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Technical analysis of a river basin-based model of advanced power plant cooling technologies for mitigating water management challenges

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Abstract
Thermoelectric power plants require large volumes of water for cooling, which can introduce drought vulnerability and compete with other water needs. Alternative cooling technologies, such as cooling towers and hybrid wet–dry or dry cooling, present opportunities to reduce water diversions. This case study uses a custom, geographically resolved river basin-based model for eleven river basins in the state of Texas (the Brazos and San Jacinto–Brazos, Colorado and Colorado–Brazos, Cypress, Neches, Nueces, Red, Sabine, San Jacinto, and Trinity River basins), focusing on the Brazos River basin, to analyze water availability during drought. We utilized two existing water availability models for our analysis: (1) the full execution of water rights—a scenario where each water rights holder diverts the full permitted volume with zero return flow, and (2) current conditions—a scenario reflecting actual diversions with associated return flows. Our model results show that switching the cooling technologies at power plants in the eleven analyzed river basins to less water-intensive alternative designs can potentially reduce annual water diversions by 247–703 million m^3—enough water for 1.3–3.6 million people annually. We consider these results in a geographic context using geographic information system tools and then analyze volume reliability, which is a policymaker's metric that indicates the percentage of total demand actually supplied over a given period. This geographic and volume reliability analysis serves as a measure of drought susceptibility in response to changes in thermoelectric cooling technologies. While these water diversion savings do not alleviate all reliability concerns, the additional streamflow from the use of dry cooling alleviates drought concerns for some municipal water rights holders and might also be sufficient to uphold instream flow requirements for important bays and estuaries on the Texas Gulf coast.

Keywords: power plants, cooling water, water rights, drought, policy, cooling towers, dry cooling

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Nomenclature

EPA	Environmental Protection Agency
GAM	Groundwater Availability Model
TCEQ	Texas Commission on Environmental Quality
TIFP	Texas Instream Flow Program
TPWD	Texas Parks and Wildlife Department
TWDB	Texas Water Development Board
WAM	Water Availability Model
WRAP	Water Rights Analysis Package

1. Introduction

Rights to surface water generally fall under state government jurisdiction in the United States, with different states following riparian, prior appropriation, or a hybrid system of water law (Getches 2009). Riparian rights allow landowners to use water adjacent to their property, while the prior appropriation doctrine assigns water rights based on the 'first in time, first in right' principle. Hybrid water rights systems operate with a mix of riparian and prior appropriation rights (Getches 2009, Kaiser 2002, Texas A&M AgriLife 2009, Texas Commission on Environmental Quality 2009a). While some states conjunctively manage surface water and groundwater, many states, including Texas, manage groundwater independently of surface water (Getches 2009).

Texas uses a hybrid system of managing surface water, with domestic and livestock riparian rights taking priority over prior appropriation rights for municipal, industrial, irrigation, mining, hydroelectric power, navigation, or recreational uses (Kaiser 2002, Texas A&M AgriLife 2009, Texas Commission on Environmental Quality 2009a). After domestic and livestock riparian rights, prior appropriation rights to divert (and store, in some cases) water are assigned priority dates and seniority based on the date of permit application. For example, an industrial water right holder with a priority date of 24 February 1926 is senior to a municipal water right holder with a priority date of 13 August 1952, regardless of their locations in the river basin.

Priority becomes important during times of water shortage, since rights to water do not guarantee availability. That is, the legal availability of water can exceed physical availability. Because this priority is established by date—not by type of use—some critical needs, including public supply, might go unfulfilled. Depending on location in the watershed and return flows, junior water rights holders can find themselves without enough water to meet their diversions because of the need to fulfil upstream or downstream senior water rights. During extreme water shortages, senior water rights holders might also have to decrease or discontinue water diversions in order to fulfill domestic and livestock riparian water rights (Texas Commission on Environmental Quality 2009a). As a result, location and priority of water rights holders becomes important for water resources planning and management. Unfortunately, planners typically lack quantitative tools to assess different water use scenarios.

Senate Bill 2 during the 77th Texas Legislature in 2001 created the Texas Instream Flow Program (TIFP) to determine appropriate instream flows to 'maintain a proper ecological environment' (TCEQ, Texas Parks and Wildlife Department (TPWD), and Texas Water Development Board (TWDB) 2008; Mallard *et al* 2005). Under this program, the Texas Commission on Environmental Quality (TCEQ), Texas Parks and Wildlife Department (TPWD), and Texas Water Development Board (TWDB) conduct studies to determine appropriate instream flows, also known as environmental flows. These instream flows affect riparian and prior appropriation water rights holders by designating quantity and timing of streamflow to support aquatic environments, likely decreasing the amount of water available for diversion.

Because of their extensive need for cooling water and risks of water-related outages, power plants are of particular interest (Stillwell *et al* 2011). Specifically, water shortages from droughts or instream flow requirements might reduce the amount of water available for power plant cooling during electricity generation, introducing vulnerabilities to the power system. Water scarcity, which is more likely in the summer, coincides with peak electricity demand, exacerbating vulnerability. However, alternative cooling technologies can be implemented to uphold instream flow requirements while serving existing water uses. Thus, while power plants are vulnerable to the risks of water scarcity, they also represent an opportunity, through the inclusion of advanced low-water cooling technologies, to improve the availability of water rights for other purposes. Previous research describes the life-cycle water withdrawal and consumption of US electricity generation (Fthenakis and Kim 2010, Macknick *et al* 2011), motivations for electric utilities to reduce water use (Wolfe *et al* 2009), models of power plant cooling in response to climate change (Koch and Vögele 2009), and changing dam operations to support instream flows (Richter and Thomas 2007). To our knowledge, our customized model is the first of its kind to simulate implementation of alternative thermoelectric cooling technologies for mitigating water management challenges and supporting instream flows on a river basin scale.

The hybrid system of water rights in Texas makes it an appropriate setting for our case study because the results might be broadly applicable to other states or countries with riparian, prior appropriation, or hybrid water management practices. Additionally, annual precipitation decreases from nearly 130 cm in the east to less than 25 cm in the west, making Texas a suitable proxy for climate variation in the continental United States (Wermund 1996). With a population of 25 million and land area of 0.69 million square kilometers, Texas is large enough to simulate other countries or regions, yet small enough to model. Many of Texas' river systems are wholly contained within the state boundaries, thus water models are relatively straightforward; since Texas has collected stream gauge information for decades, those models can be independently verified.

TCEQ has developed different Water Availability Models (WAMs) for each river basin in Texas, two of which are particularly relevant: (1) the full execution model, which simulates each perpetual water rights holder diverting the entire permitted volume of water with zero return flow; and (2) the current conditions model, which simulates actual water rights

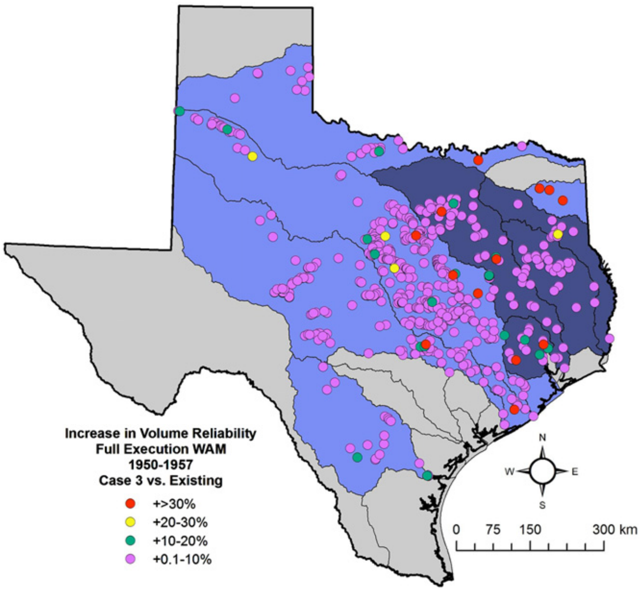

Figure 1. Eleven river basins, shown in blue and dark blue, were included in this analysis. Basins in dark blue have proposed instream flow requirements incorporated into the Water Availability Models. Volume reliability for the 1950–7 drought of record increases for the Case 3—dry cooling scenario over existing diversions under the full execution WAM scenarios. Colored dots illustrate water rights holders and the corresponding increase in volume reliability modeled in Case 3.

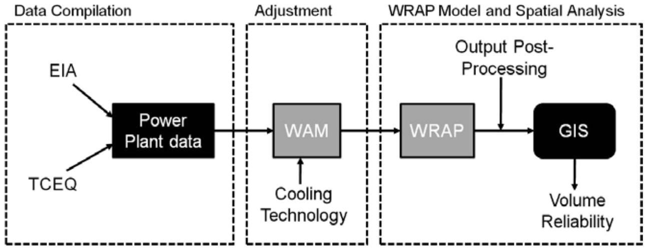

Figure 2. Modeling the implementation of alternative cooling technologies at power plants required compilation of power plant operating data from the Energy Information Administration (EIA) and the Texas Commission on Environmental Quality (TCEQ) with previous work from the authors regarding cooling technologies to modify input files for the Water Availability Model (WAM). We then used the Water Rights Analysis Package (WRAP) to simulate streamflow, and displayed volume reliability results, after post-processing, using geographic information systems (GIS).

diversions from all users (including temporary and term permit holders) with associated return flows (TCEQ 2009b). These WAMs simulate diversions from all current water right holders in a particular basin over the period of record (generally 1934–98) with naturalized streamflow, historical precipitation and evaporation, and corresponding reservoir operations. Since the model timeframe includes the Texas drought of record (1950–7), the WAMs reveal the possible effects of historical drought on current water users. TCEQ uses the full execution WAM to determine water availability for new perpetual rights (TCEQ 2009b). Generally, TCEQ issues permits when 75% of the proposed water diversion is available 75% of the time; permits for municipal water users are issued when 100% of the proposed water diversion is available 100% of the time, with this requirement relaxed when backup water rights are secured (Texas Commission on Environmental Quality 2009a).

The Water Rights Analysis Package (WRAP) developed at the Texas Water Resources Institute (Texas A&M University 2010) simulates the WAM data of actual permitted water rights with naturalized streamflow and observed meteorological conditions to model existing diversions over a historical time period. WRAP uses Fortran-based computer code to model water diversions based on priority order and geographic location in a river basin using streamflow control points and daily or monthly timesteps. The WAM combined with WRAP reveal the actual amount of water diversions available to current water rights holders based on observed historical climate conditions.

Given the complexity of water rights, availability, and priority, a subset of 11 of the 23 river basins in Texas was chosen for this analysis, as shown in blue and dark blue in figure 1: the Brazos and San Jacinto–Brazos, Colorado and Colorado–Brazos, Cypress, Neches, Nueces, Red, Sabine, San Jacinto, and Trinity River basins. These river basins constitute a majority of the land area in Texas and incorporate sufficient climatic variation to capture various water management challenges. In addition, the instream flow requirements for many of these river basins are being studied under the TIFP and proposed full execution WAMs have been created for the Neches, Sabine, San Jacinto, and Trinity River basins, shown in dark blue in figure 1 (Mallard *et al* 2005, Middle and Lower Brazos River Study Design Workgroup 2008, TCEQ, TPWD, and TWDB 2008). In particular, this analysis of drought resiliency focuses on the Brazos River basin (including the San Jacinto–Brazos coastal basin), which (1) contains the longest section of river in Texas, (2) serves major cities (Lubbock, Waco, Temple, Freeport and Galveston), and (3) represents large diversity in water use and management because of its many industrial and agricultural water users. Additionally, the Brazos River basin contains thermoelectric power plants with a variety of fuels and cooling technologies, as shown in table 1.

2. Methodology

Analysis of the full execution and current conditions WAMs in the 11 analyzed river basins was completed by integrating multiple data sets and previous work by the authors on thermoelectric cooling technologies (Stillwell *et al* 2011) with two different analytical platforms, as shown in figure 2: the Water Rights Analysis Package (WRAP) from the Texas Water Resources Institute (Texas A&M University 2010), and ArcGIS software from Esri. WRAP simulates each water rights diversion from the WAM for the period of record, which ranges from 1934 to 1998 for the river basins analyzed (Wurbs 2008, Texas A&M University 2010). Our analysis focuses on the 1950–7 time period, representing the drought of record in Texas. After post-processing the WRAP output files for different scenarios, the results were displayed spatially using ArcGIS (Center for Research in Water Resources 2007, Siler 2008). Our analysis reveals both top-level basin-wide

Table 1. Nine power plants were analyzed from the Brazos River basin using Water Availability Models (WAMs) for full execution and current conditions (Note: the Brazos River basin current conditions WAM was last updated 9 September 2008.) (King *et al* 2008, TCEQ 2009b).

						Existing diversions (thousand m^3)		Case 1 (thousand m^3)		Case 2 (thousand m^3)		Case 3 (thousand m^3)	
Power plant	Fuel[a]	Capacity (MW)	Capacity factor[b]	Cooling technology	Cooling intensity[c] (m^3 MWh^{-1})	Full execution	Current conditions	Full execution	Current conditions	Full execution	Current conditions	Full execution	Current conditions
City of Bryan	NG	138	0.10	Cooling tower	3.6	105	105	105	105	53	53	11	11
Comanche Peak	NUC	2430	0.93	Cooling reservoir	2.2	28 600	21 600	28 600	21 600	14 300	10 800	2860	2160
Gibbons Creek	SUB	454	0.91	Open-loop	10.1	12 000	5 850	8 970	5 850	4 480	2 930	897	586
Lake Creek	NG	322	0.04	Open-loop	8.9	12 300	949	349	349	175	175	35	35
Limestone	LIG	1706	0.85	Cooling tower	1.4	16 300	0	16 300	0	8 140	0	1630	0
R W Miller	NG	604	0.14	Open-loop	1.4	47 900	0	2 660	0	1 330	0	265	0
Sandow Station	LIG	363	0.78	Open-loop	4.2	17 300	0	5 710	0	2 860	0	571	0
Tradinghouse	NG	1380	0.04	Open-loop	1.6	33 300	7 740	1 820	1 820	910	910	183	183
W A Parrish	SUB	3969	0.58	Cooling tower	1.9	42 300	42 300	42 300	42 300	21 200	21 200	4230	4230

[a] NG = natural gas, NUC = nuclear, LIG = lignite, SUB = subbituminous coal.

[b] Capacity factors are calculated from rated capacity and net generation in 2006.

[c] Cooling intensity is based on actual existing diversions with current cooling technologies and 2006 net generation.

Table 2. Total annual water diversions in the analyzed river basins vary widely for different types of use (TCEQ 2009b, Clayton *et al* 2010, Stillwell *et al* 2010). Full execution indicates the full permitted diversions of perpetual (permanent) water rights holders. Current conditions indicates the actual diversions from all water rights holders, including temporary and term permits. Note: power generation is contained within industrial uses in the WAM; totals might not sum exactly due to rounding.

	Industrial (million m^3)		Power generation (million m^3)		Irrigation (million m^3)		Mining (million m^3)		Municipal (million m^3)		Other (million m^3)		Total (million m^3)	
River basin	Full execution	Current conditions	Full execution	Current conditions	Full execution	Current conditions	Full execution	Current conditions	Full execution	Current conditions	Full execution	Current conditions	Full execution	Current conditions
Brazos and San Jacinto–Brazos	645	535	210	79	326	255	120	26	1 650	996	7	34	**2 960**	**1 846**
Colorado and Colorado–Brazos	195	374	153	122	1540	1985	18	14	2 260	1247	900	0.3	**5 070**	**3 620**
Cypress	271	145	49	45	3	0.5	0	0	190	78	0	0	**513**	**224**
Neches	902	248	25	16	548	274	2	0.1	645	116	12	0.1	**2 130**	**638**
Nueces	185	116	98	6	96	61	0	0.2	274	486	382	0	**1 040**	**664**
Red	119	32	28	20	224	97	4	3	915	532	13	9	**1 300**	**673**
Sabine	1210	300	70	54	189	9	2	1	1 650	279	0	85	**3 120**	**674**
San Jacinto	220	73	49	48	30	21	0	0	364	239	2	0.7	**665**	**334**
Trinity	1090	371	73	40	391	200	13	3	4 220	2313	3	0.2	**5 790**	**2 887**
Total	**4840**	**2195**	**755**	**430**	**3350**	**2903**	**159**	**47**	**12 200**	**6256**	**1320**	**129**	**22 600**	**11 560**

changes in water diversions and spatially resolved changes with subsequent impacts on water availability for individual users.

2.1. Data compilation

Diversion, storage, and existing instream flow water rights in the WAM were sorted by priority date to examine seniority. Totals for the existing water rights are shown in table 2. Within the WAM, priority dates are given as YYYYMMDD (e.g., 19260224 for 24 February 1926). Data compilation could not be fully automated because of non-standard artifacts in the databases. Each water right (out of several thousand water rights in total) had to be examined individually because the WAM input data lack uniformity and require interpretation, as shown in figure 3 for the sample water rights from the Brazos and Sabine River basins. The Brazos water right in the top of figure 3 is a municipal (`MUN`) water right to divert 35 000 ac-ft (43 million m^3) with a priority date of 5 October 1981 (`19811005`); the details of this particular line of code describe the owner (Brazos River Authority) and location (south fork of the Double Mountain Fork of the Brazos River) of the diversion. The Sabine water right on the bottom of figure 3 is also a municipal (`MUN`) water right to divert 730 ac-ft (0.9 million m^3) with a priority date of 24 April 1935 (`19350424`); the details, however, are contained within the previous line of code as an optional comment, indicating the owner (City of Longview). When such commented details are omitted, isolating water rights for individual power plants amongst thousands of other water users becomes extremely difficult, if at all possible. Consequently, our analysis includes only the eleven river basins with descriptive details included in the respective WAMs, and required an initial line-by-line data screening step.

Once all water rights in each of the eleven basins were sorted by priority date, industrial water rights were examined further since thermoelectric power generation water rights are contained as a subset of industrial water rights. Of the power plants in Texas, we would anticipate 72 thermoelectric power plants to hold surface water rights present in the WAMs; our customized model includes 45, making our analysis a representative sample. More than 72 thermoelectric power plants are currently operating in Texas, but those using groundwater, salt water, water reuse, or air as cooling sources are not present in the WAMs, which only model surface water. On-site industrial power plants and those using municipal water for cooling are aggregated into larger water right diversions in the WAMs and can only be isolated when detailed comments are available. Of the 45 thermoelectric power plants modeled in our analysis, 25 use open-loop cooling, which diverts large volumes of water but consumes small volumes through evaporation (King *et al* 2008, Stillwell *et al* 2011). The remaining power plants in each river basin use closed-loop cooling towers or cooling reservoirs.

2.2. Adjustment for alternative cooling technologies

One possibility for upholding instream flow requirements and reducing water diversions is changing cooling technologies at thermoelectric power plants to less water-intensive configurations. Three alternative cooling scenarios were completed, referred to here as Cases 1–3.

- *Case 1: No open-loop cooling.* Case 1 represents converting open-loop systems to closed-loop cooling tower technologies. For the power plants with open-loop cooling, this scenario is modeled as power generation water diversions at volumes (per MWh generated) equal to those at power plants with cooling towers burning similar fuels, using equation (1) below:

$$Q_1 = \varepsilon f G \tag{1}$$

  where Q_1 represents the Case 1 annual water diversion; ε is a dimensionless ratio of diversion over consumption for cooling towers, here 1.25 (Stillwell *et al* 2011); f represents water consumption for power generation (m^3 MWh^{-1}); and G represents net generation at the power plant of interest (MWh). Water consumption for power generation, f, was determined as a function of fuel, cooling technology, and river basin (King *et al* 2008) to incorporate climatic variability that is absent from national average values of water for power generation. Closed-loop cooling towers divert much smaller volumes of water compared to open-loop cooling, but consume larger volumes of water through evaporation; thus, switching from open- to closed-loop cooling exhibits a tradeoff between water diversion and water consumption.
- *Case 2: 50% reduction in Case 1 water diversions.* Case 2 represents implementation of hybrid wet–dry cooling technologies at all power plants in the basin. Such technologies combine wet cooling towers with air-cooled condensers and can range in operations from completely wet to completely dry. This scenario is modeled as power generation water diversions at 50% of Case 1 diversions; that is, operating as 50% wet and 50% dry (Stillwell *et al* 2011).
- *Case 3: 90% reduction in Case 1 water diversions.* Case 3 represents implementation of dry cooling technologies using air-cooled condensers at all power plants in the basin. While air-cooled condensers do not use water during cooling operations, other power plant operations still require water, such as boiler make-up, sinks, and toilets. Based on data for different fuel technologies, these other water uses constitute 3–12% of closed-loop water diversions (US Department of Energy 2006, US DOE 2009). This scenario is modeled as power generation water diversions at 10% of the Case 1 diversions as a reasonable, yet conservative estimate.

Each of our scenarios provides an assessment of reducing water diversions for thermoelectric power plant cooling when compared to a baseline scenario of existing basin-wide diversions. Actual water diversion reductions will vary with the cooling technology implemented. Feasibility of upholding instream flow requirements with reduced power plant diversions depends on the quantity and location of such flows, so we further investigated the spatial resolution of such water diversion changes.

```
WR4146P1   35000.    MUN119811005    1    2  0.0000
           P4146_1    P414614146001      BRAZOS RIVER AUTHORITY
           S FRK DBL MTN FRK BRAZOS RIVER                     9568000000
           DMAS09        1 WSALANHN 115937.       0

**City of Longview, return flow at WW3945
WRE4759A      730    MUN19350424   2    WW3945   60504759301
           475964759301    WS R4759    183  1.0098   0.6889    0
```

Figure 3. The Water Availability Model (WAM) data lack uniformity and required line-by-line inspection to pinpoint specific water rights holders.

Table 3. Annual water diversions for power generation in each river basin under the full execution and current conditions scenarios decrease substantially with the alternative cooling technologies modeled in Cases 1–3 (Clayton *et al* 2010, Stillwell *et al* 2010). Note: totals might not sum exactly due to rounding.

	Existing diversions (million m^3)		Case 1—no open-loop cooling (million m^3)		Case 2—hybrid wet–dry cooling (million m^3)		Case 3—dry cooling (million m^3)	
River basin	Full execution	Current conditions	Full execution	Current conditions	Full execution	Current conditions	Full execution	Current conditions
Brazos and San Jacinto–Brazos	210	79	107	72	53	36	11	7
Colorado and Colorado–Brazos	153	122	95	71	47	35	9	7
Cypress	49	45	47	45	24	23	5	5
Neches	25	16	7	5	3	2	1	0.5
Nueces	98	6	98	1	49	0.7	10	0.1
Red	28	20	8	1	4	0.6	1	0.1
Sabine	70	54	58	46	35	23	7	5
San Jacinto	49	48	47	45	24	23	5	5
Trinity	73	40	41	24	20	12	4	2
Total	**755**	**430**	**508**	**311**	**259**	**156**	**52**	**31**

2.3. WRAP model and spatial analysis

For resource management of river basins, the quantity of water use is important, but is not sufficient for planning purposes. Consequently, analysis must be spatially resolved to usefully approximate actual conditions. Thus, these three alternative cooling technologies were examined with geographical fidelity, locating specific thermoelectric power plants within river basins, for the current conditions and full execution WAMs. Focusing on spatially resolved changes in water diversions, we adapted the WAM input files for the 11 river basins and then used the revised WAM files as input into the WRAP model. Results from the WRAP model quantify the effect of such cooling technology changes with historical weather data and were displayed spatially. This spatial analysis illustrates the geographic impact of changes in thermoelectric cooling technologies, revealing specific water right locations with increased water availability.

3. Results

3.1. Full execution

Of the total 22 600 million m^3 diverted from the 11 river basins annually in the full execution WAM, 755 million m^3 are water rights held by thermoelectric power plants, as shown in table 2. By implementing alternative cooling technologies at these plants, water diversion could be reduced by as much as 247–703 million m^3 $year^{-1}$ as shown in tables 3 and 4. Volume reliability, defined as the percentage of total demand that is actually supplied over the time period of interest, is used as a measure of the likelihood that water will be available over historic meteorological conditions. For the 1950–7 drought of record, volume reliability increases for the Case 3—dry cooling scenarios over existing diversions of the full execution WAM are shown in figure 1. The four river basins in dark blue in figure 1—Neches, Sabine, San Jacinto, and Trinity River basins—were modeled based on proposed instream flow measures that have already been developed under TIFP. When water rights in the 11 analyzed river basins are simulated over the drought of record, volume reliability for many water rights falls below 75%, indicating insufficient water availability for existing and new water rights holders. By contrast, some water rights experience an increase in volume reliability of greater than 30% under the dry cooling scenario, representing the potential water benefits of this approach to cooling.

Focusing on the Brazos River basin full execution WAM, the overall volume reliability for existing diversions averages 49.9% for the drought of record and improves to 50.7% under the Case 3 scenario. While this basin-wide improvement in

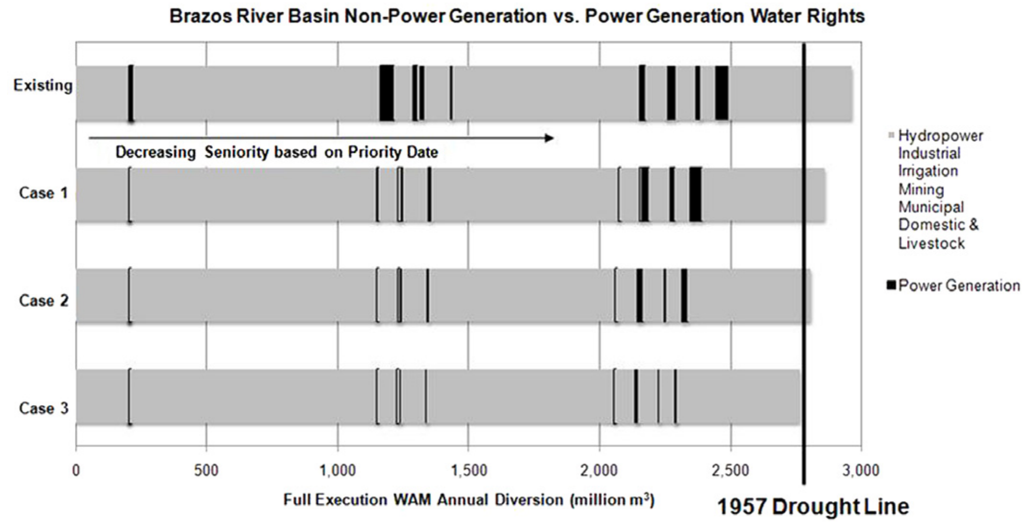

Figure 4. Water diversions for power generation in the Brazos River basin decrease substantially due to incorporation of advanced power plant cooling technologies, improving the likelihood for junior water rights to be fulfilled. Areas to the right of the 1957 drought line, representing the sum of current water diversions for the last year of the drought of record, are instances where legal availability of water exceeds physical availability.

Table 4. Potential water savings from implementation of alternative power plant cooling technologies translate to high values of human equivalence (Clayton *et al* 2010).

	Total water diversion savings (million m^3)		Human equivalent[a]	
Alternative cooling scenario	Full execution	Current conditions	Full execution	Current conditions
Case 1—no open-loop cooling	247	119	1280 000	615 000
Case 2—hybrid wet–dry cooling	496	274	2560 000	1420 000
Case 3—dry cooling	703	399	3630 000	2060 000

[a] Calculated as number of people using 0.53 m^3/d for one year.

volume reliability is small in magnitude, volume reliability increases for 421 of 1598 individual water rights. This improvement in volume reliability for individual water rights under the Case 3—dry cooling scenario might translate to water being available during drought conditions when such water would have been allocated to senior users under the existing diversions scenario, illustrated by the increases in volume reliability for certain water users in figure 1. Decreasing water diversions for power generation increases the instream flow, making a greater amount of water available for aquatic ecosystems and riparian users.

Again focusing on the Brazos River basin, figure 4 illustrates power generation water rights among the other water rights in current priority order for existing diversions and Cases 1–3 of implementing alternative cooling technologies. The annual diversion for power generation decreases substantially for Cases 1–3. As seen in figure 4, some of the thermoelectric power plants are permitted to divert water ahead of many other water users based on priority. Implementing these alternative cooling technologies could become significant to those water right holders with priority junior to the power plants in times of severe drought. As seen from the 1957 drought line, which represents the sum of annual diversions for all current water rights for the last year of the drought of record in Texas, water right holders with low priority might not have access to water in serious drought conditions. Many of the water rights holders to the right of the drought line in figure 4—likely unable to divert water during severe drought conditions—are municipal water users. By decreasing water diversions for thermoelectric power generation in the Brazos River basin, these municipal water users with junior priority are more likely to have water available during drought conditions, as shown in Case 3 of figure 4 where all water diversions are to the left of the drought line. In other words, changes in cooling technology in the thermoelectric power sector not only reduce the vulnerability of the power plant to water shortages, but it also improve the water availability for more junior rights holders. These results become important in the context of water shortage, as current drought conditions in Texas have caused junior water diversion rights in the Brazos River basin to be suspended effective 18 May 2011; municipal and power generation water rights have not been suspended in order to protect public health and welfare (TCEQ 2011).

Comparing the Brazos River basin-wide Case 3 volume reliability of 50.7% during the drought of record with the bar chart in figure 4, our results seem to conflict since many water rights holders have less than 75% volume reliability yet all users fall below the drought line in figure 4. This finding indicates that geography and priority both play a critical role in managing water availability during drought conditions. While the sum of all permitted water diversions can be fulfilled in priority order under the Case 3 scenario during the drought of record, the geographical order and priority order for the diversions in the Brazos River basin are notably different. Ensuring water availability for all water users during drought conditions requires careful management of priority and geographic locations within a river basin.

3.2. Current conditions

In order to better reflect real water use, we repeated our analysis of alternative cooling technologies with the current conditions WAMs for the eleven river basins. Distinct from the full execution WAMs, the current conditions WAMs quantify actual water diversions (potentially different from permitted full execution diversions) with associated return flows. A total of 11 560 million m^3 are diverted from the 11 river basins annually in the current conditions WAM, as shown in table 2; of this total, 430 million m^3 are water rights diversions held by thermoelectric power plants. By implementing alternative cooling technologies at these plants, water diversion could be reduced by as much as 119–399 million m^3 $year^{-1}$ as shown in tables 3 and 4.

For the 1950–7 drought of record, volume reliability increases for the Case 3—dry cooling scenarios over existing diversions of the current conditions WAM are shown in figure 5. Similar to volume reliability under the full execution WAM, volume reliability for many water rights falls below 75% when simulated over the 1950–7 drought of record, yet some water rights experience an increase in volume reliability of greater than 30% under the dry cooling scenario. Focusing on the Brazos River basin current conditions WAM, the overall volume reliability for existing diversions averages 61.4% for the drought of record and improves to 61.5% under the Case 3 scenario with volume reliability increases for 73 of 1686 total water rights. This current conditions WAM better illustrates the actual water diversion circumstances, including temporary and term water permit diversions, that are likely experienced during drought conditions. While implementation of dry cooling at thermoelectric power plants, as modeled in Case 3, alleviates some water management challenges, some diversions are left unfulfilled in response to drought.

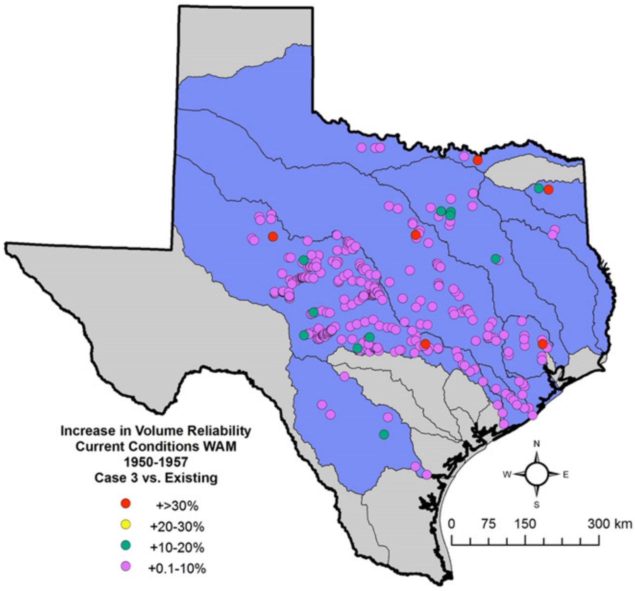

Figure 5. Eleven river basins, shown in blue, were included in this analysis. Volume reliability for the 1950–7 drought of record increases for the Case 3—dry cooling scenario over existing diversions under the current conditions WAM scenarios. Colored dots illustrate water rights holders and the corresponding increase in volume reliability modeled in Case 3.

4. Policy implications

In our analysis of mitigating water management challenges using alternative power plant cooling technologies, we find that the policymaker's metric of volume reliability becomes a less-than-useful indicator of water availability when compared to the volume of water saved in Cases 1–3, as shown in table 3. For example, Case 3—dry cooling model results show water savings equivalent to the municipal use of over 2 million people, yet average volume reliability increases by less than 5%. Thus, our results suggest that using volume reliability as a metric for water availability overlooks tremendous water savings potential. On the other hand, a metric that only considers water volumes does not account for the seasonality of the hydrologic cycle or extreme events, such as droughts and floods.

While dry cooling does reduce drought risk for other water users, cooling thermoelectric power plants with air instead of water comes with an inherent efficiency loss due to differences in heat capacities. Parasitic efficiency loss associated with dry cooling averages 2% (Smart and Aspinall 2009, US DOE 2009, Zhai and Rubin 2010), which amounts to 1.2 million MWh annually from the nine power plants analyzed in the Brazos River basin. Since this efficiency loss varies with air temperature, dry cooled power plants are increasingly less efficient during the hottest times of the year, which often corresponds to high electricity demand for air conditioning. Filling this electricity generation gap could be achieved with a variety of options. Some of these options, including end-use energy efficiency, wind, or photovoltaic solar power, have zero associated water consumption. Compensating for these power generation efficiency losses with new natural gas combined cycle power plants would require over 1 million m^3 yr^{-1} at current cooling intensities of 0.87 m^3 MWh^{-1} (King *et al* 2008).

Instream flows represent additional water uses within river basins. Incorporation of these new requirements raises the question: will instream flow programs complicate water resources management? (White 2009). Additional studies are necessary, yet 'very little water remains available in Texas for appropriation to new users' (Texas Commission on Environmental Quality 2009a). As a result, water conservation through less water-intensive thermoelectric power plant cooling might be necessary to ensure water is available to uphold instream flow requirements and mitigate water scarcity. Additional conservation by municipal, industrial, and irrigation water users might be necessary to ensure available instream flows, especially in water-stressed regions and during drought and other times of water scarcity. Projected population growth in Texas is likely to compound these water management challenges.

Implementing alternative power plant cooling technologies is possible through numerous federal and state policy levers. Phasing out open-loop cooling, as shown in Case 1, was proposed in California in 2006, by denying leases for new power plants using open-loop cooling (California State Lands Commission 2006). Decisions in the US Supreme Court in *Entergy Corp. v. Riverkeeper, Inc.* in 2009, upheld US EPA policy that cost–benefit analysis could be used to determine appropriate cooling technology while not outlawing open-loop cooling (Thacker 2004, US Supreme Court 2009). The EPA recently reviewed rulemaking under Section 316(b) of the Clean Water Act and has proposed requiring new units at existing facilities to install cooling towers. Changes in cooling at existing open-loop power plants might be required at the discretion of the water permitting authority (EPA 2011), potentially making a scenario like Case 1 required by law. Implementation of widespread hybrid wet–dry or dry cooling, as shown in Cases 2 and 3, would likely require significant policy action on the state, perhaps federal, level to dramatically reduce water diversion and consumption for thermoelectric power generation. Such hybrid wet–dry and dry cooling technologies are capital intensive and would require significant investments and incentives to facilitate adoption.

Another policy option to ensure surface water availability for instream flows is the strategic acquisition of water rights, whereby the state government or appropriate agency would essentially purchase excess water rights from existing water rights holders in the basin. Such an option requires both physical and legal water availability to form the market for water rights sales and purchases. These scenarios of incentivizing implementation of alternative cooling technologies compared to strategic acquisition of water rights constitute a complex economics analysis not considered here, where the capital and operating costs for hybrid wet–dry and dry cooling equipment compare to the purchase price for rights to surface water. Future work will evaluate the economic tradeoffs associated with power plant cooling technology changes. Preliminary results indicate that switching from open-loop cooling to cooling towers, as modeled in Case 1, would be profitable at current water right lease rates for some power plants in the Brazos River basin.

The results of our model methodology of incorporating advanced cooling technologies at power plants in the Texas river basins are limited by the structure of surface water availability modeling in Texas. While TCEQ has WAMs describing surface water conditions and TWDB has Groundwater Availability Models (GAMs) predicting groundwater conditions, these models are not integrated together to simulate the interactions between surface water and groundwater. Diverse geography in Texas causes a wide variety of relationships between groundwater and surface water, ranging from spring-fed streams consisting of all groundwater to streams feeding aquifers, flowing completely underground at some points. Complexity and structural differences in the WAMs and GAMs make integrating the two models difficult; consequently, many support improving the WAMs and GAMs individually instead of integrating the models (Dunn *et al* 2007).

Climate change might also complicate energy and water resources planning and management. Electricity demand is likely to grow in response to changing climate and increasing population. At the same time, increased use of nuclear or concentrating solar power for electricity (Stillwell *et al* 2011) and biofuels or electric vehicles for transportation (King and Webber 2008a, 2008b) in an effort to decrease carbon emissions can simultaneously increase water consumption. Legal water rights are based on fixed patterns of use that are contingent on underlying predictability of water availability. With greater weather variations predicted due to climate change, water availability might have more variation than is accounted for in current water resources management. Additionally, thermoelectric power plants are vulnerable to both water shortages and elevated water temperatures. As available water volumes decrease and incoming water temperatures increase, power plants lose efficiency for cooling a steam cycle. Consequently, adaptive management that observes and responds to a changing climate with multiple impacts on water resources might be necessary for future water resources planning and management.

5. Conclusions

We integrated spatially resolved data on water rights with updated estimation of water needs for advanced cooling technologies. We find that less water-intensive power plant cooling technologies reduce water diversions from the Brazos and San Jacinto–Brazos, Colorado and Colorado–Brazos, Cypress, Neches, Nueces, Red, Sabine, San Jacinto, and Trinity River basins and improve reliability for some rights. However, implementation of these technologies still leaves some water rights with less than 75% volume reliability. These cooling technologies reduce water diversions in the 11 river basins analyzed by 247–703 million m^3 annually under the full execution of water rights WAM, and 119–399 million m^3 annually under the current conditions WAM. These volumes of water are potentially available for other water users in the respective river basins, including instream flows for aquatic ecosystems and junior municipal water rights holders. Implementation of dry cooling technologies has the most sizable effect (at the expense of lower power plant generation efficiency); nonetheless, changing open-loop cooling power plants to closed-loop cooling towers is typically a more achievable objective that could significantly reduce water diversions, at the expense, however, of increased water consumption. Instream flow requirements and water scarcity present challenges for water resources planning and management. However, the magnitude of these challenges can be reduced through implementation of alternative cooling technologies at thermoelectric power plants.

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