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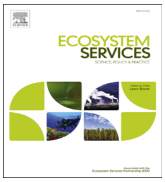

Finding solutions to water scarcity: Incorporating ecosystem service values into business planning at The Dow Chemical Company's Freeport, TX facility

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ABSTRACT

Water scarcity presents a major risk to businesses, but it can be hard to quantify. Ecosystem service valuation methods may help businesses better understand the financial impacts of water shortages and identify solutions. At The Dow Chemical Company's facility in Freeport, TX, we used natural capital asset valuation to assess the risk from future changes in industrial water supplies. We found that the value of industrial water rights may increase in the future with increased demand but that potential decreases in reliability of water rights due to demand growth and climate change could reduce their value. Using this information, experts identified 16 potential nature-based and collaborative (involving other water users) solutions to future water scarcity. We used multi-criteria analysis to select five of the 16 solutions for further analysis. Two solutions (marsh wastewater treatment, land management) were not cost-competitive and three solutions (reservoir flood pool reallocation/floodplain restoration, irrigation efficiency, municipal rebate program) were cost-competitive with the business-as-usual solution (expanding reservoir storage). However, these solutions have significant technical, legal, and political hurdles. We also found that these solutions provide substantial collective benefits to the public and biodiversity, suggesting that such solutions may be appropriate for implementation via multi-stakeholder collaboration.

1. Introduction

Businesses are extremely good at accounting for their manufactured or financial capital; however, businesses do not have good methods for understanding their natural capital assets, such as clean water. Nor are businesses able to account for the potential liabilities that come from impacts to these assets, such as pollution. These hidden assets and liabilities are now considered top business risks (ECA, 2009; KPMG, 2012). Natural capital, such as water, forests, and protective coastal habitats, have long been degraded (Millenium Ecosystem Assessment, 2005). Despite a growing awareness of these risks, businesses may be faced with financial surprises because there are rarely market prices to signal changes in the availability or quality of natural capital (Hanley and Barbier, 2009). In the absence of these price signals, economic valuation may help businesses better manage natural capital (Daily et al., 2009; WBCSD, 2011; TEEB, 2012). The methods of natural capital valuation may be especially critical to address future water scarcity caused by population growth and climate change (McDonald et al., 2011; Schewe et al., 2014).

Freshwater availability is likely to be one of the most urgent societal challenges of the 21st century and this challenge has been recognized by new global goals and commitments such as the United Nations Millennium Development Goals and CEO Water Mandate (Gleick, 2014). Declining water availability and quality affects industry, municipalities, farmers, recreational users, and

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ecosystems (Hoekstra et al., 2012). The potential impacts to business are important because many industrial facilities are unable to operate at full capacity without an adequate and high quality supply of freshwater (Renzetti, 1992). Moreover, short- and long-term options for addressing water shortages through technological change may be limited (Husemann, 2003). Given this context, businesses and other water users may need to evaluate and implement additional basin-specific adaptation actions, including ecological protection (e.g., riparian corridors) and restoration (e.g., re-connect floodplains) as well as enhanced monitoring and management systems (e.g., sustain environmental flows) (Palmer et al., 2009).

Despite the importance of water, it can be challenging for businesses to fully value the role that freshwater availability plays in their business. For many businesses, water is a utility, treated similarly to electricity, with fees paid to municipal or regional suppliers (Renzetti, 1999). For other businesses with water rights, water is essentially free, except for the costs of pumping and maintenance (Burness and Quirk, 1979). These water *expenses*, however, greatly underestimate the *value* of water to the business, much less to the public or to ecosystems (Young, 2005). The value of water to business often only becomes apparent when water is not available. Water shortages can cause business interruption and lost revenue (Ding et al., 2011) as well as require significant expenditures or capital investments to reduce water demand or increase water supplies. However, when these periodic events subside, the day-to-day costs of water provide little information to guide managers in planning for future or long-term shortages (Young, 2005).

Ecosystem service valuation provides an approach to fill this information gap. Despite calls to action from academic and science organizations and some business groups (Carpenter et al., 2009; Daily et al., 2009; TEEB, 2010, 2012; WBCSD, 2011), ecosystem services and their valuation are still only nascent considerations in business strategy and decision making. Our review of the literature indicates that few if any ecosystem service valuation studies conducted within industry have been presented in peer review journals (except see DiMuro et al., 2014; Kroeger et al., 2014). This is in part because ecosystem service valuation is a new field and the benefits of validation and knowledge sharing to business may not outweigh the cost and time of publishing (Wintgens et al., 2013). A growing number of corporations are beginning to investigate the value of water ecosystem services (WBCSD, 2012a), but most previous efforts have focused on water footprinting reports (e.g., Coca-Cola Europe, 2011; SABMiller, WWF-UK, 2009; Sikirica, 2011) rather than on economic valuation.

Mainstreaming ecosystems services in business faces two primary challenges: (1) advancing the basic science of ecosystem service production and valuation and (2) applying the science to specific business decisions. These challenges are connected because understanding how changes in ecosystem service production and value would affect a decision or be effected by a decision is critical for developing integrated analyses of ecosystems, economic benefits, and decision makers (Daily et al., 2009; Keeler et al., 2012). The over five decades of literature on economic valuation provides a critical set of methods to enable businesses to move beyond biophysical assessments of water to assessments of the value of water resources to the business and to the public (Pearce, 2002). More recent advances by academic and government analysts demonstrate how to integrate biophysical and economic analyses for water planning and policy evaluation (Booker et al., 2012; Miller and Belton, 2014).

In this paper, we demonstrate how businesses can use economic valuation of natural capital to improve business planning and risk

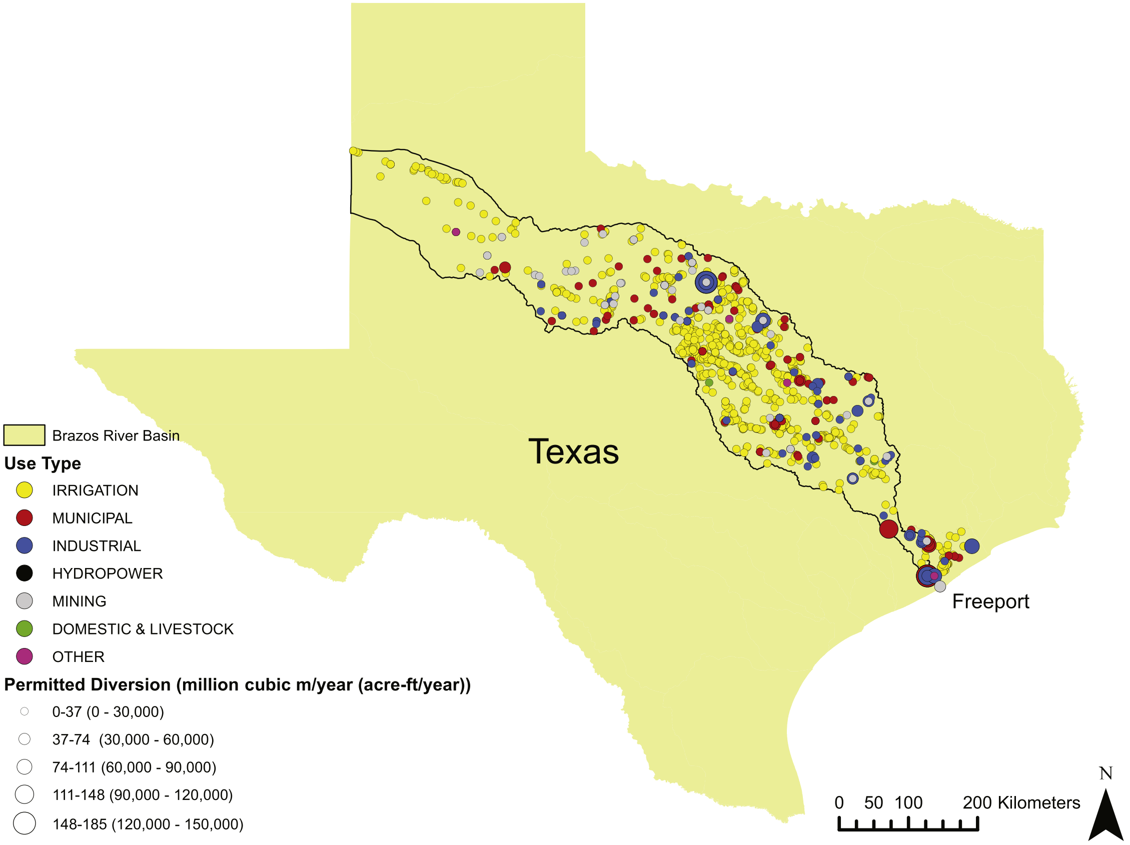

Fig. 1. Brazos River basin water right withdrawal points and permitted annual water withdrawals. Dow's Texas Operations at Freeport is located at the mouth of the Brazos River. The most common categories of water rights are irrigation for agricultural, municipal, and industrial uses. By volume, industrial and municipal water rights comprise the majority of withdrawals. [1.5 columns].

management for a critical ecosystem service, water. Using the case study of The Dow Chemical Company's operations in Freeport, Texas and the surrounding Brazos River basin (Fig. 1), we assessed the changing value of all industrial water rights in the Brazos River basin under different climate change and demand scenarios. We then identified and evaluated innovative solutions to maintain the value of the business's water rights. Specifically, we showed how accounting for private benefits as well as public and ecosystem benefits may help identify opportunities for private-public investments and account toward sustainability goals (Fig. 2). This accounting approach is a key ingredient for creating shared value—creating economic value while also creating value for society (Porter and Kramer, 2011). The concept of shared value is distinct from traditional corporate social responsibility, philanthropy, and sustainability efforts because it makes addressing social needs a core business activity rather than a peripheral activity (Porter and Kramer, 2011). We expect that better business decisions will be a product of this kind of quantitative and qualitative understanding of the value of nature to business and society. Finally, this approach is intended to be shared, copied, and advanced by others to produce the greatest business, public, and ecosystem benefit.

2. Case study: The Dow Chemical Company and the Brazos River

The Brazos River, the longest river in Texas, illustrates both the ecological and economic value of large freshwater rivers (Fig. 1). The Brazos River flows more than 800 hundred miles across the state into the Gulf of Mexico near Freeport. The upper stretches of the river are home to some candidate endangered fish species, like the sharpnose and smalleye shiner (Wilde and Urbanczyk, 2013). The Brazos ends its meandering course in coastal Texas where it nourishes the bottomland hardwood forests that are an important stopover for migratory birds (Rosen et al., 2008). Along this journey, the Brazos supports a population of nearly 8 million people, providing water for diverse municipal, agricultural, and industrial uses (TWDB, 2010a,b).

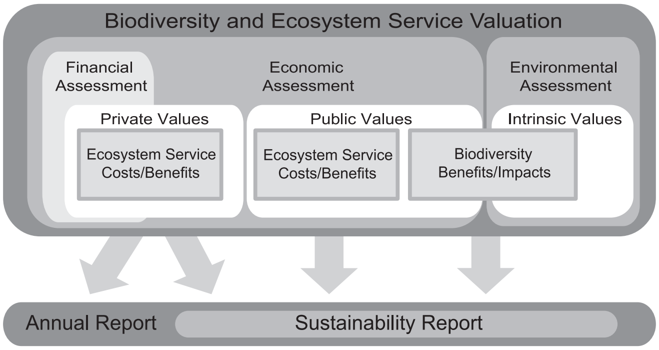

Fig. 2. Biodiversity and ecosystem service valuation provides a broader approach to evaluating business decisions. This approach captures additional biodiversity and ecosystem service values that would not be captured in a financial assessment but that could be captured through an economic assessment and an environmental assessment: (1) private economic values that are not marketed or otherwise quantified in traditional financial analyses (e.g., industrial process water), (2) public economic values (e.g., the value of water for drinking, recreation, home values, etc.), and (3) non-economic measures of biodiversity, which has its own intrinsic value and has economic value through support of ecosystem services. Although we emphasize estimating economic values in monetary terms in this paper, non-monetary indicators could also be used. The results from a biodiversity and ecosystem service valuation may be used by managers in decision making and/or corporate reporting (see discussion for more potential applications). In the context of decision making, managers may choose to weigh these new measures of value differently from traditional financial measures of value by using their professional judgment to implicitly weight different metrics or by using multi-criteria (MCA) analysis to explicitly weight and combine different metrics into one common metric (see Hajkowicz and Collins, 2006 for review of use of MCA in water resource planning, see Curtis, 2004 for application to ecosystem service valuation). [1.5 columns].

One of the largest industrial users of water from the Brazos is Dow's Texas Operations facilities, located in Freeport (TWDB, 2010a,b). Texas follows a prior appropriation doctrine for water rights, where users of water that have been located on the river longer have priority over new users in the event of a water shortage (Burness and Quirk, 1979). This priority is a recognized property right that can and often is sold, transferring the seller's priority to the purchaser(s) of the water right (Burness and Quirk, 1979). Located at the end of the Brazos River, Dow is one of the larger and more senior holders of water rights on the river, but many communities, farmers, and other businesses are upstream and have junior rights to use the water in the Brazos (TWDB, 2010a,b). Interestingly, the Brazos River is distinguished from most other rivers in the American Southwest because most of the water use is from industrial or municipal users, rather than agriculture (TWDB, 2010a,b).

Dow's facility, and other businesses, communities, and ecosystems in the basin, could not function without sufficient supplies of freshwater from the Brazos River. However, supply interruptions may become more common because of forecasted trends in supply and demand. The Brazos Regional Water Plans forecast a 47% increase in total demand in the basin over the next few decades, primarily due to increases in municipal and industrial demand (TWDB, 2010a, b). At the same time, a global multi-model assessment of the impact of a two degree rise in temperature compared to current day conditions suggests that annual water discharge in the Brazos could decrease by 10–30% (Schewe et al., 2014).

Low flow conditions, like those experienced during the 2011 drought, may become more common because of increases in demand and changes in climate. Frequent and prolonged low flow and high salinity conditions caused by the 2011 drought in the Brazos impacted Dow's Freeport operations and others in the Brazos basin. At the height of the 2011 drought, some portions of the Brazos River ran dry. Users faced water-use restrictions as drought contingency plans were implemented. During the spring and summer, diversions by junior water right holders were eliminated altogether by the Texas Commission on Environmental Quality (TCEQ). In addition, non-consumptive uses of water were impacted. Home owners and recreational users were affected by changing river and reservoir levels (Rogers, Reddy et al., Unpublished Results (In Review)). Habitat for candidate endangered fish species virtually disappeared. And, migratory bird visits were down. The estimates of the overall impact of the 2011 drought to the Brazos basin are not available, but a special report from the Texas Comptroller of Public Accounts office estimated $8.7 billion in losses to agricultural and agriculture-related industries alone (Combs, 2012). Forecasts by the Texas Water Development Board project that a multi-year drought would result in $12 billion in lost income for businesses and workers, $1.1 billion in lost taxes, and 115,000 lost jobs (Combs, 2012). The 2011 drought may have been one the worst in Texas history because of the large losses in a single year (Combs, 2012).

Although Dow is less vulnerable to drought because it is a senior water right holder and has its own water storage reservoirs, Dow still faces particular challenges related to intermittent droughts. During a drought, Dow's entire water right may not be available by the time river flows reach Dow's intakes at its Harris (river mile 46) and Brazoria (river mile 25) Reservoirs in the lower basin. In addition, high salinity conditions in the Brazos River at the reservoir intake may prevent pumping into these reservoirs. High salinity conditions are created by salt coming down from salt flats higher up in the basin under high rainfall conditions as well as saltwater coming up from the Gulf of Mexico during low flow conditions (Wurbs, 2002). Most years, salt water intrudes at least

25 river miles upstream for a continuous period of many weeks because of low flows in the Brazos River (Osting et al., 2004). As a result, Dow is often forced to shut down intake at its Brazoria Reservoir and rely on intake at its Harris Reservoir during drought conditions (TWDB, 2009). To maintain operations at extreme low flows, Dow has purchased Brazos River water stored in reservoirs owned by the Brazos River Authority (TWDB, 2009).

Dow has completed extensive water supply risk assessment work both prior to and in parallel to the analysis reported here. Dow utilized conventional water availability modeling (WAM) analysis (Wurbs, 2005), daily flows modeling tools, and stochastic modeling approaches to assess the impacts of alternative water conservation and supply improvement strategies for a range of varied river flow conditions. This modeling work considered demand growth, alternative water rights enforcements practices, and numerous actions that could be taken directly by Dow to improve water supply reliability. The analysis presented here advances and complements Dow's previous risk assessment work by incorporating modeling of the effects of climate change and translating forecasts of water availability into economic terms using natural capital asset valuation. Moreover, it advanced Dow's assessment of solutions by identifying potential nature-based or collaborative solutions and providing additional metrics of public benefits and biodiversity. Nature-based solutions are defined here as solutions that use or manage ecosystems to address water scarcity (e.g., managing plant species in a watershed to enhance flows).

3. Methods

3.1. Analysis framework

In order to assess the value of the 77 industrial water rights in the Brazos River basin under different future scenarios and identify and evaluate new solutions to future water shortages, we conducted four interrelated analyses:

1. *Future trends in ecosystem services* (Section 3.2)—In this phase, we identified climate change and demand scenarios for business planning. We used these scenarios to model changes in water availability for industrial water users.
2. *Valuation of ecosystem services* (Section 3.3)—We projected the value of industrial water rights under the nine future scenarios using an alternative cost method. This valuation used information on current costs, prices that we forecasted based on the simulation of a water market, and costs associated with alternative water sources.
3. *Identification of solutions* (Section 3.4)—Using the above information as a starting point, a workshop of experts was held to identify potential new solutions to problems of water scarcity, focusing on nature-based, collaborative, and policy-based solutions. A multi-criteria analysis was used to identify five solutions that should under-go further analysis.
4. *Cost-benefit analysis of solutions* (Section 3.5)—We used cost-benefit analysis to compare each solution to a “business-as-usual” solution, a reservoir expansion in this case. Public costs and benefits and biodiversity impacts and benefits were included to complement the private cost-benefit analysis.

3.2. Future trends in ecosystem services

3.2.1. Overview of water modeling and analysis

Water availability from 1951 to 2098 was modeled under three demand scenarios (1999, 2040, and full permit) and three climate scenarios (high, medium, and low flow) for a total of nine scenarios of climate and demand.

Using these scenarios, we modeled freshwater availability in the Brazos River in two steps. First, the impact of climate forecasts on the amount of water in the river, assuming no human use (“naturalized flow”), was modeled using a Variable Infiltration Capacity (VIC) model. Second, the quantity of water available to people and the amount left in the river after human use was modeled using a Water Availability Model (WAM) for the Brazos. The WAM provided estimates of water availability and demand shortages by water right.

We used a fixed effects Tobit regression model to estimate the effect of the climate and demand scenarios on the 90th percentile shortages for industrial water rights from 1951 to 2098. The 90th percentile shortages are shortages that are bigger than 90% of all other shortages. These shortages have a 10% change of occurring. Taking the inverse of the probability of occurrence results in an expected return rate of 10 years. A Tobit model was appropriate because the 90th percentile shortage is a limited dependent variable: shortages only take on positive values. Water right and 30-yr time period fixed effects were included to control for an unobservable heterogeneity across water rights and time periods. The unit of observation for the model was the shortage for a given industrial water right in one of five 30-yr time periods across each climate and demand scenario ($N=1310$). Note that 37% of observations had 90th percentile shortages of zero and were excluded from this analysis.

3.2.2. Water flow and climate change

Global climate projections from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl et al., 2007) formed the basis for the hydrologic impact projections in the Brazos River basin. These climate projections were collected and archived in support of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (IPCC, 2000). The hydrologic simulations based on these climate projections were commissioned by the United States Bureau of Reclamation as part of its West-Wide Climate Risk Assessments (WWCRAs) to provide risk assessment information for climate change risks to snowpack, changes in the timing of streamflow, and changes in the quantity of runoff (Bureau of Reclamation, 2011). The downscaling, bias correction, and simulation methods are described in detail in Bureau of Reclamation (2011) and the references cited therein. The hydrological simulation methods resulted in spatially distributed fields of runoff and baseflow over the western United States at a spatial resolution of 1/8-degree and with a daily time step. Although the Bureau of Reclamation produced streamflow time series for a select number of flow location in the western United States, streamflow time series were not made available for most of the locations in the Brazos River Basin.

For the purpose of this study, we routed spatial fields of runoff and baseflow through a stream network of the Brazos River Basin to produce streamflow estimates at specified flow locations for each of the 112 available climate projections. Streamflow values at each flow location and for each climate projection were subjected to a final bias-correction step based on a comparison of historic and simulated flow sequences at that location (see Appendix A for details). The methodology for flow routing and bias correction was similar to that used by the Bureau of Reclamation (2011) for other locations in the western United States. The following sections provide details on each of the links in this modeling chain.

3.2.2.1. Climate projections. The individual climate projections were generated by modeling groups around the world using emission scenarios specified by the IPCC in preparation for its Fourth Assessment Report. The effects of greenhouse gas emissions on climate were estimated in an ensemble of 16 different General Circulation Models (GCMs), to capture scientific uncertainty in how a given level of emissions will affect climate. Climate projections were evaluated for three emission scenarios (A1B, A2, and B1 IPCC, 2000) and for the 16 individual models. Although all 112 model projections processed by the Bureau of Reclamation (2011) were processed for the Brazos River Basin as well, here we just focus on projections from three GCMs for the "middle" emissions path (A1B). The "middle" emissions path (A1B) assumes that technological change in the energy system is balanced across all fossil and non-fossil energy sources, where balanced is defined as not relying too heavily on one particular source. We chose the three GCMs to represent a range of naturalized flows (see Section 3.2.3.1). Downscaled model simulations were available for the period 1950–2099. It is important to note that the climate simulations for the historic period do not match actual historic events, but provide climate projections based on free-running climate models in which the concentrations of atmospheric constituents and external solar forcings are prescribed based on historic conditions.

Each WCRP CMIP3 climate projection was bias-corrected and spatially downscaled to 1/8-degree spatial resolution to remove the bias in the simulations and to produce a higher resolution dataset useful for regional hydrologic applications (see Appendix A for details).

3.2.2.2. Hydrologic model and simulations. The daily weather sequences were used as input to the Variable Infiltration Capacity model (VIC version 4.0.7), a spatially distributed land surface hydrology model that solves the water balance at each 1/8-degree model grid cell (Liang et al., 1994, 1996; Nijssen et al., 1997). As detailed as part of the Bureau of Reclamation web archive, calibrated VIC model applications were obtained from the University of Washington and other experienced VIC model developers. The original model applications are documented in Wood and Lettenmaier (2006), Wood et al. (2005) and Maurer et al. (2002).

Daily VIC model outputs were archived by the Bureau of Reclamation for large river basins and regions in the western United States. Archived files for the West Gulf region form the basis for the streamflow projections for the Brazos developed under this study.

3.2.2.3. Flow routing. The Bureau of Reclamation used the VIC flow routing model (Lohmann et al., 1996) to route the runoff and baseflow fields generated by the VIC model through a schematic flow network to create streamflow projections for a selected number of flow locations in the American West. The same methodology was employed as part of this study to create streamflow projections for 73 individual flow locations within the Brazos basin. These sites coincided with the control points in the Texas WAM, plus an additional site at the mouth of the river. Default routing parameters as suggested on the University of Washington VIC model web site[1] were used to parameterize the model.

For each flow location, a routing network was developed at a spatial resolution of 1/8-degree. As part of this routing network a fraction file was generated that specified the fraction of each 1/8-degree grid cell within the flow network that contributed flow to the flow location. Baseflow and runoff fields were routed to produce daily streamflow estimates for the period 1950–2099 at each flow location.

3.2.2.4. Bias correction of naturalized flow time series. As described in detail in Bureau of Reclamation (2011), the routed VIC flows still show biases, both in timing and in magnitude of the flows. These biases stem from remaining biases in the climate projections, the limitations of the VIC model itself and the lack of site-specific calibrations of the routing model. Note that the latter will only affect the timing of the resulting hydrographs and not the total volume of flow, as the routing model conserves the amount of water that enters the flow network. That is, all the water entering the flow network passes the most downstream gauge and there is no exchange between the water in the channel and the streambed or banks. Similarly, evapotranspiration from open water surfaces and man-made flow diversions are not accounted for. The routed flows represent naturalized flows. To produce monthly streamflow sequences that are consistent with the historic flow sequences used as input to the Texas WAM, an additional bias correction step was implemented (see Appendix B for detailed methods).

Quantile tables were constructed for the period October 1950 through September 1997 (the training period). The first nine months of VIC simulations were discarded to minimize model artifacts associated with initial conditions and to align the period of analysis on water years (October through September). The training period in this case corresponds to water years 1951–1997. Bias corrections were then performed for the period October 1950 through September 2099 or water year 1951 through 2099.

3.2.3. Estimating changes in water availability using the WAM

To bring together information on changes in water supply and water demand, we used the version of the WAM used for the most recent Region H planning document (TCEQ, 2013; TWDB, 2010b).

3.2.3.1. Naturalized flow inputs to the WAM. We fed the bias-corrected estimates of naturalized flow under future climate scenarios from the VIC model into the WAM. Due to the complexity of the model used to estimate water availability, it was not possible to use the full ensemble of GCMs in this analysis. Instead, we selected three representative GCMs that spanned a range of predicted flows in the Brazos:

1) High flow (80% of all GCMs for flow): Max Planck Institute's ECHAM6 Model (Stevens et al., 2013),
2) Medium flow (near 50% of all GCMs for flow): Japan Meteorological Agency Meteorological Research Institute's coupled general circulation model (JMA/MRI CGCM2) (Yukimoto et al., 2001),
3) Low flow (20% of all GCMs for flow): Center for Climate System Research's Model for Interdisciplinary Research on Climate (MIROC) (K-1 Model Developers, 2004).

3.2.3.2. Future evaporation rate estimates. The WAM also requires a time-series of evaporation rates for 67 control points (e.g., reservoirs) in the Brazos Basin. In a typical WAM run, actual measurements of net evaporation (pan evaporation minus rainfall) are used. To generate future forecasts of evaporation rates, we first built a statistical model that describes for historical data how estimated net evaporation (potential evapotranspiration, calculated from temperature, rainfall, and other metrological data, minus rainfall) correlates with actual measurements of net evaporation. The correlation is very strong ($R^2 = 0.84$), and we could use this statistical relationship to forecast future evaporation rates. Since for the GCMs we can easily estimate potential evapotranspiration and precipitation is already forecast, it is easy to calculate what actual evaporation rates at these reservoirs will be in the future.

3.2.3.3. Input scenarios of demand for the WAM. Demand levels in each scenario were constant over time and were based on scenarios used in the Texas Regional Water Planning process (TWDB, 2010b).

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[1] ⟨http://www.hydro.washington.edu/Lettenmaier/Models/VIC/Documentation/Routing/RoutingInput.shtml⟩.

The 1999 demand level was based on measured historic use, assuming no growth in demand. Demand for 2040 was modeled for the purpose of the Regional Water Planning process based on trends in population growth, economic development, technology change, and historic demand. Fully permitted demand is a scenario in which water users utilize their entire legal water right.

3.3. *Valuation of ecosystem service*

For water resources, there are many methods that have been developed and applied to estimate the value of the various services water provides (e.g., irrigation for agriculture, industrial water supply, recreation, pollution abatement) in different contexts (see Young, 2005; Birol et al., 2006 for reviews of methods). The appropriate methods depend both on the technical aspects of the system and the data available. During our scoping process for methods to value industrial water supplies, we evaluated the use of market prices (e.g., Saliba et al., 1987; Brookshire et al., 2004), two revealed preference methods (residual value (e.g., Bate and Dubourg, 1997; Berbel et al., 2011), production function (e.g., Llewelyn and Featherstone, 1997; Mesa-Jurado et al., 2010) and cost-based methods (e.g., Loomis, 2010). We concluded that stated preference methods, such as contingent valuation (Carson and Hanemann, 2005), were out of the scope of the study and inappropriate for the end-users because of the cost of implementation and controversy surrounding results. Market prices for water currently do not exist for the Brazos River, although some insight can be gained by sales of water rights in the basin and elsewhere in the Southwest. The residual value and production function methods are inappropriate for our study system because of the nature of industrial water use at Dow's facility. In part because of the integrated nature of the facility, water use is not easily adjusted in the short term. Instead, managers at Dow's Freeport facility aim to supply a target level of water. In this context, the residual value method would have been unlikely to produce a reasonable estimate of the value of water because it would be extremely difficult to adequately capture all the other inputs to the integrated process. Production function approaches could not be used for the same reason as well as the fact that there is little observable variation in water inputs. Based on this scoping, we concluded that the most appropriate method was an alternative cost method (Young, 2005; Hanley and Barbier, 2009). This method identifies the value of water as the difference between the cost of using river water and the cost of the next best alternative to river water. This can be interpreted as the costs that Dow or other industrial users avoid by ensuring the reliability of their water right. It should be noted, however, that cost-based approaches are considered second-best approaches by economists because they do not capture people's willingness to pay for or value of resources (Heal et al., 2005). Yet, they are good indicators of a lower bound value of people's or businesses' willingness to pay to replace or secure a good.

We applied the alternative cost method to assess the value of all industrial water rights in the Brazos River and projected how they would change across the nine climate-demand scenarios. We assumed that desalinated water is the next best alternative to river water. The value of industrial river water rights was defined as the discounted sum over 30 years of the difference between the cost of desalinated water ($C_{D,t}$) in year t and the cost of supplying river water ($C_{R,t}$) in year t (Table 1).

$$NPV = \sum_{t=0}^{t=30} \frac{C_{D,\,t}(q_t, p_D) - C_{R,t}(q_t,\ p_R(s_t))}{(1+i)^t}$$

Annual net benefits were discounted at a rate (i) of 7%, approximately "the marginal pretax rate of return on an average investment in the private sector" (OMB, 1992). We estimated the cost of desalination by multiplying the total water demand (q_t) by the unit cost for desalinated water (p_D) (Table 1a). We assume that this unit cost is a constant price. We estimated the cost to supply river water by multiplying the water demanded by the unit cost (p_r) for river water. However, in this case, the unit cost for river water varies based on whether industrial water right holders can pump the amount of water they demand or they experience shortages (s_t) because they cannot pump the amount of water they demand (Table 1b). When industrial water right holders are pumping water out of the river, the cost of water includes the cost of pumping, maintenance, salaries, and property taxes. We assumed that when industrial water users experience shortages, as forecasted by the WAM, that they will lease water from other water right holders. To estimate the future cost of these leases, we simulated a water market for the Brazos River basin under the nine climate-demand scenarios (see Section 3.3.1 for methods).

Table 1
Cost data for alternative-cost method valuation of industrial water rights.

a. Cost of alternative to river water

Water source (conditions for use)	Cost components	Cost (2012 US $/m^3)	Cost (2012 US$/ ac-ft)	Source
Regional desalination system (long-run alternative to river water)	retail price	0.93	1141	Freeport Seawater Desalination Project (BRA, 2004)

b. Cost of river water

Water source (conditions for use)	Cost components	Cost (2012 US $/m^3)	Cost (2012 US$/ac-ft)	Source
Water right (river water available)	Pumping, maintenance, infrastructure maintenance, salaries, property tax	0.04	47.41	Cost calculation, this study
Leased water (short-term shortages make water right unreliable, need to seek other sources of river water)	Forecasted price per year and climate-demand scenario	0.11–0.53[*]	138.03–649.42[*]	Market simulation, this study
Decreased production (short-term shortages make water right unreliable and water is not available to lease)	Lost revenue	Small-0.81 medium-1.62 large-2.43[**]	Small-1000 medium-2000 large-3000[**]	Expert assumption

Pumping costs were estimated using cost functions from the University of Nebraska Water Optimization Calculator ⟨http://agecon.unl.edu/wateroptimizer/download.html⟩.

* Range of prices over 30 years under each climate-demand scenario. Specific annual values were used in cost calculation.

** Revenue losses are specific to the size of the water right and assume that the revenue per m^3 increases with the size of the water right due to economies of scale. Small: $<$62 million m^3 ($<$50,000 ac-ft), medium: $>$62 million m^3 ($>$50,000) and $\le$123 million m^3 ($\le$100,000 ac-ft), large: $>$123 million m^3 ($>$100,000 ac-ft).

The market simulation provided a forecast of the prices paid by industrial users and the amount of industrial shortages that can be made-up through leasing. In cases where data is more limited, published water price forecast data from existing water markets or expert knowledge can be used to complete the cost structure for the cost-based valuation approach. We assumed that shortages that were not made-up through leasing would result in revenue losses, which vary by the size of the water right. This is a reasonable assumption because businesses cannot easily make changes in water use efficiency in the short term.

Table 2
Water leasing prices and own-price elasticities.

Use type	**Prices** (2012 US\$/m^3)	**Prices** (2012 US\$/ac-ft)	**Elasticities**
Agriculture	0.04[a]	43.21[a]	-0.51[c]
Municipal	0.10[a]	125.20[a]	-0.51[d]
Industrial	0.06[b]	77.89[b]	-0.12[e]
Mining	0.29[b]	363.46[b]	-0.32[f]

[a] To represent prices paid during shortages, we took the 3rd quartile values from the lease prices in reported monthly between 1987 and 2007 in the journal *Water Strategist* and its predecessor the *Water Intelligence Monthly* (Donohew and Libecap, 2010). These values are consistent with real-world prices, such as the Brazos River Authority interruptible water leasing prices—US\$0.04/m^3 (US\$43.75/ac-ft) for agricultural use and US\$0.05/m^3 (US\$62.50/ac-ft) for other uses.

[b] Aylward et al. (2010).

[c] Espey et al. (1997). Other studies are consistent within this value estimate (e.g., Dalhuisen et al. 2003).

[d] Scheierling et al. (2006).

[e] Renzetti (1988). Estimates for the petrochemical industry were used because according to the 2011 Region H Water Planning document, “Two thirds of all U.S. petrochemical production and almost a third of the nation’s petroleum industries are located in Region H” (TWDB, 2010b).

[f] Renzetti (1992).

3.3.1. Market simulation of water prices and water available for leasing

We conducted a simple simulation of water trading across water use types (industrial, mining, municipal, agriculture) to project annual water prices and the water available for leasing from 2013 to 2042 under the nine climate-demand scenarios, assuming a water market existed. Trades were based on the rank order of different water user’s willingness to pay for water. Ideally, individual information could be gathered for each user to project a unique demand curve and willingness to pay. Unfortunately, such an endeavor is highly impractical because of the cost and effort or impossible because the range of data needed to estimate the demand curve is unobservable. Thus, demands and shortages were aggregated by use type, which is somewhat reasonable since trades within use groups and withdrawal locations require considerably less oversight than across use groups under Texas law. As a result, trades occurred in aggregate across use types and ignored geographic barriers. After aggregating users into sectors, constant elasticity demand curves were projected of the form:

$$Q_{it} = A_i P_{it}^{\varepsilon_i}$$

where Q_{it} is the quantity demanded by each use type (i) in each year (t), A_i is a constant calculated from initial prices and quantities, P_{it} is the price, and ε_i is the elasticity for a given use type.

To calculate marginal values under no trading and a trading scenario, we took estimates for initial marginal values (P_i^0) and elasticity (ε_i) estimates from the academic literature and public databases (Table 2). We then calculated marginal values (P_{it}^s) without trade where Q_{it} equals the amount demanded minus the shortage (S). These estimates represent future willingness to pay for an additional unit of water. The same was calculated under a trade scenario in which participants can trade until a market clearing price is reached. To introduce some realistic restrictions on trading, we assumed that agricultural users would only trade 50% of their water rights and municipal users would lease water from others but would not lease their own water.

We used a linear optimization tool (Microsoft Excel’s Solver) to calculate market clearing prices. Ideally the tool could simply optimize the total area under each demand curve to converge at an equivalent price for each use type. However, due to the functional form of the demand curves, these integrals are indefinite so price cannot be estimated in that way. Instead the integral of the inverse demand function was used, to converge on a market clearing price. The specific set of equations we optimized were:

$$\underset{Q_i}{MAX} \sum_{t=0}^{t=30} \int_0^{Q^0} (Q_{it}/A_i)^{\left(\frac{1}{\varepsilon_i}\right)} dQ - \sum_{t=0}^{t=30} \int_0^{Q^*} (Q_{it}/A_i)^{\left(\frac{1}{\varepsilon_i}\right)} dQ$$

subject to the constraints on agricultural and municipal leasing (described above) and on the total water available.

3.4. Identification of solutions

In May 2012, we held a workshop in Freeport with experts from Dow and The Nature Conservancy to review the data on likely changes in water demand and water supply and to brainstorm potential adaptation strategies. Participants included ecologists, economists, climate scientists, a water resource scientist, an engineer, business specialists, and water policy experts from The Nature Conservancy and engineers, water managers, environmental technology experts, government affairs experts, and environmental health and safety managers from Dow. Participants were instructed to consider a time horizon out to 2060 and rotated through different sessions focusing on nature-based, collaborative, and policy solutions. After grouping similar solutions together, we identified a total of 16 distinct solutions (see Supplementary Table S1). We prioritized solutions based on the highest total score across seven criteria. Experts scored the solutions (1 = low, 2 = medium, 3 = high) for their expected net benefits, potential for benefits to other stakeholders and ecosystems, impact to water availability, political and technical feasibility, and alignment with the collaboration goals (i.e., developing methods to integrate the value of nature into business decisions and, as a result, achieve outcomes for business and conservation). Scores for each criterion were weighted equally in calculating the total score. Using this simple multi-criteria analysis (MCA) as a selection process helped prevent potential conflicts of interest and bias. By specifically including criteria on the potential benefit to other stakeholders and ecosystems as well as alignment with collaboration goals, we avoided choosing solutions that would be strictly industry-friendly.

The following solutions were chosen for further investigation because they ranked in the top five based on their total scores (out of a total possible of 18):

- *Reservoir flood pool reallocation*—Restore flood plains and re-allocate reservoir flood pools to storage (score = 17).
- *Land management*—Replace invasive, high water-use plants with native, low water-use plants to enhance groundwater aquifers and/or stream flows (score = 16).
- *Marsh wastewater treatment*—Restore/create marshes to serve as a regional wastewater treatment facility (score = 15).
- *Irrigation efficiency*—Provide funds for agricultural users to install more efficient irrigation technology or fallow crops in exchange for saved water (score = 15).
- *Municipal rebate program*—Provide funds for rebate programs to incentivize municipal users to install more efficient appliances or convert to low-water use landscaping (score = 15).

The first three solutions (reservoir flood pool reallocation, land management, marsh wastewater treatment) fit the definition of nature-based solutions because they involve ecosystems or habitats, including natural flood plains, marshes, or native plants. The last two solutions (irrigation efficiency and municipal rebate program) were categorized as collaborative because they involve working with other stakeholders in the basin. Solutions that were not chosen for further investigation due to their low score included: surface water-ground water solutions (e.g., conjunctive use) (score = 14), incentives for water conservation planning (score = 11), energy-water solutions (e.g., reduce water use in energy production) (score = 12), basin-level policy (e.g., water master, voluntary information sharing) (score = 13), reduce leakage and evaporation in canals (score = 13), metered water use (score = 9), volume-based pricing (score = 13), water recycling (score = 13), water purchases (core = 14), new desalination technologies (score = 8), and a salt barrier on the river (score = 12).

3.5. *Cost-benefit analysis of solutions*

Following the biodiversity and ecosystem service valuation framework we outlined in Fig. 2, we evaluated the proposed solutions based on their (1) private costs and benefits: the annual water supply impact and 30-year cost to Dow, (2) public costs and benefits: 30-year economic costs and benefits to other users, and (3) benefits or impacts to biodiversity. It is important to note that this is not a complete accounting of the costs and benefits of the solutions. Costs and benefits were estimated in monetary terms when possible. Estimates drew on previously published studies and publicly available data (see Supplementary data). In the case of environmental flows, we estimated their value based on observations of market prices paid for environmental flows in the American West (Donohew and Libecap, 2010). We only estimated the value of environmental flows for the irrigation efficiency and municipal rebate programs because these flows have a higher certainty given that the programs would simply reduce water use. When monetary estimates were not possible, we reported qualitative costs and benefits. Habitat area changes were reported as a quantitative indicator of impacts to biodiversity when possible or appropriate. Otherwise, we reported qualitative impacts. Monetary estimates of costs and benefits to Dow were discounted at 7% and benefits to the public were discounted at 3%. The public discount rate represents the consensus agreement for discounting of social costs and benefits for projects or policies with time frames on the order of less than 25 years (Weitzman, 2001). Information on political, legal, and technical challenges was also considered. The costs and benefits of the solutions were compared to Dow's anticipated initiative to expand its existing Harris reservoir. This expansion increases storage, and is a typical “grey” infrastructure response of companies facing water scarcity, with easily estimable costs of construction and water storage benefits.

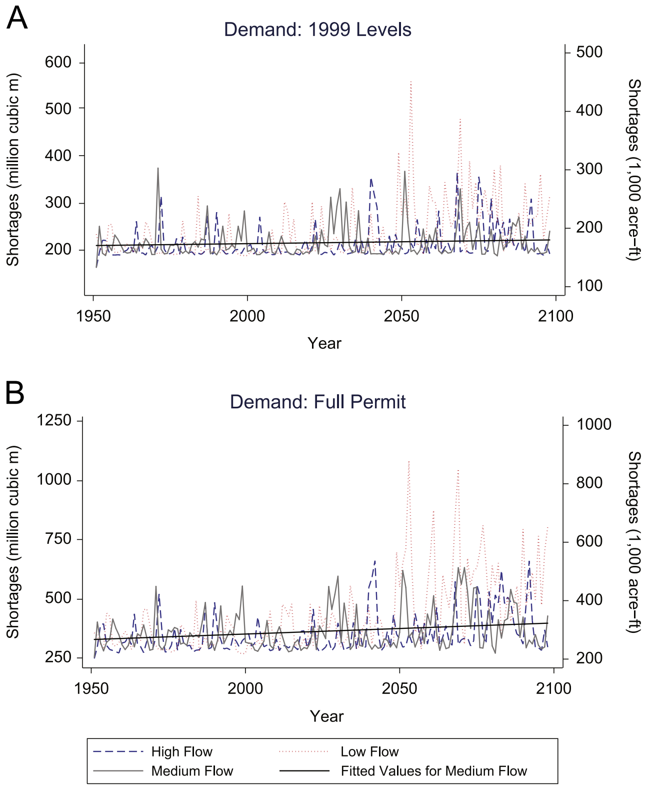

Fig. 3. Projected total basin annual water shortages under three climate scenarios (low flow, medium flow, and high flow) across two demand scenarios: (a) 1999 demand levels and (b) full permit demand levels. [1 column].

In order to be transparent and allow managers full flexibility in evaluating the solutions, we purposely presented estimates of the three criteria for each solution separately. In other contexts, managers may prefer to use MCA to explicitly weight each criteria and combine them into one common metric (see Hajkowicz and Collins, 2006 for review of use of MCA in water resource planning, see Curtis, 2004 for application to ecosystem service valuation).

4. Results

4.1. *Trends and conditions in ecosystem service*

Generally, estimates of future water flow show declines in the Brazos due to climate change, while demand increases significantly. These trends lead to an increase in the magnitude and frequency of total basin shortages (Fig. 3). Junior water right users experience the largest changes in shortages, because they are the first to lose access to water during a drought under the system of prior appropriation. Large total basins shortages increase the forecasted price of water because more water right holders are attempting to lease water and there is less overall water available. Modeled future water prices across all climate-demand scenarios ranged from US\$0.11/m^3 to US\$0.53/m^3 (US\$138.03/ac-ft to US \$649.42/ac-ft). Under 2040 demand levels and medium flow trends, the modeled median annual price was US\$0.11/m^3 (US \$141.82/ac-ft) (5th percentile: US\$0.11/m^3 (US\$139.77/ac-ft), 95th percentile: US\$0.18/m^3 (US\$224.02/ac-ft)).

The industrial sector is projected to experience similar trends in aggregate annual shortages as the total basin. The 10-year return (or 90th percentile) shortages for industry; however, are a better indicator of changes in water asset value than total shortages because value losses increase disproportionately with water shortages (Table 1, Fig. 4). Analyzing modeled trends in non-zero 10-year return shortages, we find that increases in warming and demand may result in increases in 10-year return shortages above a reference scenario of high flow-1999 demand (Table 3). A medium flow climate scenario alone may increase water shortages by a similar magnitude (40%) as an increase in demand to 2040 levels (50%) (Table 3). Increases in demand to fully permitted levels may increase shortages by 135%—more than three times the modeled increase under a high warming climate scenario (42%) (Table 3). Interestingly, there are no significant interactive effects of climate and demand scenarios (Table 3).

4.2. *Valuation of ecosystem service*

Using these projections for future shortages to industrial water rights and our alternative cost model, we estimated the 30 year (2013–2042) net present value of each industrial water right in the Brazos River basin and the aggregate value of all industrial water rights. We estimate that the median value of an industrial water right is US$40.60 million (25th percentile: US$1.50 million, 75th percentile: US$280.67 million) under a medium flow-1999 demand scenario.

There is wide variability in the modeled trends in the value of individual water right because of differences in locations on the river and priority dates. However, the overall trends are significantly affected by trends in climate change and demand (Table 3). The value of water rights may increase with higher demand, despite increases in shortages that would reduce the benefits provided by water rights (i.e., avoided costs associated with desalinated water). Under medium flow, the modeled median increase in water right value is 33% under 2040 demand and 49% under fully permitted demand. Modeled climate impacts and increases in shortages erode the value of industrial water rights; however, the effects of climate change over the next 30 years are small. Low flow scenarios may decrease water right values by less than 1% and high flow scenarios may increase asset values by less than 1%. The small apparent impact of climate change is in part because climate induced shortages are predicted to increase more in the distant future, beyond the calculation of the 30-year net present value of water rights. The modeled impacts of trends in demand and climate on individual industrial water rights are also evident in the total aggregate value of industrial water rights in the basin (Fig. 5).

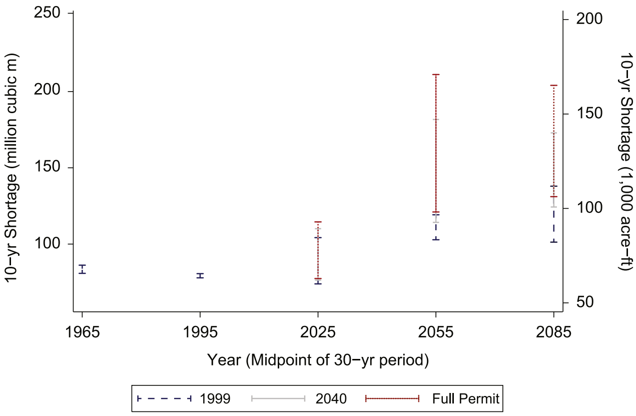

Fig. 4. 90th percentile (or 10-year return) of aggregate industrial annual shortages for each 30-year period under different demand scenarios. The range of values represents the range of the three climate scenarios. The 90th percentile shortages are shortages that are bigger than 90% of all other shortages. These shortages have a 10% change of occurring. Taking the inverse of the probability of occurrence results in an expected return rate of 10 years. [1 column].

Table 3
Tobit model estimate of the log of 90th percentile shortages for industrial water rights during five 30-year periods from 1951–2098. Reference condition: high flow-1999 demand.

Variables	Coefficient estimate
Climate = medium flow	0.338*** (0.123)
Climate = low flow	0.348*** (0.125)
Demand = 2040	0.406*** (0.108)
Demand = full permit	0.856*** (0.108)
Climate = medium flow, Demand = 2040	−0.162 (0.138)
Climate = medium flow, Demand = full permit	−0.198 (0.137)
Climate = low flow, Demand = 2040	−0.062 (0.138)
Climate = low flow, demand = full permit	−0.003 (0.138)
Constant	−1.104*** (0.121)
Sigma	0.574*** (0.018)
Time period fixed effects	Yes
Water right fixed effects	Yes
N	1310

Robust standard errors in parentheses; $^{**}p < 0.05$, $^{*}p < 0.1$.

*** $p < 0.01$.

The high and increasing value of industrial water rights suggests that even incremental investments in solutions to sustain flows in the Brazos River and enhance reliability of industrial water rights may be worthwhile.

4.3. Cost-benefit analysis of solutions

The three nature-based and two collaborative solutions that we investigated show potential to complement business-as-usual approaches to improve the reliability of Dow's water right (Fig. 6). These five options combined have an estimated 233 million m^3/year (188,000 ac-ft/year) potential water yield (Fig. 6A). Three out of the five options were cost-competitive with a business-as-usual case of reservoir expansion (62 million m^3/year (50,000 ac-ft/year) at US$0.05/$m^3$ (US$67/acre-ft) over 30 years) (Fig. 6B) and all options provided additional benefits to the public or biodiversity (Table 4). In total, the options have the potential to provide at least US$471 million in public benefits and conserve at least 8700 ha of habitat (Table 4). Below we describe each option in.

Marsh wastewater treatment, using a constructed wetland and pipelines from several communities, has the highest volume potential of the options studied, with the potential for 160 million m^3/year (128,500 ac-ft/year) (Fig. 6A). This method is already widely used across the US, with over 500 treatment wetlands currently being used (Kadlec and Wallace, 2009). Co-benefits include lower wastewater treatment costs and direct payments for participating municipalities (US$151 million) and support for biodiversity at the site of a constructed wetland, such as migratory Neotropical song birds (Table 4). The total habitat area estimate for the constructed wetland is over 1400 ha (Table 4). But this solution would require challenging and expensive conveyance, with estimated annual costs of US$0.15/$m^3$ (US$183/ac-ft) (Fig. 6B). Although this option may have substantial estimated savings, it is worth noting that municipal and industrial users will continue to increase water efficiency, and thus reduce the total water available for reuse. The specific proposal would need to be evaluated by appropriate regulatory agencies, but there is also an opportunity for wetland mitigation banking credits with this option. Yet even if credits may be available, the process of obtaining them may be cumbersome.

Reservoir flood pool reallocation, is a low cost means to increase supply (capturing unregulated flows), specifically through the

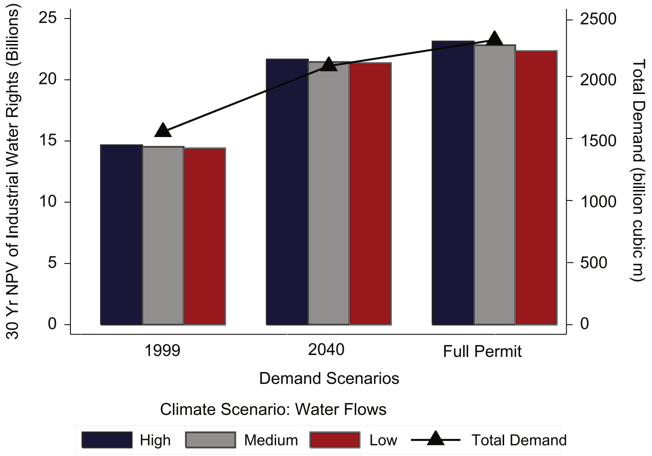

Fig. 5. The 30-year (2013–2042) aggregate net present value of industrial water rights and total water demand in the Brazos River basin under three demand and three climate scenarios. Value estimates are in billions of 2012 US$. [1 column].

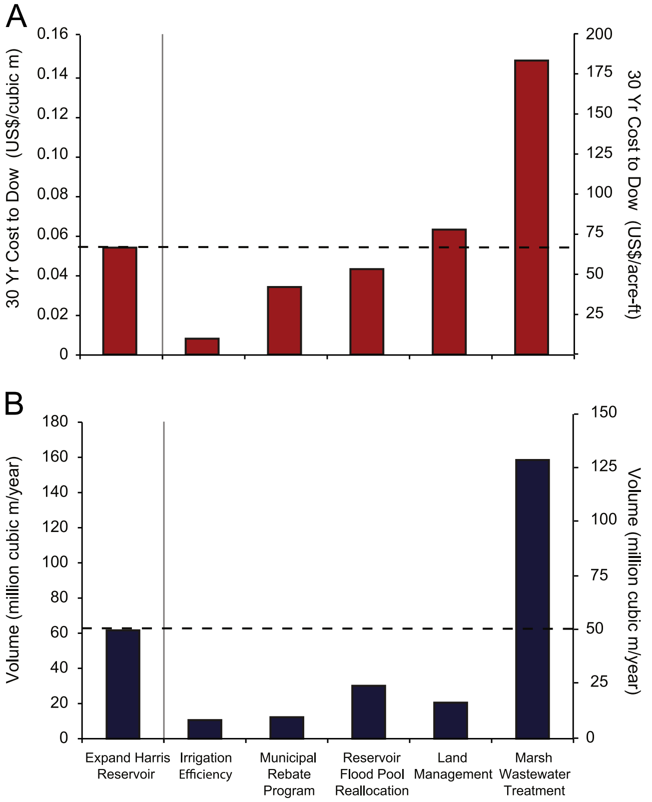

Fig. 6. Costs (a) and water supplies (b) from three nature-based solutions (reservoir flood pool reallocation, land management, marsh wastewater treatment), two collaborative solutions (irrigation efficiency, municipal rebate program), and one business-as-usual solution (expand Harris reservoir). Costs are in 2012 US\$. [1 column].

reallocation of flood reserve portions of U.S. Army Corps of Engineers (USACE) reservoirs for other uses. Reservoir storage reallocation is a method for meeting increasing demands and is gaining support in Texas and elsewhere. This strategy involves converting large volumes of flood control storage capacity contained in multiple-purpose reservoirs for water supply and other conservation purposes. The USACE has already performed an initial study (USACE, 2008). This initiative could provide 30 million m^3 (24,400 ac-ft) of water annually (Fig. 6A) at a cost of US\$0.04/m^3 (US\$53/ac-ft) per year (Fig. 6B) although it would require Texas Commission on Environmental Quality (TCEQ) permits, and extensive collaboration between the Brazos River Authority (BRA) and USACE[2]. The USCOE does not own water, only storage capacity, and thus the increased supply would likely go to BRA and increase the reliable supply in the basin. Flood pool reallocation would also bring about additional benefits and impacts to the public and ecosystems. Reducing the flood pool could reduce the flood protection benefits provided by the reservoir (USACE, 2008); however, this may be offset by increased flood storage in natural or restored floodplains (Warner et al., 2011) (Table 4). Periodic flooding of floodplain habitats would increase natural habitat areas (estimated at 400 ha) and support biodiversity (Warner et al., 2011) (Table 4). In addition, the extra water Dow would contract would increase base flows from the upper to lower basin, thereby improving riverine recreational opportunities and habitats for riverine species (USACE, 2008) (Table 4). Yet, recreational opportunities on the reservoir itself may be negatively impacted in the short-term due to changes in lake levels (USACE, 2008) (Table 4). Note that the USACE is currently evaluating reallocation at three reservoirs: Aquilla, Granger, and Stillhouse (USACE, 2008).

Land management, specifically removal of water-hungry, invasive species in the upper basin, could positively impact river flows by 20 million m^3/year (16,600 ac-ft/year) (Fig. 6A) at an estimated yearly cost of US\$0.06/m^3 (US\$78/ac-ft) (Fig. 6B). Land cover data (GAP, 2011) indicates that there are 13,800 ha of land covered with invasive salt cedar. We conservatively assume that 50% of this land could be restored, resulting in 6900 ha of restored land in the upper basin (Table 4). Water yield (3760 m^3/ha/yr) and restoration cost estimates (\$8550/ha 30 yr PV) were based on data from Zavaleta (2000). Increasing flows in the basin may benefit many users, but it is unclear how much of the saved water could be appropriated by Dow, in part, because of potentially large losses that may occur as the water flows down river. However, this option would bring about positive environmental outcomes such as increased habitat for native riverine and plant species (Table 4).

Municipal rebate programs provide incentives for conservation initiatives by municipal water users. These options include rebates for low-water use technologies or practices such as xeriscaping, toilets, and washing machines. The option carries a low cost but brings only indirect benefits to other water users in the basin, unless the saved water is sold or traded. Additionally, many municipalities are already pursuing these programs to address their own shortages and are therefore unlikely to trade their water savings in dry years. Estimates of water conserved by this solution may reach nearly 12 million m^3/year (10,000 ac-ft/year) (Fig. 6A) at an estimated 30-year cost of US\$0.03/m^3 (US\$42/ac-ft) (Fig. 6B). Co-benefits are significant, with an estimated 30-year PV of at least \$297 million or US\$0.80/m^3 (US\$992/ac-ft) from savings from lower utility costs for residential consumers (\$285 million 30 yr PV), decreased operating costs for treatment plants (no monetary estimate available), and increased environmental flows (\$12 million 30 yr PV) (Table 4). In addition, some water savings options, such as xeriscaping, could help create habitat for native species (Table 4). This does not include other options for supply side initiatives, such as methods to reduce reservoir evaporation, or building code changes or retrofit programs for raingardens, greenroofs, and groundwater recharge infrastructure.

Irrigation efficiency—Instead of simply buying or leasing water from agricultural users, Dow could facilitate investment in more efficient irrigation systems through a type of rebate or cost sharing program, in combination with existing Farm Bill programs. Even if farmers are amenable to this collaboration under current institutions it is unclear that Dow would be able to appropriate these water savings. If we assume a 50% adoption rate, increased irrigation efficiency could produce 11 million m^3 (8600 ac-ft) of water annually (Fig. 6A) at an estimated cost of just US\$0.01/m^3 (US\$10/ac-ft) over 30 years (Table 4), although this cost estimate assumes the water use is saved every year regardless of drought conditions. Note that this cost estimate may be low because much of the savings calculated depends on switching from standard to surge furrow, which is a relatively cheap investment. Many farmers may have already invested in this technology and will therefore require more costly upgrades to achieve these savings. Co-benefits include lower operational costs for farmers (\$7 million 30 yr PV), decreased pesticide and nutrient runoff, increased yields due to decreased soil salinity (\$6 million 30 yr PV), and increased environmental flows (\$10 million 30 yr NPV), as well improved habitat quality for river species (Table 4).

5. Discussion

This study addressed the basic and applied science challenges of integrating water ecosystem services values into business

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[2] This assumes that Dow contracts 25% of COE reallocated flood pool water, pays for 15% of the transaction costs, and pays the system rate for contract water.

Table 4
Summary of private costs and benefits (water supply) (see Fig. 6), public costs and benefits, and biodiversity benefits or impacts from three nature-based or two collaborative solutions. All monetary estimates are in 2012 US$, present value (PV).

Solution	Cost-effective	Water supply	Public benefits and costs (30 yr PV or qualitative)	Biodiversity benefit or impact
Irrigation efficiency	Yes	Low	• Environmental flows (US$10 million) • Farm operations savings (US$7 million) • Soil conservation (US$6 million) • Avoided costs from reduced pesticide use and nutrient runoff	• Improved flows for riverine species
Municipal rebate program	Yes	Low	• Environmental flows (US$12 million) • Lower utility costs (US$285 million) • Decreased operating costs for treatment plants	• Improved flows for riverine species Native plant habitat (e.g., xeriscaping)
Reservoir flood pool reallocation	Yes	Medium	• Environmental flows • Enhanced riverine recreation, negative impacts to lake (reservoir) recreation • Reduced or unchanged flood reduction benefits	• Improved flows for riverine species • Floodplain habitat (400 ha)
Land management	No	Low	• Environmental flows	• Native plant habitat (6900 ha) • Improved flows for riverine species
Marsh wastewater treatment	No	High	• Lower water treatment costs • Direct payments (US$151 million)	• 1400 ha of marsh • Habitat for migratory Neotropical song birds and other marsh species

decisions by advancing linked ecological and economic analyses of ecosystem services (Keeler et al., 2012) and applying these analyses in the context of a specific decision (Daily et al., 2009). By contributing to the extremely limited number of published studies on business and ecosystems services (Wintgens et al., 2013), these ecosystem service valuation methods and results have advanced ecosystem service science and have the potential to inform the efforts by many businesses to integrate the value of natural capital, especially water resources, into their business practices (WBCSD, 2011, 2012a).

A key ecosystem service modeling advance was using downscaled climate data and local water demand scenarios to forecast future trends in water availability. Although global analyses of trends in water resources (e.g., Schewe et al., 2014) are useful for understanding broad trends, they may not be useful for decisions at the scale of a river basin or industrial site. We demonstrated how results from the Bureau of Reclamation's (2011) assessment of climate on natural hydrology can be used, together with additional local data and models, to understand future local trends in water availability. Prior to this study, neither the Regional Water Planning Groups for the Brazos (TWDB, 2010a,b) nor Dow had integrated the potential effects of climate change into their water availability analyses. The extent to which climate change, as modeled in this study, could adversely impact water availability to all users in the basin was a key lesson learned for Dow. The analysis created an elevated sensitivity among Dow Operations personnel in Freeport and elsewhere in the corporation to this future issue and greater awareness of these risks are expected to be incorporated into the forward strategy of the facility. Importantly, this type of analysis may have an even larger impact on other businesses than it had on Dow because Dow had already made large investments in assessing and treating risk related to water availability.

Our use of these water availability data in the valuation of industrial water rights advances water risk assessments by accounting for the economic effects of supply and demand. We show that water supply shortage presents a higher financial risk when the demand, or value of water to the business, is higher. This means that physical water risk assessments, used increasingly by businesses (Larson et al., 2012), may underestimate water risk. Yet, our analysis may underestimate risk by not accounting for water risk in the supply chain, a risk that water footprint analyses may help reveal (Zhang et al., 2013). Importantly, water risk assessment based on physical and economic assessments analyses can help managers characterize their water scarcity problem such that they can take the next step of identifying and evaluating potential solutions.

By evaluating water solutions using private, public, and biodiversity costs and benefits, we provided a specific, empirical demonstration of a project evaluation framework that implements the concepts underlying shared value creation (Kramer and Porter, 2011) and ecosystem service valuation (Hanley and Barbier, 2009; WBCSD, 2012b). Our approach followed best practices in economic valuation by identifying and estimating the costs and benefits that are most critical to the decision (Heal et al., 2005). When data was available, we used standard methods from economics to estimate the monetary values from ecosystem services (Pearce, 2002); otherwise, we reported costs and benefits qualitatively. Although this approach was informative in this business context, the summary estimate of public net benefits does not include all costs and benefits because not all were estimated monetarily (e.g., avoided costs from reduced pesticide and nutrient runoff). Even when public values were estimated monetarily, transferring estimates from previous studies or using market prices to estimate benefits introduces error (Boyle and Bergstrom, 1992; Young, 2005). Non-monetary valuation techniques, such as MCA (Hajkowicz and Collins, 2006), or economic benefit indicators are two alternative approaches that could be used (NESP, 2015). Although MCA avoids some challenges associated with monetary valuation by presenting preferences in relative terms and it would have provided a single metric for prioritizing solutions, MCA was purposely not used here. Presenting multiple metrics provided information on the business's primary decision criteria, the cost-effectiveness of each solution, and helped reveal the potential alignment of the business's interests with the sustainability of the river overall, a secondary criteria. For instance, given Dow's position at the end of the river, any investments that Dow might make in enhancing flows in the river would not only have the potential to benefit themselves but also environmental flow targets (i.e., levels of water needed to sustain a healthy river ecosystem) (BBEST, 2012).

This analysis helped the business expand the scope of its solutions beyond traditional technological solutions to regional nature-based and collaborative solutions, which will be increasingly important for address water scarcity (Huesemann, 2003; Palmer et al., 2009). Although three out of five solutions are cost-competitive with a business-as-usual solution, these solutions face classic challenges associated with investments with solutions with public good attributes. Individual stakeholders are dis-incented to invest in these types of solutions because they bear all the costs, while the benefits accrue to multiple stakeholders, with uncertain returns for the investor. Mechanisms, such as water funds (Goldman-Benner et al., 2012) or other payment for ecosystem services arrangements (Jack et al., 2008), are needed to align resource beneficiaries with resource investors and reduce transaction costs. Given these challenges, Dow decided to proceed with shorter-term and more certain projects while continuing to look for mechanisms to effectively engage others in the basin to create collaborative low-cost nature-based solutions.

This study is not without its shortcomings. The climate, demand, and price forecasting involved in the study incorporated some degree of uncertainty and complexity. Despite this, the water shortage and water rights value projections provide relative trends that can be used as directional signals for business decision making. The complexity and time required to complete this study, nearly two years, might discourage others from replicating this study for their companies. However, conducting this study elsewhere may not require as much time or resources because the methodology has now been developed and documented. Nevertheless, another development opportunity would be to build a tool for rapid, site-level water risk assessments that is “good enough” (i.e., balances the tradeoff between ease-of-use and analytical power) to provide insight and decision-support.

6. Conclusions

Freshwater assets are of substantial economic value, far exceeding the limited costs currently associated with pumping water. Putting this element of natural capital into financial terms has facilitated business planning around future water scarcity. In particular, providing quantitative economic information on future water scarcity improved understanding of risk and helped identify and evaluate a set of five potential nature-based and collaborative solutions. This demonstrated how the valuation of water ecosystem services, now and in the future, may be critical to evaluating the costs and benefits of businesses’ water strategies.

Future applications for water ecosystem service valuation at a business may include internal water pricing and tracking of public and biodiversity benefits or costs from changes in industrial water use. These new applications would complement the primary applications we demonstrated in this study (water risk assessment, natural capital asset valuation, and project evaluation). Currently, over 150 major companies are using internal prices for carbon to incent greenhouse gas reductions (CDP, 2014). A logical next step would be for businesses to use internal prices for water that account for trends in climate change and demand to incent water conservation and fund water sustainability projects. Managers could also gain further information on how to improve the design of projects or business processes and projects by estimating water ecosystem service benefits and impacts to the public and biodiversity. Outcomes could be reported as part of an environmental profit and loss statements (see PUMA, 2011) or as part of tracking toward a sustainability goal. Importantly, more peer-reviewed research and applications are urgently needed to test, refine, and share ecosystem service valuation approaches in a business context.

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Appendix A. Bias correction and statistical downscaling of climate projections

Climate models exhibit significant biases in their simulation of current climate and by extension future climate. These biases stem from a variety of sources. For example, the coarse resolution at which the models are applied means that mountain ranges are poorly resolved and that small-scale processes cannot be represented explicitly, but must be parameterized. In addition, the coarse resolution of the climate model simulations means that the results are often not directly applicable for regional studies.

Each WCRP CMIP3 climate projection was bias-corrected and spatially downscaled to 1/8-degree spatial resolution to remove the bias in the simulations and to produce a higher resolution dataset useful for regional hydrologic applications. A statistical downscaling method was used rather than a dynamic downscaling method, which would involve the use of a high-resolution regional climate model. The bias correction and statistical downscaling (BCSD) method is described in detail by Wood et al. (2002), (2004) and Maurer et al. (2002) and the strengths and weaknesses of the method are discussed as part of the Reclamation web archive[3]. Note that the BCSD methodology assumes that the GCM biases have the same structure during the 20th and 21st century simulations.

The WCRP CMIP3 archived climate sequences consist of time series of monthly values. As part of the construction of the archive of hydrologic projections, daily sequences were generated that are consistent with the monthly BCSD climate projections. This disaggregation procedure uses spatial fields of historical precipitation and temperature fields to ensure that the structure of constructed daily precipitation and temperature fields is realistic.

Appendix B. Bias correction of streamflow time series

This quantile-based mapping method is similar to the one used in Bureau of Reclamation (2011), except that the historic naturalized WAM flows were used as the baseline data set rather than observed flows. The quantile-based bias correction method (Wood and Lettenmaier, 2006) has been used extensively for other climate change projects. Cumulative density functions (CDFs) are determined for each month based on an overlapping period for which both simulated and historic flows are available. In this case, the historic monthly flows are the WAM data, while the simulated monthly flows are the VIC modeled flows from the climate runs aggregated to monthly values. The CDFs are then used as lookup tables to bias-correct the simulated flows, by mapping the quantile associated with the simulated flow to the same quantile in the WAM-based CDF. The simulated flow value is then replaced with the WAM flow value that represents the same quantile in the WAM-based CDF. Flows from the climate projections are treated in a similar fashion. For each future flow value, the associated quantile is determined from the historic simulation-based CDF.

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[3] ⟨http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html⟩.

That quantile is then used to derive a bias-corrected flow value from the WAM-based CDF. Note that quantile tables were determined for each individual month.

Additional work is required when the future simulated flow is smaller or larger than the simulated flows in the quantile table. A log normal distribution was used to extrapolate both the historic WAM and simulated flows in that case. To handle zero flows (for which a log value cannot be calculated), a threshold was defined and all flow values below the threshold were set equal to the threshold before the log transform. At the end of the bias correction process all values at or below the threshold were set equal to zero to preserve days with zero flows.

To preserve the annual distribution of flows, a second step was implemented in the bias correction process. In this step, the annual mean flows are bias-corrected in the same way as described before, but this bias correction step is performed independently of the previous step. The bias-corrected monthly flows are then scaled to sum to the bias-corrected annual values. These are the final flows. This annual bias correction step ensures that the annual values do not show unrealistically large outliers, which can otherwise occur when a few months in a row have extrapolations that lead to unrealistically high or low values.

The quantile lookup method does not work well when there are plateaus in the CDFs (these occur when flow values in the quantile tables are repeated). In that case, it is not possible to uniquely define a quantile. In the method implemented for the Brazos, a very small random value is added to each flow value to ensure that flows are unique. In effect this means that a random quantile is assigned within the range of quantile values that correspond to the plateau in the CDF. These small additions are accounted for before converting the flows at or below the threshold back to zero.

Appendix. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.ecoser.2014.12.001.

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