulnerability remain relatively constant. All three metrics remain relatively constant with increasing reservoir storage, with the exception of one power plant. As reservoir storage changes at power plants, other water users in the basin are also affected. In general, decreasing water storage is beneficial to other water users in the basin, and increasing storage is detrimental for many other users. Our analysis reveals basin-wide and individual power plant-level impacts of changing reservoir storage, demonstrating a methodology for evaluation of the sustainability and feasibility of constructing new reservoir storage as a water and energy management approach.

Keywords: power plants, reliability, reservoir storage, resiliency, surface water, vulnerability

1. Introduction and background: water for thermoelectric power plants

Energy and water are interrelated, particularly for thermoelectric power generation where water is typically used for power plant cooling. Such thermoelectric power plants burn or react fuel to create heat that converts high-purity water into steam in a boiler. That steam then turns a turbine connected to a generator, thereby producing electric power. A condenser, generally using cooling water, then condenses the steam back into high-purity water in a closed system. The cooling water used for steam condensation is the largest use of water in a power plant, representing about 90% or more of total plant water use [1], and varies based on fuel source, power generation technology, cooling system, and other climatic and external factors [2–6]. In particular, the type of boiler used at a power plant (subcritical, supercritical, or ultra-supercritical) and the cooling technology (open-loop, cooling reservoir, cooling tower, hybrid wet–dry, or dry cooling) can introduce marked variation in water withdrawal and consumption rates (in m^3 kWh^{-1}, or similar units) (see [7] for full discussion). The need for cooling water makes thermoelectric power plants vulnerable to water constraints. Extended droughts and heat waves can affect the quantity and quality of water available, making it difficult to balance competing uses. Consequently, some power plants might need to curtail or suspend operations due to lack of water availability, as was observed during the 2007–2008 drought in the southeast United States [8, 9], the 2011 drought in Texas [10], and the 2012 drought throughout the midwest United States [11].

Storage of a resource is commonly accepted as beneficial, providing a stable supply even in the event of disruption. For water resources, storage in the form of reservoirs, aquifers, or engineered systems can retain excess rainfall and runoff for future use. In many cases, construction of new reservoirs and other storage sinks is a common approach to increasing and stabilizing water supply. However, closed basins where no excess water flows into sinks can create a 'zero-sum game', where increased water use in one area requires decreased use in another [12]. Additional reservoir storage in a closed basin could detrimentally affect downstream water users as streamflow decreases in response to filling reservoirs. Therefore, changes in the amount of reservoir storage at thermoelectric power plants could increase or decrease basin-wide water availability, depending on site- and basin-specific characteristics. Unfortunately, no single analytical framework exists (to the authors' knowledge) for quantifying these impacts and tradeoffs in a comprehensive way for the power sector on a river basin scale.

Many metrics exist to quantify the performance and possibility of failure for vital infrastructure. Among these metrics are reliability, resiliency, and vulnerability. Based on Hashimoto *et al*, reliability and resiliency are probabilistic measures, indicating the likelihood of failure and how quickly a system recovers, respectively (see equations (1) and (2)) [13]. Vulnerability measures the severity of the consequences of failure [13], a volumetric measure when evaluating water constraints for power plants (see equation (3)). In equations (1)–(3), X^{T} is the threshold value and X_t is the value at time t (both measured in ac-ft for this analysis), such that a satisfactory value is one where $X_t \geq X^{\mathrm{T}}$ [13, 14]. These parameters can be applied to thermoelectric power plants to indicate the drought susceptibility of power generation infrastructure.

$$\text{Reliability} = \frac{\text{number of data time periods } t \text{ where } X_t \geq X^{\mathrm{T}}}{\text{total number of data}} \tag{1}$$

$$\text{Resiliency} = \frac{\text{number of times a satisfactory value follows an unsatisfactory value}}{\text{number of times unsatisfactory value occurred}} \tag{2}$$

$$\text{Vulnerability} = \frac{\text{sum of positive values of } (X^{\mathrm{T}} - X_t)}{\text{number of times unsatisfactory value occurred}}. \tag{3}$$

The 2011 drought in Texas—lower-than-average precipitation combined with higher-than-average temperatures—left the water levels in many reservoirs markedly low with the statewide average of <60% full in November of 2011. As of early February 2013, the statewide average for all monitored reservoirs was 67% full, yet many reservoirs were less than 10% full (one in particular was 0.5% full) with recorded levels at a minimum for the past decade [15]. A similar event occurred in the midwest United States in 2012. Some climate change projections predict worsening drought in various parts of the world [16], which could leave other power plants worldwide susceptible to water-related operational challenges. Since reservoirs provide water storage for use during dry periods, falling water levels in those reservoirs can have important consequences for thermoelectric power plants. For example, water levels can fall below intake structures, leaving power plants physically unable to withdraw water. Similarly, decreased water availability can leave power plants at greater risk of exceeding thermal pollution limits or legally unable to withdraw water due to prior appropriation water law doctrine. The nuances of thermal pollution limits, including legal constraints and system feedback from heated discharge water, are beyond the scope of this work.

While the value of water storage has been known for centuries, to the best of the authors' knowledge, no one has (1) quantified its benefits in a scientifically-rigorous way from the perspective of power plant operators, or (2) evaluated these benefits in terms of other users for a resource constrained system with geographic and temporal resolution. As water resources become increasingly strained, potential solutions to increase water supply could benefit from considering the larger context of a watershed or river basin scale. While increasing reservoir storage at a particular power plant might mitigate its susceptibility to drought, the redistribution of water might adversely affect other water users in the basin.

Despite the prevalence of various metrics, no single methodology exists for evaluating power generation operations in response to changing water storage circumstances. Our work aims to fill that gap analytically by developing a methodology to quantify the dynamic impacts of surface water reservoir storage on thermoelectric power generation operations, in terms of reliability, resiliency, and vulnerability. We demonstrate our methodology by using Texas as a convenient testbed, integrating together historical drought conditions, legal water rights priority structure, and previous work by the authors regarding water availability for thermoelectric power plants [17, 18]. Although our results are unique to Texas, this methodology is applicable to other areas throughout the world with similar water constraints on power generation operations and existing water law structures governing users in a given area.

2. Methodology

To evaluate Texas power generation operations in response to changing water storage circumstances, we adapted an existing river basin-based model of Texas surface water rights holders. This model was previously used to evaluate the technological and economic feasibility of alternative cooling technologies at thermoelectric power plants [17, 19]; this new analysis focuses on changes in reservoir

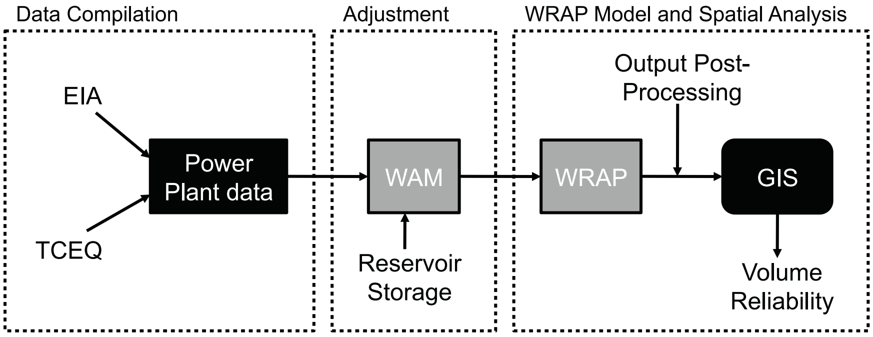

Figure 1. Power plant operating data from the Energy Information Administration (EIA) and Texas Commission on Environmental Quality (TCEQ) along with new reservoir storage parameters were used to modify input files for the Water Availability Model (WAM). The Water Rights Analysis Package (WRAP) was then used to simulate streamflow and volume reliability results were displayed using geographic information systems (GIS).

storage. Our modeling approach, illustrated in figure 1, integrates power plant water use data from the Energy Information Administration (EIA) and Texas Commission on Environmental Quality (TCEQ) into existing Water Availability Models (WAMs) [20]. The WAMs are then edited to reflect changes in reservoir storage allocations, executed using the Water Rights Analysis Package (WRAP) [21], organized using post-processing algorithms, and, finally, volume reliability results are displayed geographically using ArcGIS geographic information systems [22].

The WAMs simulate current water rights holders in a river basin using water over historical meteorological and naturalized streamflow conditions, capturing the 1950–1957 Texas drought of record (but not the drought of 2011, which was equally as intense over a shorter duration). Two particular WAMs are of interest to our analysis: (1) the Full Execution model, simulating perpetual water rights holders withdrawing their entire permitted volume with zero return flow, and (2) the Current Conditions model, simulating all water rights holders withdrawing at current use rates with associated return flow [20]. While most water users have an associated return flow, the Full Execution model represents a 'worst-case' scenario (e.g., maximum withdrawals) and is used by TCEQ to evaluate availability for new permit applications. Consequently, the Full Execution WAM is an appropriate basis for long-term planning and decision making. Our analysis uses both the Full Execution and Current Conditions WAMs on monthly time steps to capture a range of physical and regulatory water management approaches.

We investigate the dynamic impacts of changing reservoir storage on power generation operations with five unique cases (referred to later as Cases 1–5): (1) storage decrease of existing capacity of 10%, (2) storage decrease of 50%, (3) complete elimination of storage, (4) storage increase of 10% (all at existing locations), and (5) construction of new reservoirs (at new locations) at power plants with no existing water storage rights—a total increase in baseline reservoir capacity for power plant cooling of 9%. These cases represent the outcomes of possible natural conditions given low reservoir levels in recent Texas history [15], such as drought or reservoir sedimentation, and policy mechanisms, such as reallocation of water rights. Each of these five cases is then compared to a baseline of current basin-wide water availability for existing water rights in both the Full Execution and Current Conditions WAMs. We consider 11 river basins (Brazos and San Jacinto-Brazos, Colorado and Colorado-Brazos, Cypress, Neches, Nueces, Red, Sabine, San Jacinto, and Trinity River basins) represented in 9 WAM files (the associated coastal basins are combined into the Brazos and Colorado River basins). As a result, our analysis is based on the results of 96 model runs (shown in appendix A): 9 WAMs for the baseline and Cases 1–4, plus 3 WAMs for Case 5 power plants without existing storage rights (Brazos, Colorado, and Sabine), each in the Full Execution and Current Conditions simulations. These model runs reflect changes in reservoir storage at 38 thermoelectric power plants in Texas, the details of which are shown in appendix B.

While the modeled changes in storage are straightforward for Cases 1–4 described above, modeling construction of new reservoirs requires customization of existing computer code to simulate the filling and depletion of surface water storage. We demonstrate this methodology by focusing on surface water reservoir storage; consideration of underground aquifer storage is also possible with customization of the WAM code. Texas water law considers surface water and groundwater separately, so focusing our analysis on surface water storage and use is consistent with the existing policy framework. Four power plants in our analysis sample do not have existing surface water storage rights. To model construction of reservoirs at these facilities, we determined an appropriate amount of water storage based on current power plant withdrawal rates (in ac-ft kWh^{-1} or m^3 kWh^{-1}) to introduce into the WAMs. (See appendix B for withdrawal rates for the 38 facilities in this analysis, including the 4 plants without existing storage rights.) New annual water storage rights (ac-ft) were modeled for each of the four power plants as equal to the volume of water withdrawn in one month, based on average monthly power generation (reported in [23]), as shown in equation (4) and listed in table 1:

$$V_s = w\left(\frac{G}{12}\right) \tag{4}$$

Table 1. Four power plants in the analysis sample do not have existing storage rights in the WAMs. Construction of new reservoir storage was simulated using these values calculated using equation (4).

Power plant	River basin	Calculated new reservoir storage (ac-ft)
R W Miller	Brazos	87 223
Fayette	Colorado	86 960
Lost Pines I	Colorado	191
Harrison County	Sabine	65

where V_s is the volume of reservoir storage (ac-ft or m^3), w is the plant-specific withdrawal rate on an energetic basis (ac-ft kWh^{-1} or m^3 kWh^{-1}), and G is the plant's annual electricity generation (kWh yr^{-1}). The value of V_s is normalized for the case in which the storage is equal to one month's withdrawal (hence the factor of 12 in equation (4)) for water storage rights modeled in Case 5 representing the construction of new reservoirs, shown in table 1. Normalized V_s calculated using equation (4) assumes a constant water withdrawal rate (ac-ft kWh^{-1}) throughout the year, yet withdrawal varies seasonally for most power plants. To maintain the broad applicability of our results throughout the year, we use equation (4) to approximate the average water storage for one month at a given power plant; however, this methodology could be easily adapted for temporally resolved data and analysis. These new water storage off-channel reservoirs are filled and depleted in the WRAP simulation via water right diversions, and increase the total baseline reservoir capacity for power plant cooling by 9%. Consequently, the new reservoirs have zero water stored when water withdrawals are also zero.

Since the WAM and WRAP structures simulate historical climate conditions (including monthly precipitation, evaporation, and infiltration), we incorporated storage volume versus surface area relationships for each modeled reservoir into our analysis. These storage–area relationships allow the model to incorporate net evaporation (based on precipitation and surface flux) from the reservoir surface during the WRAP simulation routine, and are represented as follows (as presented in [24]):

$$A = aS^b + c \tag{5}$$

where A is the area, S is storage volume, and a, b, and c are constants in equation (5) with units appropriate for surface area measured in acres and storage measured in ac-ft. Since the WAM and WRAP routines are both based on units common to the western United States, the units for a, b, and c must fit with surface area in acres and storage in ac-ft. These constants establish a mathematical relationship between reservoir storage and surface area. In our analysis, we assign values of a, b, and c based on the basin-wide constants used in the WAMs: $a = 0.5228$, $b = 0.8206$, and $c = 0$ in the Brazos River basin; $a = 0.911$, $b = 0.695$, and $c = 0$ in the Colorado River basin; and $a = 1.0098$, $b = 0.6889$, and $c = 0$ in the Sabine River basin, with surface area measured in acres and storage in ac-ft [20]. Unmeasured error is likely introduced by using identical constants for an entire river basin, especially in the Brazos and Colorado basins that span from the arid west to the relatively wet east, yet this approach is consistent with what is used in the existing WAMs. If reservoir construction was to proceed beyond this hypothetical phase, site-specific data would need to be collected to determine suitable values for a, b, and c at each location; our selected values represent one possible option in light of significant uncertainty. Estimating the storage–area relationships for each facility in table 1 allows for more realistic simulation of the construction of new reservoir storage, such that the WRAP routine accounts for meteorological impacts like evaporation and precipitation.

Extending this analysis to consider underground aquifer storage would require modification of the storage–area relationship, as underground storage incurs no evaporation and no surface land area, though it might have seepage as an analogous flow to consider. Our analysis presented here focuses on surface water reservoir storage as it pertains to drought conditions. However, customizing Case 5 for new aquifer storage at the four facilities in table 1 yielded nearly identical results.

Based on Cases 1–5 compared to the baseline of existing basin-wide water availability, we can estimate the changes in power generation operations in response to changing surface water storage conditions. These cases encompass a range of hydrologic and policy conditions, including moderate to extreme drought (Cases 1–3), planned expansion or dredging of existing reservoirs (Case 4), and reallocation of water storage rights (Cases 1–5). While the conditions represented by these cases are not exhaustive, they provide a useful snapshot of the possible dynamic impacts a change in water storage can have on power plants and other surface water rights holders in a river basin.

3. Results

Simulated changes in reservoir water storage yield two sets of impacts: variation in storage can affect power plant operations and also other water users in the basin. To capture both basin-wide and plant-scale impacts, we analyzed the dynamic impacts of reservoir storage via basin-wide changes in volume reliability for surface water rights holders and metrics indicating the success of power plant operations. We also assessed the annualized cost of constructing new surface water reservoirs at sites where increased storage is beneficial based on plant-specific and basin-wide metrics. Here, we first present the basin-wide impacts of changes in storage, indicating the Brazos River basin as an area of particular interest. We then present power plant operational metrics in the Brazos River basin specifically, and finally present an assessment of plant-specific water availability changes from constructing new reservoir storage within that basin.

3.1. Basin-wide impacts of changes in reservoir storage

Water availability in a particular river basin is dependent on the various water users in that basin. Consequently, significant changes in a small number of water rights for withdrawal or storage can affect many other users throughout the river basin, both positively and negatively. Quantifying the effect that changes in water availability have on particular water users is possible using the metric of volume reliability, defined as the per cent of water available for withdrawal over a period of time (for our analysis, the 1950–1957 drought of record in Texas, which is the convention). For example, if a user held a water right to withdraw 12 ac-ft/month and was able to withdraw 12 ac-ft, 9 ac-ft, and 11 ac-ft for each month, respectively, the facility's volume reliability would be 88.9% (32 ac-ft/36 ac-ft) for the 3 month period. Since volume reliability is based on historical or simulated withdrawals, it is inherently a retrospective metric; however, when simulated meteorological conditions span a sufficient range or record event, volume reliability can be a probabilistic measure of water availability. TCEQ uses volume reliability results from the Full Execution WAMs to evaluate applications for new water rights. When 75% of the requested water volume is available 75% of the time, new permits are typically granted; municipal water rights are required to have 100% of the water available 100% of the time, or secure a backup water right [25].

We modeled Cases 1–5 described previously over the 1950–1957 drought of record in Texas, simulating the volume reliability of current water rights holders using water during historic drought conditions. As water storage rights at thermoelectric power plants change, volume reliability changes for other water rights holders in the river basin, as shown in figures 2 and 3 for the Full Execution and Current Conditions WAMs, respectively. Each of the five cases were compared to the Existing scenario as a baseline, such that the change in volume reliability shown in panels (a)–(e) is

$$\Delta VR = VR_i - VR_{\text{existing}} \tag{6}$$

where VR represents that volume reliability and i corresponds to Cases 1–5, such that ΔVR is the change in volume reliability for a particular case. Positive changes in volume reliability (warm colors in figures 2 and 3) are indications that the change in water storage was beneficial for a water rights holder; negative changes (cool colors in figures 2 and 3) indicate detrimental impacts from changes in water storage. Water rights with zero change in volume reliability are not shown for clarity.

Based on figures 2 and 3, changing water storage rights at thermoelectric power plants can be both beneficial and detrimental to other water users in a river basin, even for the same analysis scenario in the same basin. Depending on geography and water rights priority, decreasing reservoir storage at a particular power plant can be beneficial to some water users in the basin because additional streamflow is available at certain times. At the same time, decreasing storage at a power plant can be detrimental to other users because some reservoir releases no longer take place. In general, decreasing water storage at thermoelectric power plants (Cases 1–3) is beneficial to other water users in the basin, with the largest increases in volume reliability for other users associated with Case 3 simulating no power plant reservoir storage. On the other hand, additional water storage at thermoelectric power plants can be detrimental for many other water users, as shown in Cases 4 (storage increase of 10%) and 5 (construction of new reservoirs), though some areas do show marked improvement in volume reliability. That is, allocating additional water storage to thermoelectric power plants can have negative effects on other water users in the basin. These generalized conclusions regarding the detrimental impacts to other water users from increasing reservoir storage for power plants might be indications of overallocated surface water resources where little to no excess water remains for new or expanding uses.

Construction of new power plant storage can have markedly different impacts on other water rights holders in a basin based on many external factors, including the amount of unallocated water and river basin management, among others. These different impacts become apparent in figure 2(e), where construction of new reservoirs in the Colorado River basin (southernmost analyzed basin) is generally neutral or detrimental to other water users, while new reservoirs in the Brazos River basin (immediately north of the Colorado) are generally beneficial [18]. Based on the classifications given by Keller *et al* [12], the Colorado River basin is likely a semi-closed or closed basin while the Brazos River basin could be labeled as an open basin with excess runoff. These distinctions become important when considering the supply-side approach of constructing new reservoirs (for various purposes) as a large-scale water management strategy. While new surface water storage might be beneficial at a local level, negative impacts are possible on a basin-wide scale, as shown by our analysis.

Comparing our analysis with a previous analysis by the authors reveals interesting data pertaining to Case 5 (construction of new reservoir storage). In a previous analysis [18], the constants in equation (5) were set equal to $a = 326.86$, $b = 0.752$, and $c = 0$ based on values reported in literature [26]. In the analysis presented here, we have assigned the following values: $a = 0.5228$, $b = 0.8206$, and $c = 0$ in the Brazos River basin; $a = 0.911$, $b = 0.695$, and $c = 0$ in the Colorado River basin; and $a = 1.0098$, $b = 0.6889$, and $c = 0$ in the Sabine River basin, equal to the basin-wide values currently used in the WAMs [20]. This change in the values of a and b in equation (5) caused a marked change in the Colorado River basin, but no change in the Brazos and Sabine River basins. Changing $a = 325.86$ and $b = 0.752$ to $a = 0.911$ and $b = 0.695$ in the Colorado River basin caused the basin-wide average volume reliability to increase from 27.1% to 31.1% in the Full Execution WAM, and increase from 36.9% to 43.1% in the Current Conditions WAM. That is, the detrimental impacts of constructing new reservoir storage are less pronounced in the Colorado River basin with lower values of a and b in equation (5). While we have not completed a full sensitivity analysis on these variables, we can infer that the impacts of evaporation, as expressed by the values of a and b, have high influence on volume reliability in the Colorado River basin.

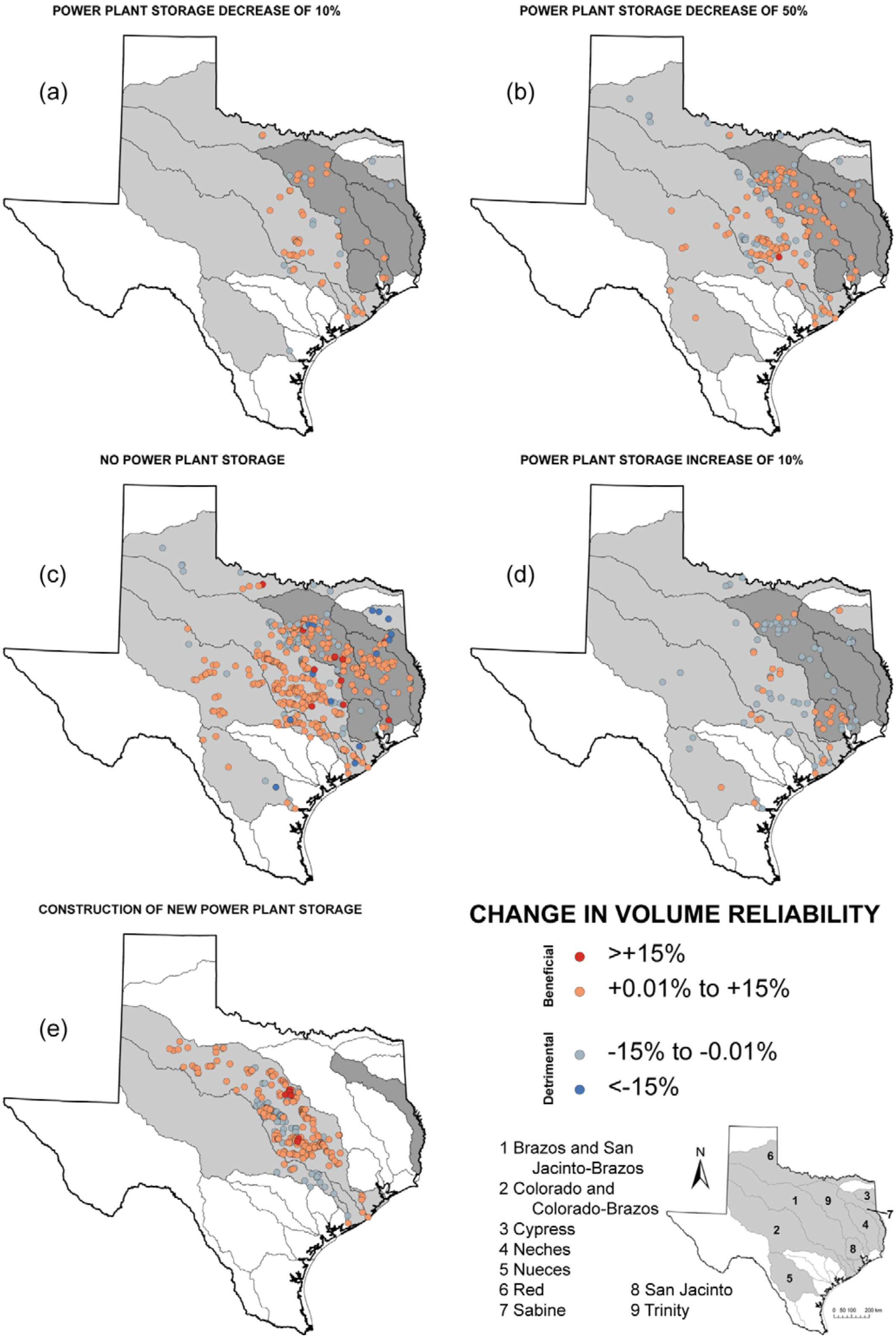

Figure 2. In the full execution WAM, volume reliability increases (warm colors) and decreases (cool colors) for basin-wide water users in response to different changes in power plant surface water reservoir storage rights during the 1950–1957 drought of record: (a) decrease of 10%, (b) decrease of 50%, (c) no storage, (d) increase of 10%, and (e) construction of new storage at power plants without existing storage rights. Analyzed river basins are shown in gray with those having current instream flow models shown in dark gray. Note that some analyzed basins exhibited no change and, therefore, show no water rights.

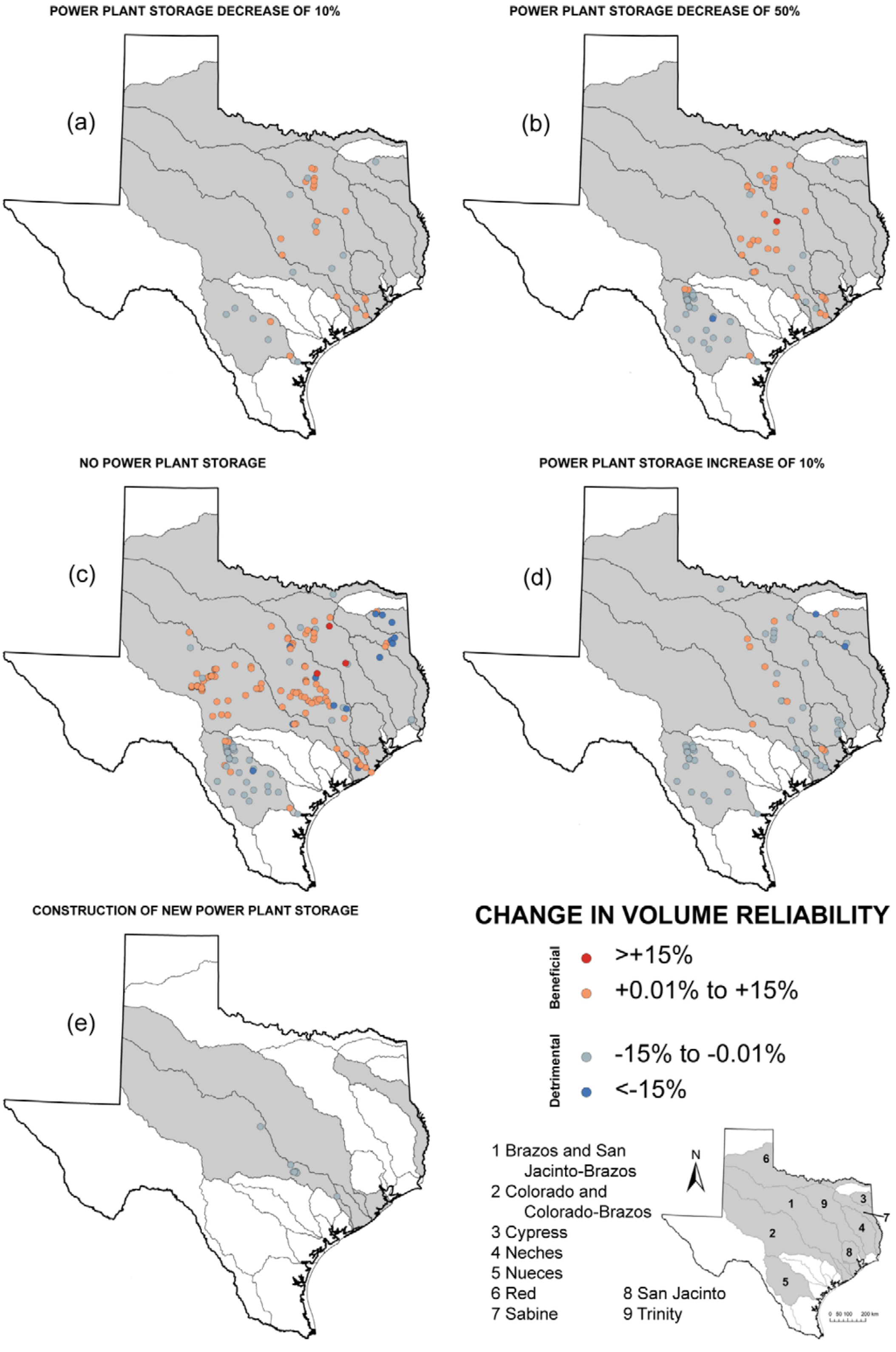

Figure 3. In the Current Conditions WAM, volume reliability increases (warm colors) and decreases (cool colors) for basin-wide water users in response to different changes in power plant surface water reservoir storage rights during the 1950–1957 drought of record: (a) decrease of 10%, (b) decrease of 50%, (c) no storage, (d) increase of 10%, and (e) construction of new storage at power plants without existing storage rights. Analyzed river basins are shown in gray; no instream flow models currently exist under the Current Conditions WAM. Note that some analyzed basins exhibited no change and, therefore, show no water rights. Generally speaking, the Current Conditions WAM impacted fewer water rights holders.

3.2. Metrics of power plant operations

Using figures 2 and 3, we selected the Brazos River basin (including the San Jacinto-Brazos coastal basin) as an area of particular interest for evaluating operations at the power plant level. The Brazos River basin is a representative sample of surface water management in Texas since it is among the longest rivers in the state, has large diversity in water uses, and contains multiple thermoelectric power plants. The nine thermoelectric power plants analyzed from the Brazos River basin span an appropriate range of generation capacity and capacity factors, and use a variety of fuels and cooling technologies, as shown in appendix B and reported previously [17].

Using the metrics described previously in equations (1)–(3), we evaluated power plant operations in the Brazos River basin in terms of reliability, resiliency, and vulnerability. These metrics, evaluated using 2011 data for all water uses in the Full Execution WAM on a monthly time step over the 1950–1957 drought of record in Texas, are shown in tables 2–4. Simulating 2011 water uses over the 1950–1957 drought of record captures the possible effects of a modern-day drought of equal duration and intensity. Reliability and resiliency are both measured as percentages, with larger values indicating better operations in response to drought. That is, power plants with high reliability and high resiliency are less susceptible to drought. Since resiliency is measured as the likelihood that a successful event will follow an unsuccessful event, the metric is undefined when no unsuccessful events occur (i.e., when reliability is 100%). Similarly, vulnerability measures the volumetric severity of drought consequences and is undefined when no unsuccessful events occur.

Based on the results in tables 2–4, thermoelectric power plants have a range of moderate to high susceptibility to drought. In particular, when reservoir storage is completely depleted, as in Case 3 with no reservoirs, reliability is substantially lower for most power plants compared to existing conditions. Although complete depletion of reservoirs is an extreme and unlikely event, many Texas reservoirs were dangerously low during the 2011 drought conditions, making such an analysis relevant for long-term planning. These results for the Brazos River basin show that reliability generally decreases or remains relatively constant with decreasing storage, and is relatively unaffected by increasing storage (with the exception of the R W Miller power plant), as shown in table 2. Resiliency, on the other hand, fluctuates with increases and decreases in storage, as shown in table 3, likely indicating the presence of site-specific factors. Similar to reliability, vulnerability typically increases (more severe consequences of drought) with decreasing storage, and remains relatively constant with increasing storage.

In Case 3 with no reservoirs, site-specific factors affect our results. For example, resiliency increases at the Tradinghouse plant in Case 3 compared to the baseline, likely due to an increase in streamflow without water storage for upstream thermoelectric power plants. On the other hand, resiliency at the Lake Creek power plant (with open-loop cooling) significantly decreases in response to Case 3, while the measure stays constant at the Limestone power plant (with a cooling tower). Resiliency, as a measure of the likelihood of success (water available for diversion) following failure, is highly variable based on site-specific factors of geography and cooling systems.

The variation in reliability, resiliency, and vulnerability results for the analyzed power plants in the Brazos River basin emphasizes the importance of using more than one metric to evaluate power generation responses to changing surface water storage conditions. For example, the W A Parish power plant has high reliability for all analyzed cases, but when an unsuccessful event occurs (less water is available than the target withdrawal) in Cases 2 and 3, the power plant has a 50% and 40% chance, respectively, of observing another unsuccessful event the following month (i.e., has 50% and 60% resiliency, respectively). In other words, failure is rare but when failure does occur, unsuccessful events are likely to be repeated, making the small reliability sacrifice more serious. Consequently, the W A Parish power plant is highly reliable during the 1950–1957 drought of record in response to changing reservoir storage conditions, but less resilient than other facilities such that target withdrawals might not be met over a multi-month time period. The consequences of such unsuccessful events in Cases 2 and 3 for the W A Parish power plant are measured as vulnerability of 1345 ac-ft and 3109 ac-ft (1.66 million m^3 and 3.83 million m^3), respectively.

These metrics might not capture some critical elements of a natural water system or actual current water use, however, as is seen with the Comanche Peak and Limestone power plants. In all of the cases analyzed, the reliability of Comanche Peak is 7%–12%, as shown in table 2, yet the facility's capacity factor is quite high at 88.5% (see appendix B). Similarly, reliability at the Limestone power plant ranges from 17 to 30%, yet the capacity factor is 83.9%. This analysis uses the Full Execution WAM simulated over the 1950–1957 drought of record and represents a 'worst-case' scenario. Therefore, we cannot directly compare actual modern operations with simulated operations during historic drought conditions, as these facilities began operations in the late 1980s and early 1990s after that extended drought had ended. Based on these results, a few explanations might address this apparent discrepancy between reliability and capacity factor: (1) non-negligible error is present in the existing WAM models, (2) these facilities are at significant risk to drought, and/or (3) reliability alone is an insufficient metric for evaluating power plant operations during drought.

Our results suggest that a single metric is limited in evaluating power plant operations in response to changing surface water storage conditions. Although reliability alone is typically used to evaluate new water use permits in Texas (and in many other states), using reliability, resiliency, and vulnerability together might better illuminate tradeoffs between various water use and management decisions. Thus, it is clear that reliability needs to be interpreted in proper context. Quantitative metrics of reliability, resiliency, and vulnerability can aid in evaluating power generation

Table 2. Reliability, the per cent of time a power plant receives its target water diversion, varies for power plants in the Brazos River basin in response to changes in reservoir storage during the 1950–1957 drought of record. (Note: values have been rounded.)

Power plant	Reliability					
	Existing (%)	Case 1 Less 10% (%)	Case 2 Less 50% (%)	Case 3 No reservoirs (%)	Case 4 Add 10% (%)	Case 5 Add new reservoirs (%)
City of Bryan	100	100	100	40	100	100
Comanche Peak	12	12	12	7	12	12
Gibbons Creek	100	100	100	40	100	100
Lake Creek	99	99	99	10	99	100
Limestone	24	24	24	12	24	24
R W Miller	43	43	43	43	43	100
Sandow Station	100	100	93	1	100	100
Tradinghouse	29	25	25	17	30	29
W A Parish	100	100	98	95	100	100

Table 3. Resiliency, the probability that a power plant below its target water diversion will meet the target the next month, varies for power plants in the Brazos River basin in response to changes in reservoir storage during the 1950–1957 drought of record. (Note: values have been rounded; '—' indicates that resiliency is undefined.)

Power plant	Resiliency					
	Existing (%)	Case 1 Less 10% (%)	Case 2 Less 50% (%)	Case 3 No reservoirs (%)	Case 4 Add 10% (%)	Case 5 Add new reservoirs (%)
City of Bryan	—	—	—	26	—	—
Comanche Peak	4	4	4	4	4	4
Gibbons Creek	—	—	—	26	—	—
Lake Creek	100	100	100	7	100	—
Limestone	14	14	14	14	14	14
R W Miller	33	33	33	33	33	—
Sandow Station	—	—	43	1	—	—
Tradinghouse	9	10	10	11	9	9
W A Parish	—	—	50	60	—	—

Table 4. Vulnerability, a volumetric measure (here in ac-ft) of how severe the consequences of drought might be, varies for power plants in the Brazos River basin in response to changes in reservoir storage during the 1950–1957 drought of record. (Note: values have been rounded; '—' indicates that vulnerability is undefined.)

Power plant	Vulnerability (ac-ft)					
	Existing	Case 1 Less 10% (%)	Case 2 Less 50% (%)	Case 3 No reservoirs (%)	Case 4 Add 10% (%)	Case 5 Add new reservoirs (%)
City of Bryan	—	—	—	6	—	—
Comanche Peak	1728	1728	1728	1701	1728	1726
Gibbons Creek	—	—	—	747	—	—
Lake Creek	420	423	439	723	417	—
Limestone	957	957	957	1007	957	957
R W Miller	2864	2864	2864	2864	2864	—
Sandow Station	—	—	571	1100	—	—
Tradinghouse	1039	1011	1013	1055	1025	1038
W A Parish	—	—	1345	3109	—	—

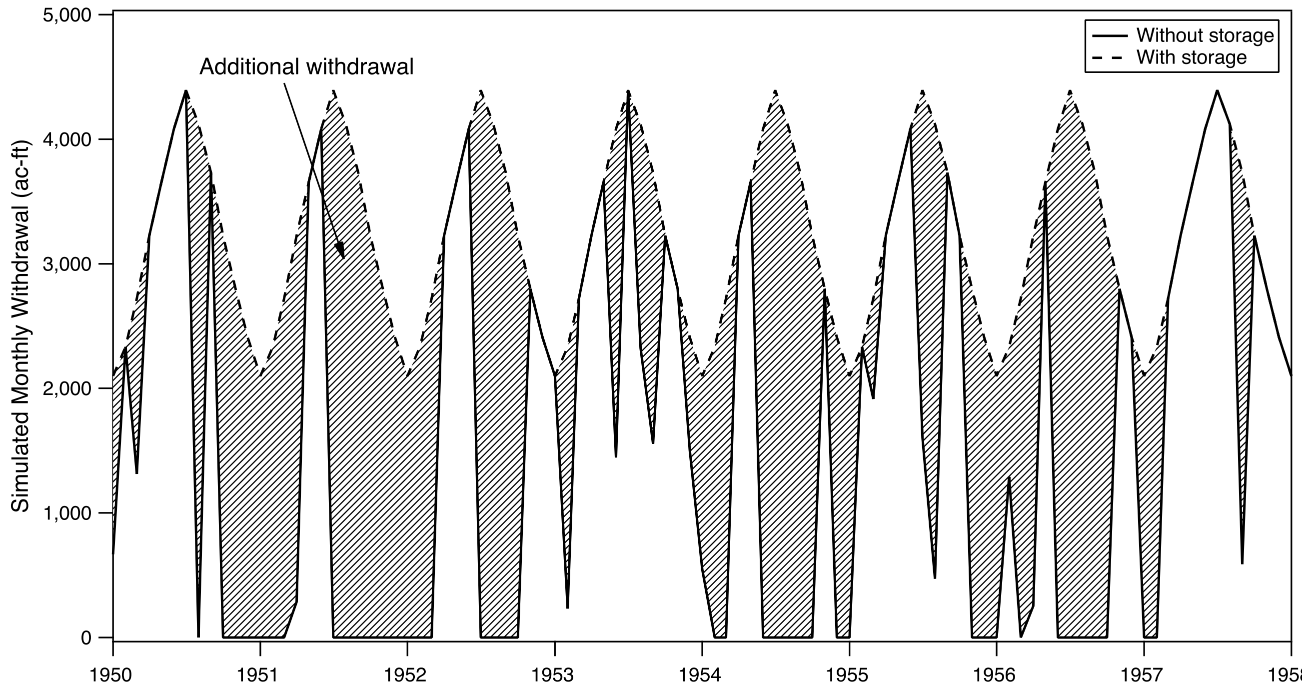

Figure 4. Monthly water withdrawals are notably higher at the R W Miller power plant with reservoir storage (dashed line) compared to without storage (solid line). The shaded area between lines represents the potential additional water volumes associated with power plant operations with reservoir storage. This additional water availability could be used for additional power generation, creating additional revenues for the power plant.

operations, yet these values are not exhaustive in reflecting actual generation.

3.3. Plant-specific water availability from constructing new reservoir storage

As shown in table 2, reliability increases markedly for the R W Miller power plant in Case 5 (adding new reservoirs). We performed a plant-specific assessment of water availability changes on monthly time steps, indicating times when additional water might be available for increased power generation. These results indicate that water availability associated with construction of new reservoir storage often exceeds availability without reservoir storage, as shown in figure 4 by the area between the dashed and solid lines.

The dashed line in figure 4 (withdrawals with storage) represents all of the target water withdrawals for the R W Miller power plant, since reliability is 100% for Case 5 as shown in table 2. Target withdrawals vary throughout the year, with a peak in the summer and lower targets in the winter. Construction of reservoir storage at the R W Miller power plant changes the monthly water withdrawal simulated over the 1950–1957 drought of record as shown by the hatched area between the dashed and solid lines in figure 4.

Additional water withdrawals are possible with construction of storage, but the timing of these withdrawals can be nearly as important as the additional water volume. Notably, additional withdrawals are possible with construction of storage during the peak summer months, especially the summers of 1951, 1952, 1954, and 1956. The R W Miller power plant is a peaking facility, operating only during times of high electricity prices and high demand, often during summer months [27]. As such, additional water availability during summer months could lead to additional power generation and increased revenues for the R W Miller facility.

Since construction of new reservoirs at power plants without existing water storage rights incurs significant costs, we performed a first-order capital and operations cost analysis for the R W Miller power plant, evaluating the tradeoffs between construction costs and increased withdrawals for power plants operations. Annualized cost, A_c, was represented as

$$A_c = V_s P \left[\frac{i(1+i)^t}{(1+i)^t - 1} \right] + A_{O\&M}, \qquad (7)$$

where the volume of storage V_s (ac-ft) is calculated using equation (4), P is the principal reservoir construction cost (including land acquisition) (\$ ac-ft^{-1}), i is the annual discount rate, t is the reservoir lifetime (yr), and $A_{O\&M}$ is the annual operations and maintenance cost (\$ yr^{-1}). In this analysis, we use a 5% discount rate over a lifetime of 30 yr, and $P = \$2000$ ac-ft^{-1} (\$1.60 m^{-3}) since reported construction costs range from \$800 to \$4400 ac-ft^{-1} [28]. Operations and maintenance costs have been reported as 1.5% of the estimated construction cost [28]. Additionally, we assume land is available for reservoir construction, though this is obviously a potential constraint for an actual project. Using equation (4), we modeled new annual reservoir storage of 87 223 ac-ft (108 million m^3) at the R W Miller power plant. With reservoir construction costs of \$2000 ac-ft^{-1}, the annualized cost of constructing new reservoir storage at the R W Miller power plant was estimated as $14 million, which is comparable to other reported reservoir construction costs.

Although construction of such a reservoir is expensive, it increases the reliability of power plant operations such that additional electricity could be generated and sold to the grid. Quantifying the timing and amount of generation possible from additional power plant operations are beyond the scope of this analysis and likely require a sophisticated power dispatch model to account for electricity generation and ancillary services within the existing market structure. Initial high-level investigation using the reported heat rate for the R W Miller power plant (from the Electric Reliability Council of Texas, as reported in [29, 30]), variable operations and maintenance costs [29, 30], and 2010 electricity [31] and natural gas [32] prices with 2010 generation data [27] reveals an unexpected layer of complexity such that current power plant operations do not appear profitable in the balancing energy market alone. Our analysis is built on an assumption that enabling additional power generation by increasing water availability would lead to additional revenues, yet additional generation is not favorable when operating costs exceed electricity prices. Such details on plant-level dispatch and operations in the balancing energy and ancillary services markets are reserved for future work.

4. Policy implications

Thermoelectric power plants are susceptible to drought conditions and other water constraints. As surface water reservoir storage levels change, power generation operations have a dynamic response to water withdrawal limitations. Based on our analysis, constructing new reservoir storage (Case 5) could increase the reliability and resiliency of a particular power plant, but could also harm other water users in a river basin, as shown in figures 2(e) and 3(e). When constructing new storage causes detrimental impacts to other water users, such changes could indicate full- or over-allocation of water in the river basin; Keller *et al* classify this situation as a closed basin [12]. Construction of new surface water reservoirs has local and basin-wide implications; consequently, all water users might benefit from both local and basin-wide analyses prior to proceeding with plans for major reservoirs.

The supply-side solution of constructing new reservoirs is only one of many water management approaches that can benefit water users in a river basin. Using low-water cooling technologies (e.g., switching from open-loop cooling to cooling reservoirs or towers) at thermoelectric power plants reduces the water withdrawal requirements for operations, with the tradeoff of increased water consumption and additional up-front costs [17, 19]. Consequently, tradeoffs exist between reducing water withdrawals and increasing water consumption. Reducing water withdrawals for power plants becomes important in the context of drought, since enough water might not be available for power generation operations. Low-water cooling technologies, such as cooling towers, hybrid wet–dry, and dry cooling, can decrease the drought susceptibility of power plants since less water withdrawal is required. In addition to drought conditions, state and federal policies might motivate or require switching to low-water cooling technologies at many thermoelectric power plants [33].

In the context of drought and the susceptibility of power generation operations, both supply- and demand-side approaches to water management can be useful. As our analysis showed, construction of new surface water reservoirs can decrease a power plant's susceptibility to drought. Using the R W Miller power plant, for example, adding reservoir storage equal to one month's water withdrawal increases reliability from 43% to 100% over the drought of record, as shown in table 2. Annualized cost of constructing a new reservoir was estimated at $14 million for 87 223 ac-ft (108 million m^3) of storage, bringing the effective cost of water to approximately $160 ac-ft^{-1} ($0.13 m^{-3}), which is notably higher than reported lease rates for Texas surface water [34, 19]. Focusing on demand-side approaches, annualized cost of retrofitting a dry cooling system at the R W Miller power plant was estimated at $4.7–$7.0 million and would avoid 34 920 ac-ft (43 million m^3) in water withdrawals annually (based on data from [19]), an effective cost of water of $130–$200 ac-ft^{-1} ($0.11–$0.16 m^{-3}). Alternatively, the generation from the R W Miller power plant could be replaced with construction of a new natural gas combined-cycle power plant or other water-lean power generation technology, which would reduce water needs and continue to produce electricity for many decades into the future. These cost estimates are based on first-order analyses only and lack site-specific data necessary for informed decision making, yet our results suggest that both supply- and demand-side approaches to water management could be considered in terms of sustainable basin-wide water management.

5. Conclusions

We used a customized, river basin-based model of surface water storage to evaluate the dynamic impacts of reservoirs on thermoelectric power plants. Using our methodology, we simulated surface water rights in 11 river basins in response to changes in reservoir storage at power plants using five cases: (1) storage decrease of existing capacity of 10%, (2) storage decrease of 50%, (3) complete elimination of storage, (4) storage increase of 10% (all at existing locations), and (5) construction of new reservoirs (at new locations) at power plants with no existing water storage rights—a total increase in baseline reservoir capacity for power plant cooling of 9%. These five cases allow us to explore a range of drought conditions, decreasing water storage, and possible water supply management approaches increasing water storage. Results vary by river basin; in general, decreasing water storage at thermoelectric power plants is beneficial to other water users in the basin, and increasing water storage is detrimental for many other water users (including some power plants). However, there are some nuanced, non-obvious results where decreasing reservoir storage at a power plant can have both beneficial and detrimental impacts on different water users in the same basin due to legal and geographic factors. Our methodology allows for capturing the tradeoffs with other water users in a river basin.

At the individual power plant level using the Brazos River basin as an appropriate sample, we evaluated power generation operations in terms of reliability, resiliency, and vulnerability, with high reliability, high resiliency, and low vulnerability associated with power plants that are less susceptible to drought. As simulated water storage decreases, reliability generally decreases and resiliency and vulnerability remain relatively constant. All three metrics remain relatively constant with simulated increases in reservoir storage, with the exception of the R W Miller power plant. Construction of a new surface water reservoir at the R W Miller facility was shown to markedly increase water availability for withdrawals, especially during summer months, at an estimated annualized cost of $14 million.

Due to the interconnection between energy and water, understanding the dynamic impacts of changing surface water storage along with various cooling technologies could be useful for future resource management, especially in light of more frequent and increasingly intense drought conditions. Our analysis presents a methodology for revealing the dynamic impacts of water storage and tradeoffs between water withdrawal and consumption for power plants. Evaluating thermoelectric power plant operations in terms of reliability, resiliency, and vulnerability, instead of a single metric, reveals the likelihood of failure, speed of recovery from failure, and magnitude of the consequences of failure. Considering each of these metrics in light of possible economic or environmental tradeoffs can help inform balanced policymaking and sustainable decision making.

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Appendix A. Cases included in analysis

See table A.1.

Appendix B. Power plants included in analysis

See table B.1.

Table A.1. Number of cases included in analysis of applying methodology to Texas.

River basin	Existing	Case 1 Less 10%	Case 2 Less 50%	Case 3 No reservoirs	Case 4 Add 10%	Case 5 Add new reservoirs	Total
				Full Execution WAM			
Brazos and San Jacinto-Brazos	1	1	1	1	1	1	6
Colorado and Colorado-Brazos	1	1	1	1	1	1	6
Cypress	1	1	1	1	1	0	5
Neches	1	1	1	1	1	0	5
Nueces	1	1	1	1	1	0	5
Red	1	1	1	1	1	0	5
Sabine	1	1	1	1	1	1	6
San Jacinto	1	1	1	1	1	0	5
Trinity	1	1	1	1	1	0	5
				Current Conditions WAM			
Brazos and San Jacinto-Brazos	1	1	1	1	1	1	6
Colorado and Colorado-Brazos	1	1	1	1	1	1	6
Cypress	1	1	1	1	1	0	5
Neches	1	1	1	1	1	0	5
Nueces	1	1	1	1	1	0	5
Red	1	1	1	1	1	0	5
Sabine	1	1	1	1	1	1	6
San Jacinto	1	1	1	1	1	0	5
Trinity	1	1	1	1	1	0	5
Total							96

Table B.1. Power plants included in analysis of applying methodology to Texas. (Note: '—' represents a data gap; NG = natural gas, NUC = nuclear, LIG = lignite, SUB = subbituminous coal; CR = cooling reservoir, CT = cooling tower, OL = open-loop.)

Power plant	Fuel	Capacity (MW)	Capacity factor	Cooling technology[a]	Withdrawal rate[b] (m^3 MWh^{-1})	Consumption rate[b] (m^3 MWh^{-1})	Full Execution storage right (ac-ft)	Current Conditions storage right (ac-ft)
Big Brown	LIG	1187	0.822	CR	83.3	1.1	50 600	43 884
City of Bryan	NG	138	0.001	CT	598.1	3.6	15 227	15 227
Comanche Peak	NUC	2430	0.885	CR	208.2	2.2	151 500	151 015
Corpus Refinery	NG	55	0.477	CT	0.2	0.2	1 406	1 406
Decker Creek	NG	932	0.141	OL	946.4	1.9	33 940	33 724
Eastman Cogeneration	NG	468	0.516	CT	—	—	14 341	397 583
EG178 Yates	NG	121	0.529	CT	0.2	0.2	204 000	200 604
Fayette	SUB	1690	0.820	OL	106.0	1.3	0	0
Gibbons Creek	SUB	454	0.867	OL	143.8	10.1	26 824	26 824
Greens Bayou	NG	878	0.029	CT	23.5	3.1	152 000	58 800
Handley	NG	1433	0.021	OL	492.1	1.8	71 310	63 392
Harrison County	NG	570	0.220	CT	0.9	0.9	0	0
Knox Lee	NG	501	0.122	OL	—	—	124 800	82 314
Lake Creek	NG	322	0.021	OL	492.1	8.9	8 000	7 910
Lake Hubbard	NG	928	0.070	OL	2082.0	1.7	490 000	484 495
Lewis Creek	NG	543	0.362	OL	—	—	17 000	17 000
Limestone	LIG	1706	0.839	CT	3.4	0.0	30 319	29 611
Lost Pines 1	NG	595	0.623	OL	0.9	0.9	0	0
Martin Lake	LIG	2380	0.867	OL	147.6	1.4	77 619	75 050
Mirant Wichita Falls LP	NG	80	0.109	CT	0.5	0.5	13 050	13 050
Monticello	LIG	1980	0.888	CR	124.9	0.8	80 200	34 732
Morgan Creek	NG	1364	0.014	OL	1.0	1.0	42 500	41 356
Mountain Creek	NG	958	0.045	OL	416.4	1.8	22 840	22 840
Newgulf Cogeneration	NG	79	0.016	CT	0.2	0.2	16 648	16 648
North Lake	NG	709	0.012	OL	—	—	17 100	16 985
Pearsall	NG	66	0.038	CT	5.9	5.9	6 600	7 500

Table B.1. (Continued.)

Power plant	Fuel	Capacity (MW)	Capacity factor	Cooling technology[a]	Withdrawal rate[b] (m^3 MWh^{-1})	Consumption rate[b] (m^3 MWh^{-1})	Full Execution storage right (ac-ft)	Current Conditions storage right (ac-ft)
Pirkey	LIG	721	0.713	OL	—	—	29 513	28 986
R W Miller	NG	604	0.059	OL	4164.0	0.0	0	0
Sand Hill	NG	594	0.351	CT	28.9	0.9	3 520	3 520
Sandow Station	LIG	363	0.861	OL	1.3	1.3	15 650	13 876
Stryker Creek	NG	713	0.125	OL	1249.2	1.1	80 420	67 854
Sweeny Cogeneration	NG	572	0.652	CT	0.2	0.2	300	300
Tradinghouse	NG	1380	0.033	OL	1059.9	1.6	37 800	37 065
Trinidad	NG	243	0.033	OL	2.5	2.5	12 400	12 400
Valley	NG	1175	0.021	OL	3369.0	1.4	30 000	29 882
W A Parish	SUB	3969	0.577	CT	155.2	1.9	56 250	55 275
Welsh	SUB	1674	0.684	CR	—	—	23 587	20 242
Wilkes	NG	882	0.197	OL	—	—	10 100	10 100

[a] Cooling reservoirs and cooling towers represent specific types of closed-loop recirculation cooling systems. See [3] for further description.

[b] Source: plant-specific values originally from data from the Texas Commission on Environmental Quality and Texas Water Development Board with updates and modifications from Energy Information Administration forms 860 and 923 by King as reported in [23].

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