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Decision-centric adaptation appraisal for water management across Colorado's Continental Divide

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ABSTRACT

A multi-step decision support process was developed and applied to the physically and legally complex case of water diversions from the Upper Colorado River across the Continental Divide to serve cities and farms along Colorado's Front Range. We illustrate our approach by simulating the performance of an existing drought-response measure, the Shoshone Call Relaxation Agreement (SCRA) [the adaptation measure], using the Water Evaluation and Planning (WEAP) tool [the hydrologic cycle and water systems model]; and the Statistical DownScaling Model (SDSM-DC) [the stochastic climate scenario generator]. Scenarios relevant to the decision community were analyzed and results indicate that this drought management measure would provide only a small storage benefit in offsetting the impacts of a shift to a warmer and drier future climate coupled with related environmental changes. The analysis demonstrates the importance of engaging water managers in the development of credible and computationally efficient decision support tools that accurately capture the physical, legal and contractual dimensions of their climate risk management problems.

Introduction

There is a growing recognition that planning for adaptation to climate change must proceed despite the limited predictability of hydro-climatic changes on temporal and spatial scales relevant for water resource planning (WUCA, 2010; Miller, 2010;Yates and Miller, 2011; Deser et al., 2012a,b). There are irreducible uncertainties in multi-decadal regional climate projections (Kundzewicz and Stakhiv, 2010; Pielke and Wilby, 2012) with internal climate system variability playing the dominant role in driving that uncertainty, especially for precipitation projections over the next half century (Hawkins and Sutton, 2010; Deser et al., 2012a,b). In addition, recognized limitations of regional climate downscaling further impair the utility of climate model output for decision-making (Salzmann and Mearns, 2012).

The conventional "top down" approach to providing advice for adaptation planning is poorly suited to the task. That approach involves downscaling future climate scenarios, generating input data for impact models, evaluating the consequences relative to present climate, and finally considering adaptation responses. Typically, large uncertainties attached to climate model scenarios accrue into even larger uncertainties in downscaled regional climate change scenarios and impacts.

Planners are then left with an intractable range of possibilities, and may habitually resort to "low regret" decisions (World Bank Independent Evaluation Group, 2012). These are measures that are believed to yield benefits regardless of the climate

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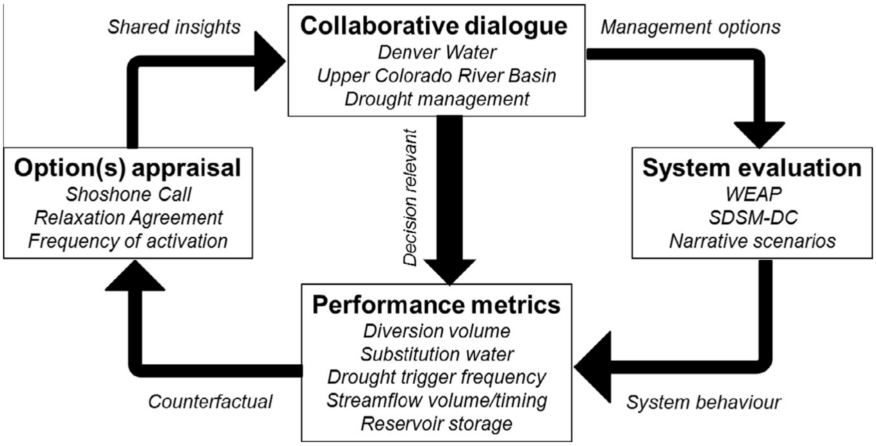

Fig. 1. The adaptation option appraisal process (illustrated using attributes of the Upper Colorado River Basin shown in italics).

outlook. Although that may be a safe strategy, a more pro-active planning approach may yield better results. Water management professionals increasingly comprehend the value of a systematic risk-management approach to adaptation planning that focuses on identifying and reducing vulnerabilities to a plausible range of climate scenarios, while maintaining the flexibility to respond to evolving conditions (WUCA, 2010; Lempert et al., 2006).

A useful approach for such planning is to turn the traditional top-down framework upside down and place greater emphasis on identifying and appraising adaptation choices from the outset (Wilby and Dessai, 2010). In this configuration, the scenario is used much later in the process to evaluate the performance or "stress test" adaptation decisions. As such, the scenario does not need to be explicitly tied to a given climate model or ensemble. For example, plausible futures can be generated stochastically (Steinschneider and Brown, 2013; Nazemi et al., 2013) and then used to test the sensitivity of the system, ideally to reveal non-linear or threshold behaviors to the climate-forcing (as in Brown et al., 2011; Brown and Wilby, 2012; Lopez et al., 2009; Prudhomme et al., 2010; Stakhiv, 2011; Whitehead et al., 2006). This paper demonstrates how downscaling and water systems models can be used in ways that focus the effort on evaluating adaptation measures despite large uncertainty about future climatic and non-climatic stressors.

Our collaborative decision support process comprises four elements (Fig. 1): (i) identifying management practice(s) or adaptation option(s) to be evaluated; (ii) modelling the water supply through physical representation of the hydrologic cycle; (iii) modelling the water collection and distribution systems in the context of the hydrologic cycle and the legal water rights; and (iv) stress-testing the system using narratives of future climatic and non-climatic conditions to explore the performance of the adaptation option(s) in supporting overall water supply.

We illustrate our approach by simulating the performance of an existing drought-response measure, the Shoshone Call Relaxation Agreement (SCRA[1]) [the adaptation measure], using the Water Evaluation and Planning (WEAP) tool [the hydrologic cycle and water systems model]; and the Statistical DownScaling Model (SDSM-DC) [the stochastic scenario generator]. This analysis involves downscaling multi-basin, multi-elevation daily temperature and precipitation scenarios for the Upper Colorado River Basin (UCRB). These scenarios are used alongside broader narratives of future conditions in the basin that could affect security of water supplies and to evaluate the benefits of steps taken to manage these risks. Our main aim is to highlight the potential benefits and portability of the process using water resource and river flow obligations in the Upper Colorado as an exemplar.

The following section provides further details of the study area and water system, including a synopsis of the pertinent water rights. Sections 3 and 4 outline the WEAP and SDSM models respectively. WEAP is used as the laboratory for appraising the SCRA under specified climatic and non-climatic narratives; SDSM is used to generate daily weather inputs to stress test the Upper Colorado hydrology and water management systems as simulated by WEAP. Section 5 provides an overview of our chosen narratives for basin wide stressors on the water supply system. Section 6 reports the findings of the analysis using metrics of water system performance with and without the SCRA, while Section 7 summarizes the study by drawing out key findings, considers the transferability of the process to other water systems, and identifies opportunities for further research.

Study area and characteristics

Droughts are a recurrent feature of Colorado's climate (McKee et al., 2000) and there is consensus amongst climate models that future air temperatures will rise, implying earlier and shorter snow melt seasons (Rasmussen et al., 2014; Miller and

[1] The Shoshone Call Relaxation Agreement (SCRA, 2006) is an agreement between Denver and Xcel Energy, the owner of the Shoshone hydroelectric power plant, allowing an early start to storage operations during drought years. The agreement has been endorsed by Western Slope water interests because they may benefit from increased drought-year water storage in the UCRB reservoirs.

Piechota, 2011; Lukas et al., 2014; Christensen and Lettenmaier, 2007). However, climate model projections (derived from CMIP3 and CMIP5) show large uncertainty in future precipitation and consequently river flow for the region (Mearns et al., 2013; Salzmann and Mearns, 2012). Most of Colorado's water supply originates as runoff from the state's high mountain areas, including the UCRB, where the seasonal snowpack provides the primary form of water storage. This water supply is important to communities, irrigators and recreational interests on the western side of the Continental Divide as well as to the major cities and much of the state's irrigated agricultural land on Colorado's Eastern Slope. The Eastern Slope includes the Colorado Front Range corridor, which is the most populous region of the state, with nearly 3 million inhabitants nearly all of whom benefit from transbasin water diversions. Denver Water (hereafter abbreviated as "Denver") is a large municipal utility within the Front Range, which provides potable water to about 1.3 million customers. Recognizing the need for flexibility and contingency planning to accommodate uncertain stressors on the water system, Denver is looking to develop cost-effective methods for exploring options to cope with near-term drought and adapt to multi-decadal climate change.

The water supply system

Colorado's Eastern Slope municipalities and agricultural irrigators long ago turned to importing water primarily via tunnel, from the UCRB to augment locally available water supplies on the East Slope (Fig. 2). At present, these transbasin diversions account for more than 40% of the water that Denver delivers to its customers, while for the organizations belonging to the Front Range Water Council (FRWC)[2] as a whole, water diverted from the UCRB is estimated to account for 72 percent of the water delivered to their customers (Summit Economics and The Adams Group 2009:31).

Denver's reservoirs and operations serve as the exemplar for our analysis because they play important roles in the overall UCRB water supply system. While the majority of Denver's supplies come from mountain snowmelt, the utility has diversified its sources of supply across several watersheds. The South Platte River, Blue River, Williams Fork River and Fraser River watersheds are the major sources of supply, and Denver's collection system encompasses a set of diversion structures, ditches and tunnels spread across approximately 10,300 km^2 (4000 $miles^2$) in more than eight counties.

Denver controls about 865 million m^3 or MM3 (700 thousand acre-feet or TAF) of storage capacity in 15 reservoirs, with slightly more than half of that capacity located on the western side of the Continental Divide (Denver Water, 2013a). Dillon Reservoir is by far the largest of these with a capacity of 320 MM3 (257 TAF), accounting for 37% of Denver's total reservoir capacity and, when full, its volume approximately equals Denver's average annual water deliveries (Denver Water, 2013a). These major reservoirs are crucial for providing water supply security for Denver's customers. The practice of drawing water from widely separated basins also provides drought protection by allowing operational flexibility. In addition, inter-annual variations in snowpack and runoff volumes differ somewhat across these basins (USDA-NRCS, 2013).

The reliability of Denver's water supplies depends not only on the volume and timing of mountain stream flows, but also on Denver's ability to divert and store those flows given its infrastructure and the priority position of its water rights under Colorado's prior appropriation system of water law. This system of law, characterized as "first in time, first in right", dictates that when river flows are too low to fully serve all decreed rights, a "first" or senior right-holder may place a "call" on a stream to obtain a full supply, requiring upstream junior right holders to cease diverting water until the senior right has been satisfied (Jones and Cech, 2009). Alternatively, the law allows a junior right holder to satisfy the senior call "by exchange," a practice involving releasing water from another source (usually a reservoir) to satisfy the call while continuing to divert water at the location subject to the call (Colorado Division of Water Resources, 2011). Water rights are differentiated according to type but all rights, whether for direct diversion or for storage in a reservoir, are administered within the same priority hierarchy. Once water is placed into a reservoir, the storage owner is free to determine the timing of its use.

Denver's water rights for its diversions are located near the top of the UCRB, and are junior to some Western Slope water rights as well as to the State of Colorado's obligations to downstream states under the Colorado River Compact. Thus, Denver's water rights can be subject to senior calls from these downstream, senior right holders. These priority relationships and their administration determine Denver's ability to fill the City's reservoirs and to divert water to the Eastern Slope, and exchanges play an important role in the management of Denver's supply system, as described below.

As elsewhere in the Western US, Colorado's water is managed according to a water-year that begins in October, marking the beginning of the snow accumulation and the extended low-flow period. For reservoir storage, Colorado follows a one-fill rule unless the storage right decree issued by the division water court specifies a right to refill the reservoir. This means that the reservoir owner is entitled to divert water into storage whenever the water right is in priority and water is physically available, but once the reservoir has been filled, its right goes out of priority until the following water year. Even though the storage right loses its ability to call out other water rights once the reservoir has filled, if "free river conditions" exist, meaning that all downstream rights are fully satisfied, additional water can be put into storage. Furthermore, some reservoirs have refill rights, often established at a later date, that allow water to be stored when the junior refill right is in priority (Colorado Division of Water Resources, 2011).

Arguably the most controlling water rights on the Colorado River, in terms of size and seniority, belong to the Shoshone Power Plant, located in Glenwood Canyon below the major UCRB reservoirs. These non-consumptive, hydropower water

[2] The members of the FRWC include: Aurora Water, Denver Water, Colorado Springs Utilities, Northern Water, Pueblo Board of Water Works, Southeastern Colorado Water Conservancy District, and Twin Lakes Reservoir and Canal Company, (http://denverwater.org/AboutUs/PressRoom/A569A08B-92D9-E00F-25C1DDCC7A1F950B/).

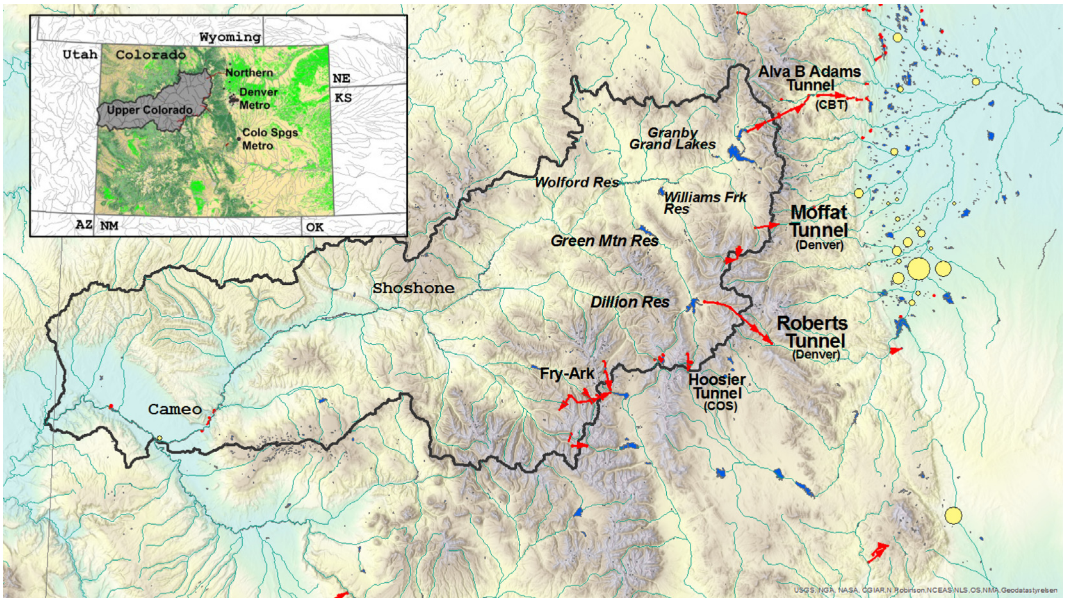

Fig. 2. Domain of the Upper Colorado River Basin and key model elements. The green area in the inset figure shows the irrigated agricultural areas of Colorado, including those that benefit from transbasin diversions on the eastern plains. Tunnels and canals for transbasin diversions are shown in red. CBT is Colorado Big Thompson project and COS is Colorado Springs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

rights benefit a variety of downstream water uses including rafting and fishing by maintaining higher flows throughout the summer. During much of the water-year, especially in mid-to-late summer through the following early spring, the water rights for the Shoshone Power Plant are very large relative to the flow of the Colorado River at that location, and they pre-date the majority of the water projects upstream – i.e. 35.4 cms (1250 cfs) with a 1902 priority date and an additional 4.5 cms (158 cfs) with a 1929 priority date (City and County of Denver et al., 2012). So when the Shoshone Plant is calling, out-of-priority upstream users must cease diverting or storing water unless they simultaneously replace their depletions by releasing water from one of their reservoirs to satisfy the call.

Dillon Reservoir, from which Denver draws the largest share of its Western Slope water through the Roberts Tunnel, is only one in a sequence of interconnected reservoirs upstream of the Shoshone Power Plant. Dillon Reservoir (1946 priority) and Denver's and Colorado Springs' Blue River direct diversion rights are upstream of and junior in priority to the Federal Government's Green Mountain Reservoir (1935). Green Mountain Reservoir stores water to provide exchanges to meet the requirements of senior water rights holders downstream along the Colorado River and to allow water diversions by the Colorado Big Thompson Project (CBT) to the East Slope. The CBT is jointly operated by the United States Bureau of Reclamation (USBR) and the Northern Colorado Water Conservancy District (Northern). The CBT is the largest transbasin diversion averaging 320 MM3 (260 TAF) annually and includes the large storage reservoirs of the Granby/Grand Lake system, with a capacity of 665 MM3 (540 TAF).

Denver's other major transbasin diversion is through the Moffat tunnel, located on the Fraser River. It too is upstream of Shoshone and is essentially a run-of-the-river diversion, since there is little storage on this portion of the system. Denver has historically diverted an average of 75 MM3 (61 TAF) annually through the Roberts tunnel and 65 MM3 (53 TAF) through the Moffat tunnel to help meet its supply needs. Dillon, Green Mountain, and the CBT systems are all junior to the full Shoshone Call, while the 1921 priority date for the Moffat Tunnel falls between the priority dates for the larger (1902) and smaller (1929) Shoshone rights.

The spring melt period is critical for filling these reservoirs. When flows are high enough to satisfy the Shoshone and other downstream senior direct diversion rights, Green Mountain Reservoir can begin storing water under its 1935 First Fill Right of 191 MM3 (155 TAF). Rather than requiring Denver to wait until Green Mountain is full before starting to fill Dillon, agreements allow Denver and Colorado Springs to store water in Dillon and make diversions from the Blue River's natural inflows, even when they are out-of-priority to Green Mountain's storage right, provided that they maintain the capacity to replace their depletions through exchanges of newly or previously stored water. This practice is designed to ensure efficient utilization of Colorado's reservoirs by allowing as much water as possible to be captured and stored during the short snowmelt season.

The Green Mountain Reservoir warrants additional description. An intricate set of arrangements between the rights-holders tracks both the theoretical fill of Green Mountain, as-if no out-of-priority diversions or storage had occurred-(i.e. the 'paper-fill') and the Reservoir's physical fill. If Green Mountain paper-fills but does not physically fill, then junior rights holders upstream of Green Mountain (Denver Water and Colorado Springs Utilities) must "payback" the remaining difference between the paper and physical fill at the end of the water-year. That is, they must release an equivalent quantity of water from storage in Williams Fork, Wolford, Dillon, or another source. If the senior reservoir (Green Mountain) does physically fill, the junior reservoir (Dillon) is allowed to retain the water stored out of priority and payback is not required.

Another critical Denver asset is the Williams Fork Reservoir (1959) on the Williams Fork tributary, with a capacity of approximately 120 MM3 (97 TAF). Denver also leases 40% of the storage capacity in Wolford Mountain Reservoir (1995) on the Muddy Creek tributary, amounting to roughly 31 MM3 (25 TAF) of storage. The storage in these reservoirs enhances the reliability of transbasin diversions to the East Slope by providing water for exchange and payback to satisfy downstream senior water rights (Colorado Water Conservation Board, 2009; Green Mountain Reservoir Administrative Protocol, 2012).

Drought management measures

Denver has developed a diverse suite of both demand side and supply side drought response measures, and has defined triggers for imposition of more stringent actions during more severe droughts (Denver Water, 2011). These drought response plans are undergoing further development, which provides a need and opportunity for critical assessment of the merits and design of alternative measures. Here, we focus on stress-testing one of Denver's strategies for enhancing the yield of their water system during drought years, namely the SCRA. Under the terms of the SCRA, Xcel energy has agreed to partially forego its right to place a call for water delivery to the Shoshone hydroelectric power plant on the main-stem of the Colorado River during part of the spring melt season (March 14 to May 20, which corresponds to Week 11 through Week 21 of the Water Year). To secure this concession, Denver agreed to compensate Xcel for any reduction in its hydropower generation caused by relaxation of the call by making cash payments calculated on the basis of the cost of replacement power and the change in net turbine flows at Shoshone, regardless of which upstream entity actually stored the water not called. The agreement also calls for these payments to be partially offset by Denver's delivery of additional cooling water to Xcel's Front Range thermoelectric power plants (City and County of Denver and Xcel Energy, 2006).

For the purposes of demonstrating our approach, we explored the long-standing SCRA conditions that come into effect when Denver is faced with certain drought conditions, which are roughly equivalent to a "drought watch" (stage one) as defined in the utility's Drought Plan (Denver Water, 2011). Specifically, Xcel Energy has agreed to reduce the call at the Shoshone Power Plant from 40 m^3/s or cms (1408 ft^3/s or cfs) to 20 cms (704 cfs) between those dates when two conditions apply: (1) Denver's July 1 reservoir storage is forecast to be at or below 80% full, and (2) the April-July flow of the Colorado River at the Kremmling gage is forecast to be less than or equal to 85% of average. We have confined the analysis to this definition of the conditions and time window for relaxation. Recently agreed provisions (City and County of Denver et al., 2012; Denver Water, 2013b) for extension of the relaxation period in the event of severe droughts are not explicitly modelled because those provisions entail subjective decisions and they have never yet been triggered. However, implications and plans for future analysis are discussed.

The SCRA allows reservoirs in the UCRB, upstream of the Shoshone Power Plant, to begin storing water earlier than would otherwise be permitted. This may enhance drought-year water supply security, but the magnitude of the benefit depends on the details of flow volumes and timing at various points throughout the UCRB. Modelling the operation of this agreement and its effects on Denver's water supplies is far from simple, and requires accurate representation of the previously described physical and legal relationships among the various reservoirs and diversion rights in the UCRB.

Adaptation performance metrics

To evaluate the performance of the SCRA under different future climatic conditions, it is important to first identify metrics of performance. As an urban water provider, Denver is naturally concerned with the reliable yield of its system and the frequency with which thresholds are crossed which trigger drought management measures. The volume of water that must be actively exchanged when Denver is out of priority and wants to store or divert water and the amount of water they must pay back to Green Mountain Reservoir at the end of the season are other issues of concern. In addition, the utility recognizes the importance of maintaining good relations with Western Slope water users, including recreational users who benefit from the maintenance of adequate river flow to support rafting or sport fishing. Possible impacts on the integrity of aquatic ecosystems are also of concern.

Some of the questions that are explored with this decision-centric analytical approach include:

(1) How beneficial is the currently defined SCRA relaxation agreement to Denver's water supplies under alternative future scenarios?
(2) How much and how often would Denver need to make a water payback to Green Mountain at the end of the water-year under these different scenarios?
(3) How might the SCRA drought-management plan affect Colorado River main-stem flows and the availability of water in Western Slope reservoirs in a future, warmer climate?

For the purposes of this exploratory analysis, performance metrics are considered that reflect both direct impacts on Denver and impacts on other water interests in the UCRB. The simulations described below estimate performance under current climate and several future narrative climate scenarios both with the SCRA in place and without it. The results provide insights on the extent to which the agreement can ameliorate drought impacts for these entities both now and under the future conditions. Some of the metrics used in the analysis include:

- The volume of Denver's' diversions via the Roberts and Moffat tunnels from the UCRB to its service area.
- The volume of water stored in the UCRB reservoirs during the course of the water year, with and without the SCRA.
- The volume of Colorado River flows at Shoshone.
- The volume of water paid-back by Denver to Green Mountain Reservoir at the end of the storage season to compensate for the utility's out-of-priority storage in Dillon Reservoir or diversion out of the reservoir through the Roberts tunnel.
- The frequency with which drought conditions cause the SCRA to be invoked.

The WEAP-Upper Colorado River Basin Model (WEAP-*UCRB*)

We have built a model of the Upper Colorado River Basin (USGS HUC 140100) within the Water Evaluation and Planning (WEAP; Yates et al., 2005) system, which we refer to as WEAP-*UCRB*. Briefly, WEAP is an integrated hydrologic simulation and water management decision support system that includes a robust and flexible representation of water demands by sector and programmable operating rules for infrastructure elements such as reservoirs, hydropower systems, canals, tunnels, etc.; together with the rules and water rights which govern their management. Demands for water and the infrastructure used for its management are dynamically integrated within the climatically driven, hydrological process model. The hydrologic simulation includes a physically-based, catchment model, driven by climate inputs. The model simulates soil moisture dynamics, the rain/snow phase, snow accumulation and melt, evaporative losses, streamflow generation, groundwater recharge and other components of the hydrologic cycle (Yates et al., 2005, 2009). These attributes allow planners to explore how specific configurations of infrastructure, operating rules, and priorities will affect access to water under particular rights, in-stream flow requirements, water delivery, water demand, and other components within a changing environment.

The WEAP-*UCRB* model includes governing logic that controls the diversion of water from the West Slope, across the Continental Divide. These diversions include non-Denver water from the Colorado Big-Thompson (CBT) Project, the largest of the transbasin diversions, with simulated annual average deliveries of 284 MM3 (230 TAF) and diversions into the Arkansas Basin from the Homestake water collection system (City of Colorado Springs and City of Aurora, Colorado), and the USBR Frying Pan-Arkansas Project with annual average water diversions of 171 MM3 (139 TAF). These elements are included to ensure that the senior agricultural water rights at Cameo are also considered (see Fig. 1).

Denver's diversions include those through the Moffat tunnel from the Fraser River, averaging about 65 MM3 (53 TAF) annually; and from the Blue River through the Robert's tunnel out of Dillon Reservoir, averaging 75 MM3 (61 TAF). Since there is no storage on the Fraser River, the Moffat Diversion is taken as a fraction of flow of its collection system; while for the Roberts Diversion, model logic considers the storage in Dillon and the water year type (dry, normal, or wet). Water diversions by Denver and other Front Range entities are junior to Shoshone (40 cms or 1408 cfs). During the irrigation season, other rights like Cameo (about 28 cms or 1000 cfs) play a role in west-to-east diversions across the Continental Divide for entities like Colorado Springs and the City of Aurora, which draw water from tributaries that join the Colorado River below Shoshone. For simulating Denver's rights, we consider both their storage and diversion rights; and when Denver is being "called-out" by senior rights holders such as Shoshone and Green Mountain, the WEAP-*UCRB* simulates an "exchange", whereby previously stored water is sequentially released from Williams Fork, Wolford, and/or Dillon Reservoirs. The model will not allow an out-of-priority diversion if there is not sufficient water in storage to accommodate an exchange.

The WEAP-*UCRB* tracks both the physical and paper fill of Green Mountain Reservoir, and determines if a water payback must be made and by how much for both Denver and Colorado Springs. Water payback is a situation that both utilities try to avoid, which has typically occurred in about 1-in-8 years.

Hydrologic simulation

The WEAP-*UCRB* comprises 31 sub-basins of the Upper Colorado, comprising 166 WEAP catchment objects covering roughly 25,900 km^2 (10,000 mi^2). Catchments in the headwater regions of the Upper Colorado were more finely discretized to capture important topographically driven climate gradients with an average size of 175 km^2, median of 124 km^2, and maximum of 800 km^2. The model was run on a weekly time step using the gridded, continental U.S. Daymet dataset (Thornton et al., 2012), where estimates were made of weekly average temperature and weekly total precipitation for each catchment for the period 1981 to 2010.

The model was calibrated and validated against observations for the period 1981 to 2010, with model performance locations indicated in Fig. 2. The accuracy of the model for simulations of streamflow, reservoir storage, and transbasin diversions was quantified using goodness-of-fit statistics for monthly and yearly time series (Fig. 3). The statistical measures included the Nash-Sutcliffe Efficiency or NSE, for which a 1.0 indicates a perfect match of observed and simulated flows, a value of 0.0

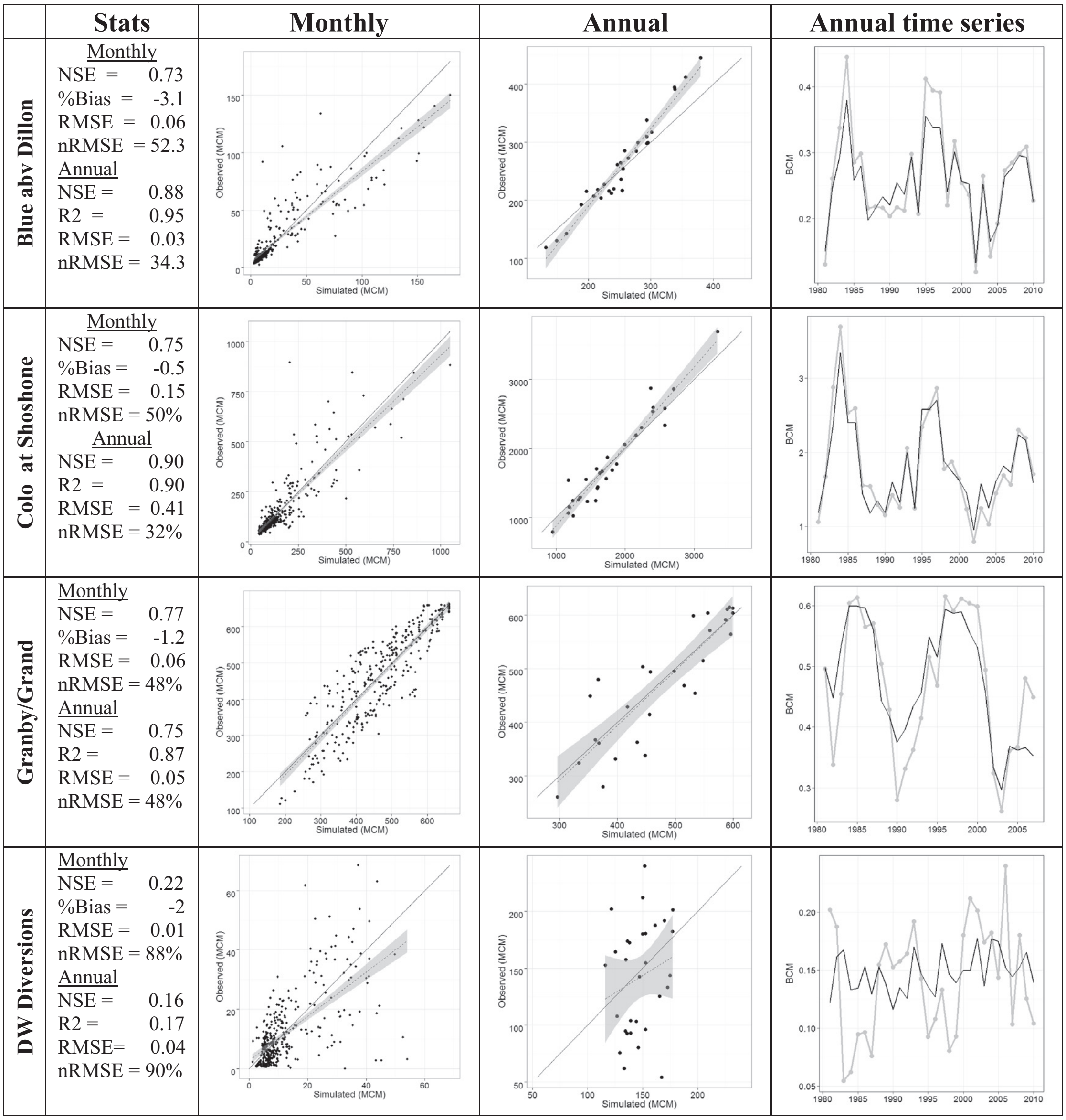

Fig. 3. Simulated and observed monthly and annual streamflow volume for the Blue River above Dillon (top) and the Colorado River at Shoshone (row 2). Simulated and observed mean monthly and mean annual storage in Granby/Grand Lakes (row 3), and total monthly and annual diversion by Denver through Roberts and Moffat Tunnels (row 4). Dark Shaded area is the 95% confidence interval. Statistical performance summary is in the Statistics column.

indicates that the estimates are as good as the mean of the observed value, while a value less than zero suggests that the observed mean is a better predictor than the estimate. The percent bias indicates if the model is over (positive) or under (negative) estimating the observed value. We also report the Root Mean Square Error (RMSE) and the normalized Root Mean Square Error (nRMSE), where a value of 100% indicates that the prediction errors are of the same magnitude as the variability of the observations. A lower nRMSE indicates greater predictive accuracy.

The correlation coefficients are reported for annual values. The model tends to under-represent the extreme high flow conditions while simulated low-flows compare more closely to observations (Colorado at Shoshone and Blue River above Dillon); while the simulated storage of Granby/Grand Lake compared reasonably well with observation. For the water diverted by Denver through the Roberts Tunnel (Dillon Reservoir) and the Moffat Tunnel (Fraser River), the model was configured to capture the mean behavior of deliveries from each system, and thus does not simulate the impacts of ad hoc management decisions related to infrastructure outages, repairs, and other managerial issues. The model characterizes deliveries through the Roberts Tunnel as dependent on storage in Dillon, the seasonal snowpack in the Blue River Basin and year type, i.e.: below normal, normal, or above normal water-year characteristics. The model captures the mean annual Denver diversions of about 140 million MM3 (113,000 acre-feet) and reflects some but not all of the observed inter-annual variability.

The 1981 to 2010 average annual observed flow at Shoshone was about 3500 MM3 (2800 TAF), with historical average West to East Slope diversions of 630 MM3 (510 TAF) per year. The diversions simulated by WEAP-*UCRB* for the same period were somewhat higher, at an annual average of 650 MM3 (530 TAF), with a minimum of 505 MM3 (410 TAF) and a maximum of 775 MM3 (630 TAF). Note that two very different conditions can lead to reductions in transbasin diversions: in very wet years, diversions can be reduced because of smaller demands and limited storage on the East-Slope; and in very dry years transbasin diversions can decrease because there is an inadequate water supply, particularly for the junior rights holders.

SDSM calibration and evaluation

The Statistical DownScaling Model (SDSM) has been described in detail elsewhere (Wilby et al., 2002, 2003; Wilby and Dawson, 2013). The tool enables production of climate change time series at sites for which there are *daily* data for model calibration, as well as archived General Circulation Model (GCM) output to generate scenarios for future decades. The most recent Decision Centric (SDSM-DC) version can also produce synthetic weather series and fill gaps in observed meteorological data (Wilby et al., 2014).

At the heart of SDSM-DC is a conditional weather generator that relates atmospheric circulation indices and regional moisture variables to time-varying parameters describing daily weather at individual sites (e.g., precipitation occurrence, wet-day amount distributions, or daily mean temperatures). All downscaling parameters are obtained by least squares calibration of the local predictand(s) against regional predictor variables derived from the National Center for Environmental Prediction (NCEP) re-analysis (Kalnay et al., 1996) using data for any period within 1961–2000. Predictands are downscaled separately so any covariance must be conveyed by common predictor variables and/or correlation between predictors. Model testing suggests that this is a reasonable assumption (Wilby et al., 1998).

Although the public domain version of SDSM is for single sites, the basic model can be adapted for multi-site applications (following Wilby et al., 2003). This involves two steps. First, a ‘marker’ series based on daily area averages from several sites (or a single key site) is generated using NCEP predictors. Second, the area-average is disaggregated to observed daily series recorded at the constituent sites. This is achieved by resampling multi-site values on the date with observed area-average closest to the downscaled area-average.

Since actual patterns of values are being re-sampled, both the area average of the marker series and the spatial covariance of the multi-site array are preserved (Wilby et al., 2003; Harpham and Wilby, 2005). Area averages are favored over single site marker series because there is less risk of employing a non-homogeneous or non-representative record, and predictability is generally greater (because of larger signal-to-noise ratio). As with other resampling methods, the maximum daily value generated cannot exceed the maximum daily amount in the observations without invoking additional steps (see below).

For the purpose of the present study, SDSM was calibrated using the daily precipitation and mean temperature series generated for the 166 WEAP-*UCRB* catchment objects for the period 1981–2010. These data were used to calculate daily averages for the UCRB, weighted by area of sub-basins and elevation bands in WEAP (see above). SDSM reproduces monthly unconditional wet-day occurrence, totals and 95th percentile amounts, but underestimates persistence of mean dry-spell lengths (Fig. 4). The wet-day distribution and inter-annual variability of precipitation totals are simulated well (Fig. 4e–f).

SDSM also explains a large proportion of the variance in daily mean temperatures (R^2 = 79%), plus captures the monthly regime (Fig. 5a), overall temperature distribution and inter-annual variability (Fig. 5b). SDSM ($r = -0.12$) preserves observed ($r = -0.11$) correlation between area-average temperature and precipitation.

Downscaled basin-average daily precipitation and temperature series were used to conditionally resample multi-site series. Following Wilby et al. (2003) pairwise correlations of observed and downscaled daily precipitation were compared across all possible combinations of sites; the same test was applied to the multi-site temperature output. SDSM reproduces the observed range of inter-site correlations for both rainfall and temperature. Overall, across the UCRB, the spatial autocorrelation in daily temperature (mean $r_{obs} = 0.98$; $r_{SDSM} = 0.98$), is more homogeneous than for precipitation (mean $r_{obs} = 0.72$; $r_{SDSM} = 0.69$).

Narrative scenarios

Climate change is one of many exogenous factors and uncertainties that potentially affect water supply security in the UCRB. Other indirect climate and non-climatic factors include forest fires, legal access to land and water, water allocations for critical habitat and protected species, water right decree conditions, contractual obligations, and infrastructure performance. Hence, utilities in the Colorado basin are beginning to think about climate change within a more holistic risk profile. For example, Colorado Springs Utilities have identified 50 high priority risk-based scenarios, mapped to projects, programs or policies designed to mitigate these pressures (Basdekas, *pers. comm.*). In parallel to these developments, some providers of climate risk information have been reappraising the ways in which climate model output is delivered to “users”. For example, Whetton et al. (2012) proposed the use of Representative Climate Futures (RCFs) as a way of balancing considerations of uncertainty and simplicity of scenarios for adaptation planners. These are a small set of scenarios with descriptors (such as “slightly warmer with little rainfall change” or “hotter and drier”) with relative likelihoods given by climate model ensembles.

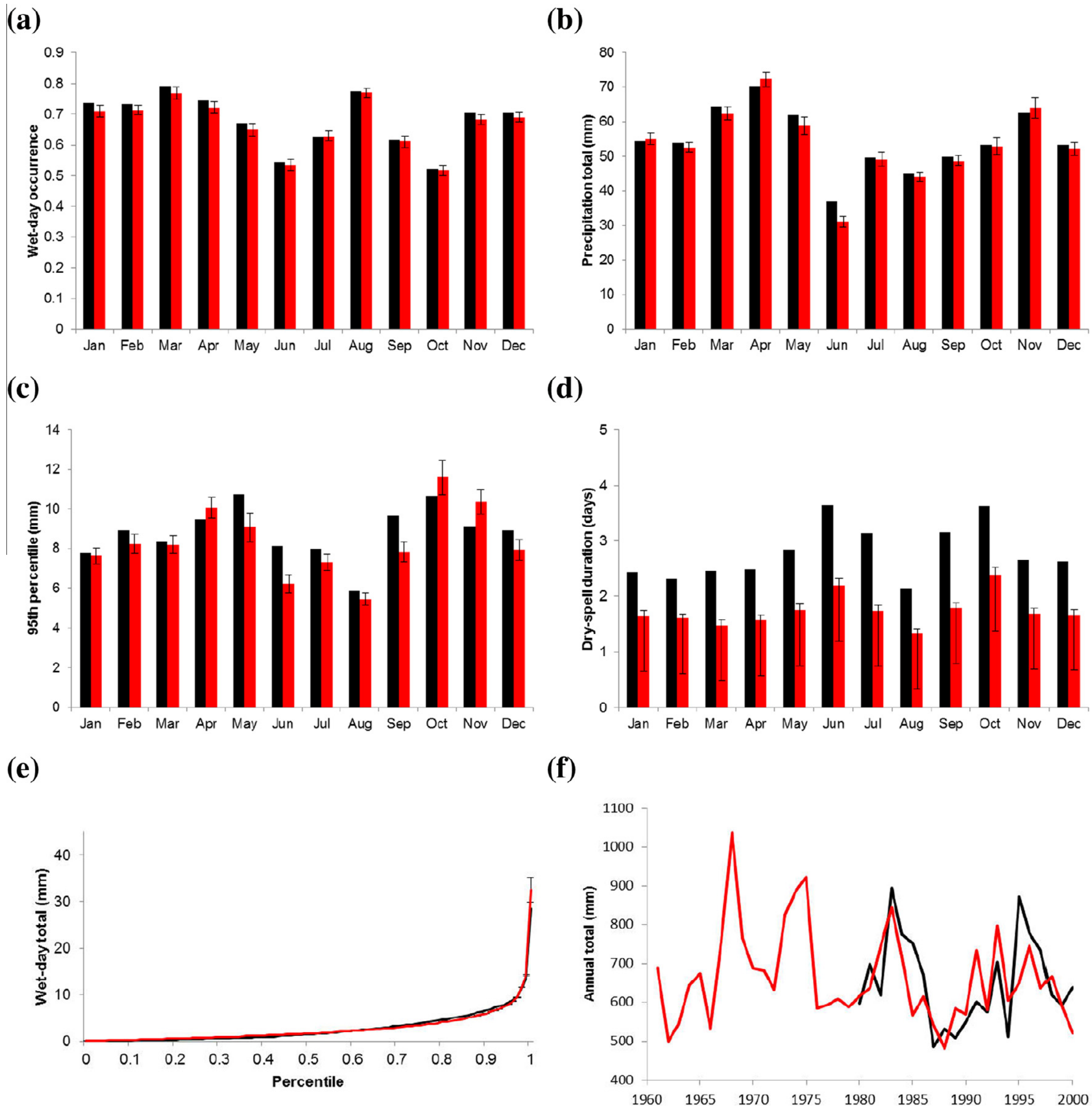

Fig. 4. Observed (black) and downscaled (red) basin-average: (a) wet day occurrence; (b) precipitation total; (c) 95th percentile wet-day amount; (d) mean dry-spell length; (e) wet-day amount distribution; and (f) annual precipitation totals. Bars indicate the 95% confidence range in the downscaled estimate. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

We combine these approaches by considering plausible scenarios of climate change with indirect consequences of basin change. In addition to the current-climate simulations, the following narrative scenarios have been modelled in this demonstration (Table 1):

(1) Altered vegetation and runoff rates caused by fewer cold winters and prolonged episodes of drought with beetle attack, coupled with a reduction in precipitation of −20% and an overall change in temperature of +2 °C (*PM20T2VC*).
(2) A decline in snow albedo caused by more frequent dust on snow events associated with regional desiccation and warming represented by precipitation change of −10% and a temperature change of +1 °C (*PM10T1DS*).
(3) No change in land surface characteristics and no change in overall precipitation, but with moderate warming of +2 °C on average (*PM0T2WM*).
(4) A fourth, control scenario, assumes a statistically similar climate as represented by the Daymet climate of 1981 through 2010 and no change in temperature (*CNTL*).

WEAP model parameters were adjusted to represent the attendant changes in land-surface properties, such as reduced vegetative area, dust-on-snow, and interception losses and evaporation with changes in snowmelt rates and runoff fraction

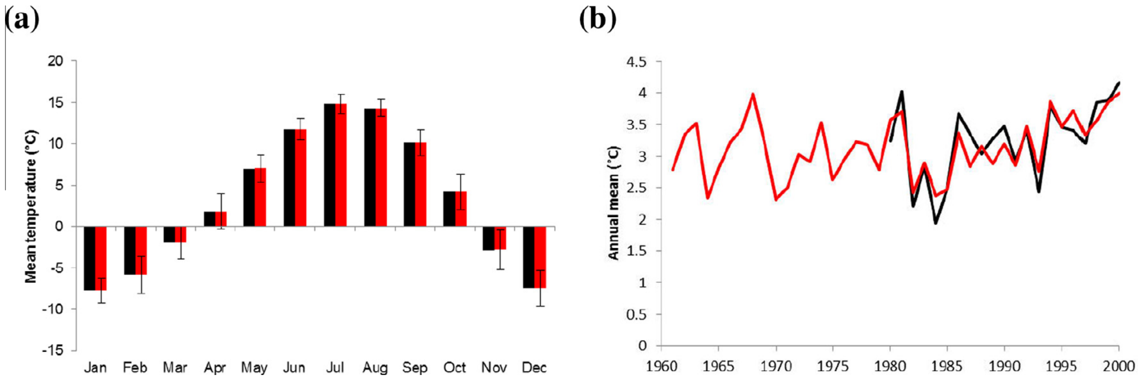

Fig. 5. Observed (black) and downscaled (red) basin-average: (a) mean monthly temperature; and (b) annual mean temperature. Bars indicate the 95% confidence range in the downscaled estimate. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Narrative scenarios and WEAP settings for the Upper Colorado River Basin.

Scenario	Description	Climate	WEAP parameterization	Sources
Vegetative change (*PM20T2VC*)	Fewer cold winters reduce mortality amongst infecting beetle populations. Warmer, prolonged dry conditions stress forests increasing their susceptibility to insect attack[1]. 5% of forest dies above reservoirs GranbyGrand, and Green Mountain permanently replaced by low scrub.	P-20% T + 2 °C	Adjust vegetative area in GIS; 15 year lag post-outbreak; reduced interception (increase incident precipitation to that of open areas); snowmelt rate set to open area (Rnet_other parameter); reduced ET (Kc variable) in affected area; increased ET elsewhere	Harma et al. (2012) and Ault et al. (2014)
Dust on snow (*PM10T1DS*)	Modest warming and drying increases the annual likelihood of dust on snow events by 10%. No other effects.	P-10% T + 1 °C	Adjust snow albedo decay functions (albedo ~0.3 is reported by CODOS[2] for individual events); reset to fresh snow value (0.85) if precipitation >10 mm; earlier warming and wetting of snowpack increases sublimation; increased ET from exposed vegetated areas; *no attempt is made here to represent any spatial variation in dust accumulation and radiative forcing due to preferential dust emission pathways in any given year* (Painter et al); CODOS log shows monthly variation in timing and up 12 events per WY	Painter et al. (2010, 2012), CODOS, Harma et al. (2012) and Skiles et al. (2012)
Mild Warming (*PM0T2WM*)	Seasonal precipitation totals are unchanged but temperatures are warmer across all seasons.	P-0% T + 2 °C	Warming causes increased ET from vegetated areas; deplete downstream reservoir volume	

Notes: [1]Colorado State Fire Service Map of High Wildfire Risk (http://www.coloradowildfirerisk.com/map); [2]Colorado Dust on Snow Program (CODOS) (http://snowstudies.org/CODOS/).

(see Table 1 and supporting literature). Following Steinschneider and Brown (2013) daily temperature and precipitation scenarios were stochastically generated for the prescribed changes in mean climate for the UCRB given in Table 1. These adjustments were informed by the range of changes given by CMIP3 and CMIP5, as well as by paleo-climate reconstruction (e.g., Meko et al., 2007). SDSM-DC was used to apply changes to temperature (by addition) and precipitation (by multiplication) with respect to the baseline climate (1981–2000). The new UCRB average series were then disaggregated to each sub-basin and elevation zone using the multi-site version of SDSM-DC described above.

Results

The model was run for 30 years using the climate narratives generated from SDSM and described above. Figs. 6 and 7 show results of simulations without the Relaxation Agreement for the same water supply metrics presented in Fig. 3 for each of the four scenarios. The results suggest the strong sensitivity of the UCRB, first to changes in precipitation and then to changes in temperature and other environmental conditions such as dust-on-snow. The +2 °C moderate warming of the *PM0T2WM* scenario results in an earlier peak runoff for both the Upper Blue and Colorado Rivers at Shoshone, with the magnitude of the peak considerably lower for both, with June flows reduced by 31% on the Blue River above Dillon and by and

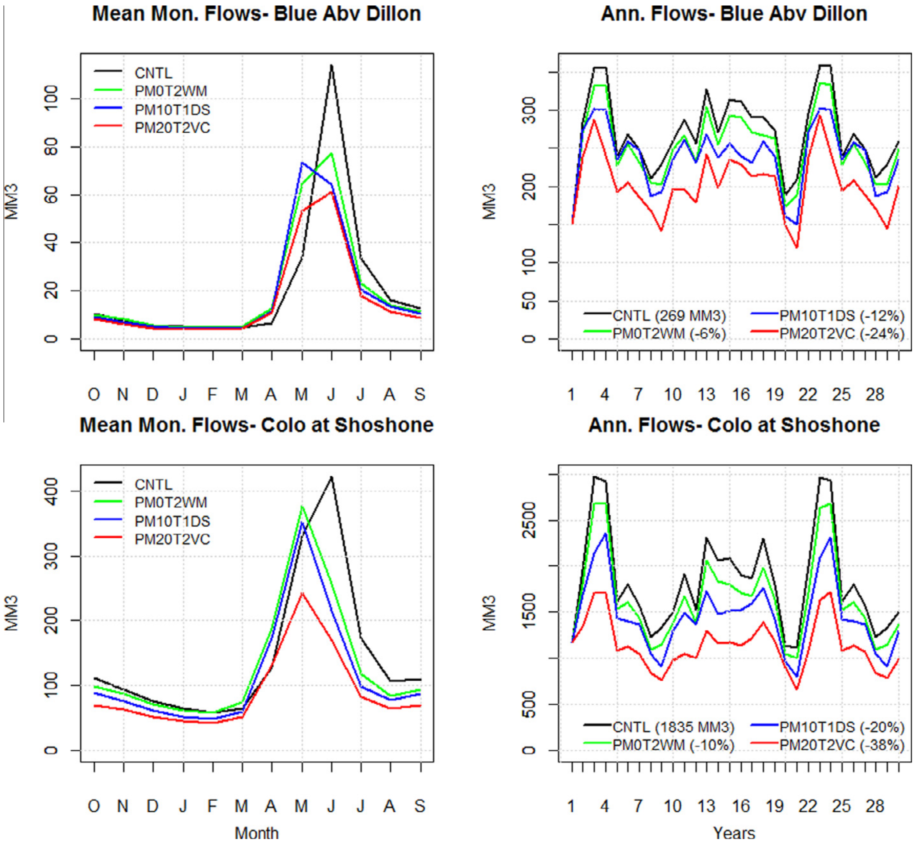

Fig. 6. Mean monthly and annual flow volumes for the Blue River at Dillon (top) and the Colorado River at Shoshone (bottom), simulated without the Relaxation Agreement. MM3 is million cubic meters, where 1 MM3 = 810 acre-feet (e.g. 25 MM3 = 20,300 acre-feet). Annual legend includes percent change relative to the CNTL scenario shown in MM3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

39% on the Colorado River at Shoshone. Total annual runoff volume for all scenarios are given in Fig. 6, with changes relative to the *CNTL* scenario summarized in the figure legend.

The two scenarios with reductions in precipitation, *PM10T1DS* (dust-on-snow) and *PM20T2VC* (vegetative change) show similar seasonal shifts in runoff, with reduced peaks and substantial reductions in overall annual flow volume. For those two scenarios, annual flows declined by 12% and 24% for the Blue River; and 20% and 38% for the Colorado at Shoshone, respectively (see Figure legend). Reductions in precipitation and warming have a greater impact on the lower-elevation western tributaries of the Upper Colorado than on the higher elevation basins, like the Blue River which are somewhat insulated from the warmer conditions. As a result, the climate change scenarios result in a more pronounced change to earlier seasonal peak and lower flow at Shoshone than in the Blue River and other high mountain tributaries.

Fig. 7 shows Denver Water diversions (top) and the average monthly and annual storage at Granby/Grand Lakes, which represents about 1/3 of the total storage in the Upper Colorado Basin (bottom), simulated without the Relaxation Agreement. Changes in storage from just warming (*PM0T2WM*) are modest, while changes in storage attributed to reductions in precipitation (the *PM10T1DS* and *PM20T2VC* scenarios) are considerably greater. The average Denver diversions for the *CNTL* scenario are 143 MM3 (116 TAF), with changes for each of the narratives shown in the figure, including their percent change. Denver's upper basin storage moderates the impacts of reduced streamflow, with average annual Denver diversions through Moffat and Roberts given for each of the narrative scenarios in Fig. 7. Diversions from the Colorado-Big Thompson Project out of Granby/Grand Lakes are reduced by 6%, 8%, and 21% for these scenarios (not shown).

While changes in total Denver diversions are relatively modest, even under the most extreme scenario, these diversions are supported through payback to Green Mountain Reservoir and exchange from Williams Fork, Wolford and Dillon Reservoirs when Denver stores or diverts through Roberts and Moffat tunnels and they are out-of-priority. Fig. 8 shows total annual end-of-season water payback Denver owes because Green Mountain Reservoir physical fill fell short of the paper fill (left) and the total water exchanged (right), with the number at the top indicating the number of years that payback or exchange occurred over the 30-year simulation period. Note that the warmer climate scenarios are associated with a greater frequency and volume of exchange and Green Mountain payback and exchange happens every year in all scenarios.

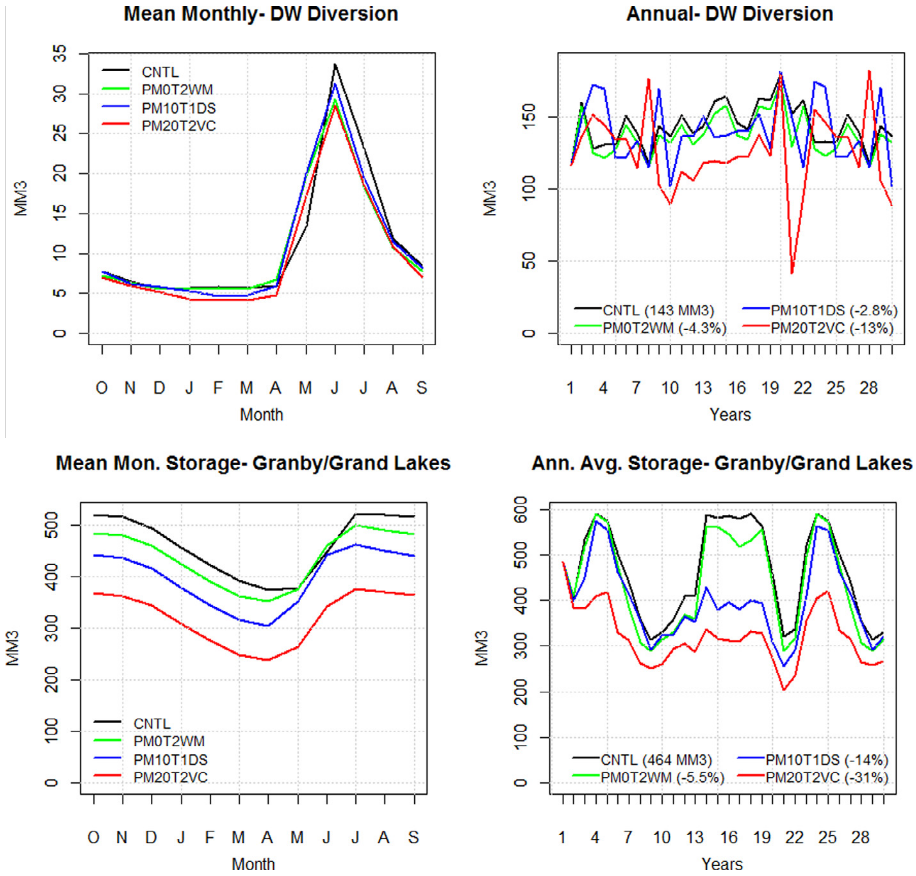

Fig. 7. Mean monthly and total annual diversions for Denver Water as the sum of the Moffat and Roberts tunnel deliveries (top) and the mean monthly and annual average storage for the Granby/Grand Lakes (bottom). MM3 is million cubic meters, where 1 MM3 = 810 acre-feet (100 MM3 = 81,000 acre-feet). Annual legend includes percent change relative to the CNTL scenario shown in MM3.

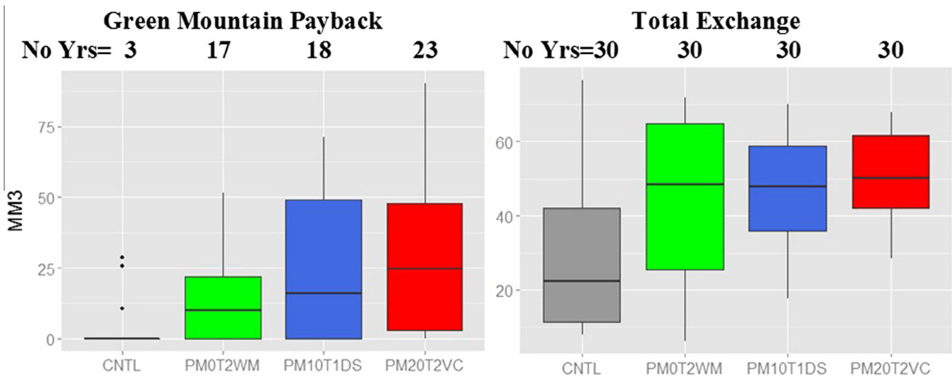

Fig. 8. The 30-year annual exchange (right) and Green Mountain Payback volume (left) for the four narrative scenarios without the SCRA (MM3). Black is CNTL; Green is PM0T2WM; Blue is PM10T1; and red is PM20T2. MM3 is million cubic meters, which is equivalent to 810 acre-feet (25 MM3 = 20,300 acre-feet). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The Shoshone Relaxation Agreement

We examined how the current Shoshone Relaxation Agreement (SCRA) might benefit Denver and its possible impacts on other components of the Upper Colorado River system. Recall that the SCRA reduces the Shoshone flow right from 1408 cfs (40 cms) to 704 cfs (20 cms); but can only be invoked in the spring, from early March (about week 11) until mid-May (about week 21). This is the period when Denver has reduced storage in their system and flows on the Colorado River are low, but

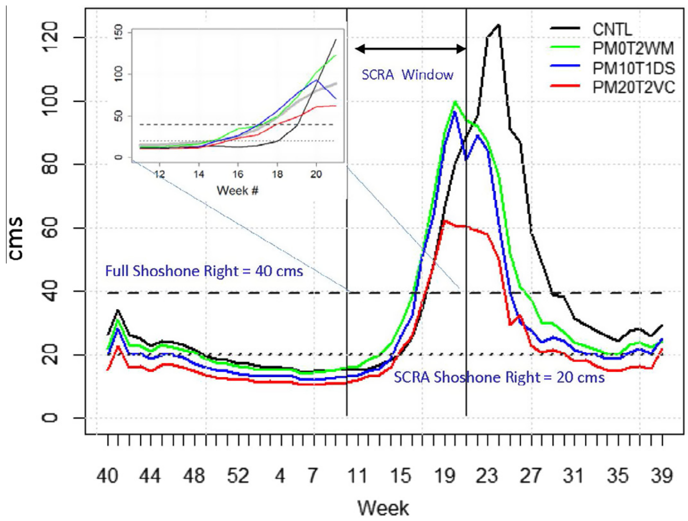

Fig. 9. Weekly mean flows at Shoshone (Week 40 = Oct. 1st) for the four Narrative Scenarios without Relaxation. The inset diagram are the average Shoshone flows for the four Narrative Scenarios, but only for and during Relaxation.

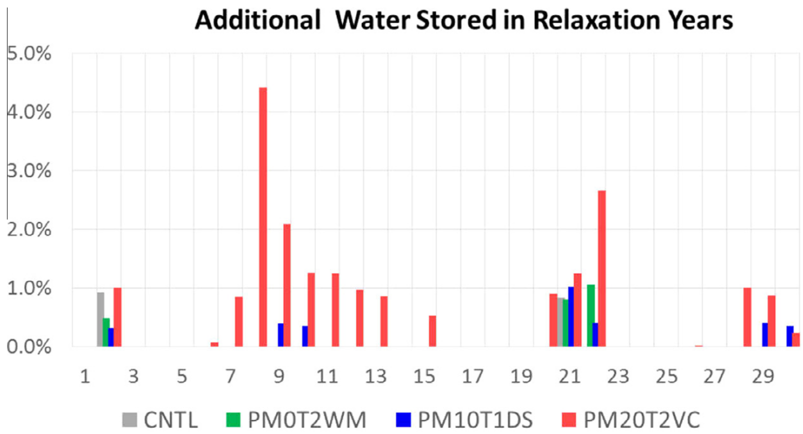

Fig. 10. Percent increase in UCRB storage attributed to relaxation.

beginning to rise. Fig. 9 shows for each narrative scenario, the mean weekly Colorado River flows at Shoshone for the 30-year period, with the SCRA window indicated by the vertical lines. The inset diagram in Fig. 9 shows the mean flow during the Relaxation period for each scenario, computed only for the years when Relaxation is active, with the exception of the thick, gray line, which serves as a reference for the other scenarios by showing the weekly mean flow for all years of the *CNTL* scenario.

The benefits of the SCRA to Denver in terms of additional water supply are marginal. Relaxation provides additional diversions of less than 1%, even for the most extreme *PM20T2VC* scenario. The most significant benefits to Denver come primarily in the form of some additional water saved for exchange and payback in Williams Fork, Dillon and Wolford Reservoirs.

For all of the scenarios, Fig. 9 demonstrates how the SCRA would be beneficial for only a brief period, starting when flows exceed the 704 cfs (20 cms) threshold, and terminating a few weeks later when spring runoff causes flows at Shoshone to rise above the full Shoshone Call threshold of 1408 cfs (40 cms). Once that occurs, the Shoshone Call is satisfied and upstream storage and diversions can proceed unimpeded. In these simulations, the effective relaxation period is thus only on the order of three weeks.

It is especially short for the *CNTL* scenario, in which the SCRA calls for Relaxation in only 2-of-30 years, and in those years, simulated flows at Shoshone remain below the relaxed SCRA limit of 704 cfs (20 cms) until after week 17 and then jump quickly above the full Call threshold within about two weeks. The frequency of active relaxation under the SCRA is greater for the three narrative scenarios when compared to the *CNTL*, with the *PM20T2VC* scenario simulating relaxation a little over half the time or 17-in-30 years.

Also note that in the warmer future climate scenarios, the storage season ends much earlier on average as flows quickly recede, falling below the Shoshone Call threshold at about Weeks 25 and 26, whereas under the *CNTL* scenario, this limit was not reached until about Week 29. The benefits of the SCRA relaxation are therefore limited to a very short period early in the spring and these benefits are small when compared to the simulated climate-related impacts on UCRB water supplies.

The primary objective of the SCRA is to increase water held in storage in the UCRB reservoirs, facilitating subsequently greater deliveries than would have otherwise occurred. Fig. 10 summarizes this system-wide increase in stored water during relaxation for Dillon, Williams Fork, Wolford, Green Mountain, and Granby Grand Lake. We have simply computed the percent increase in total storage between weeks 11 to 20 for each of the narrative scenarios, with the SCRA as opposed to without it. For the CNTL scenario, relaxation occurs only 2 of 30 years, with storage increase of less than 1%.

Not surprising, the additional storage benefits provided by the SCRA are most frequent in the warmest/driest *PM20T2VC* scenario, where relaxation occurs in 17 of 30 years. For this scenario, the maximum increase in storage due to relaxation is a little over 4% or about 40 MM3 (32 TAF). For the *PM10T1DS* scenario, relaxation occurs in 7 of 30 years, with a maximum benefit of about 1% of additional storage or 10 MM3 (8 TAF), while for the PM0T2WM scenario, relaxation occurs in 3 of 30 years.

Summary and conclusions

We have demonstrated the application of a decision-centric adaptation appraisal process using the Upper Colorado River Basin as a case study. The Water Evaluation and Planning (WEAP) model was used to characterize and simulate the physical hydrology, water resource management practices, and regulatory environment of the system. WEAP-*UCRB* captured the inter- and intra-annual variability of streamflow and reservoir storage; and reflects the water rights that often constrain the biggest transbasin diversions across the Continental Divide, such as by the metropolitan water providers on the eastern plains (Denver, Colorado Springs, Aurora, etc.) and the agricultural irrigators. Through a set of narrative scenarios that reflect changes in both climate and watershed conditions, we demonstrated the sensitivity of the region's water resources to warmer temperature and changing precipitation characteristics. While the UCRB is indeed sensitive to these changes, the relatively high elevation of most of its reservoir storage capacity provides a buffer to these changes; although the system may be put to an even greater test than has already occurred in recent years.

After calibrating and validating the WEAP-*UCRB* model as a tool to simulate the hydrology and major water rights of the region, we assessed a drought management tool negotiated by Denver Water known as the Shoshone Call Relaxation Agreement or SCRA, which is meant to allow all of the UCRB reservoirs to store water earlier in the spring during water stressed years despite being out of priority to the more senior right on the Colorado River at Shoshone.

Overall, the results show that the SCRA has a small impact on the performance metrics under current climate conditions. For example, a comparison of simulations with and without the SCRA shows that it allows a slight increase in the long-term average volume and reliability of Denver's diversions of UCRB water to the Front Range. This is because the SCRA, as assessed here, is limited to a small window of time during the spring, when runoff from snowmelt is beginning to rise. Under the three narrative scenarios, climate warming generally leads to earlier snowmelt resulting in higher flows during the relaxation window, but also an earlier end to the SCRA benefit when flows become high enough to satisfy the full Shoshone Call. While the SCRA yields a small benefit, it can do little to soften the impacts or characteristics of the warming and/or drying scenarios. As simulated here, the SCRA itself has no discernible impact on Western Slope water availability, as measured by flows at Shoshone. The climate scenarios, however would substantially reduce summer flows at those locations and also would reduce the average annual transbasin water diversions by Denver and other Front Range water providers.

The results depicted in Fig. 9 also suggest that the newly agreed strategy of initiating Relaxation as early as November 1 during severe drought episodes (City and County of Denver, et al., 2012) is likely to have a similarly small impact on water supply security for water users dependent on storage in UCRB reservoirs. The two scenarios with reduced precipitation that might mimic such drought conditions show flows below the relaxation threshold for virtually all of that extended period. The case study strongly indicates that Colorado's water resource managers will need to look elsewhere for effective climate risk management strategies.

A general lesson that can be taken from this analysis is that management options based on fixed terms or thresholds that may appear sensible under current climate conditions may fail to perform as desired in a changed future climate. The specific flow thresholds and conditions for activation of the SCRA make the agreement quite weak as a drought management tool. When considering alternative drought response and climate adaptation options, Colorado's water managers would do well to evaluate the performance of their proposed strategies under a plausible range of future climatic, biophysical and socioeconomic conditions.

The modelling capability developed as part of this project can contribute usefully to the search for effective water management strategies. Indeed, evaluation of climate adaptation options in such complex settings will require credible and computationally efficient decision support tools, like the WEAP-*UCRB* model described here. To be useful, such tools must be sufficiently detailed to accurately mimic the behavior of the managed system, but sufficiently streamlined to facilitate cost-effective exploration multiple adaptation options over a range of plausible future scenarios. In addition, it is important to consider the salience of the scenarios to the target community. As evidenced here, urban water planners understand that their systems face multiple sources of risk. As a result, they may especially wish to focus on scenarios involving interactions between a specific potentially problematic set of climatic changes, and changes in other factors, such as land surface conditions or dust deposition from remote sources.

More generally, we see merit in applying our pragmatic adaptation option appraisal process (Fig. 1) in other situations where a range of climatic and non-climatic factors must be taken into account. Through a deliberative and collaborative decision support process involving analysts and stakeholders, we have learned the value of defining shared understanding of the system behaviour and performance metrics from the outset. This strengthens the credibility, legitimacy and saliency of the model results. We have applied combined climate downscaling, watershed hydrology, and water system modelling as a 'virtual laboratory' within which to explore the outcome of narratives describing multiple, internally consistent catchment forcings. We assert that this is a more fruitful application of resources than conventional predict-then-act modelling strategies. However, overall portability and value-added (in terms of insights gained) of this decision-centric approach needs to be tested in other adaptation contexts.

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