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SCENARIO-BASED AND SCENARIO-NEUTRAL ASSESSMENT OF CLIMATE CHANGE IMPACTS ON OPERATIONAL PERFORMANCE OF A MULTIPURPOSE RESERVOIR[1]

Allison G. Danner, Mohammad Safeeq, Gordon E. Grant, Charlotte Wickham, Desirée Tullos, and Mary V. Santelmann[2]

ABSTRACT: Scenario-based and scenario-neutral impacts assessment approaches provide complementary information about how climate change-driven effects on streamflow may change the operational performance of multipurpose dams. Examining a case study of Cougar Dam in Oregon, United States, we simulated current reservoir operations under scenarios of plausible future hydrology. Streamflow projections from the CGCM3.1 general circulation model for the A1B emission scenario were used to generate stochastic reservoir inflows that were then further perturbed to simulate a potentially drier future. These were then used to drive a simple reservoir model. In the scenario-based analysis, we found reservoir operations are vulnerable to climate change. Increases in fall and winter inflow could lead to more frequent flood storage, reducing flexibility to store incoming flood flows. Uncertainty in spring inflow volume complicates projection of future filling performance. The reservoir may fill more or less often, depending on whether springs are wetter or drier. In the summer, drawdown may occur earlier to meet conservation objectives. From the scenario-neutral analysis, we identified thresholds of streamflow magnitude that can predict climate change impacts for a wide range of scenarios. Our results highlight projected operational challenges for Cougar Dam and provide an example of how scenario-based and scenario-neutral approaches may be applied concurrently to assess climate change impacts.

(KEY TERMS: climate variability/change; impacts assessment; dam/reservoir operations; Willamette River Basin; Cougar Dam; dam/reservoir modeling; water resources management planning; stochastic models.)

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INTRODUCTION

Growing evidence that climate change is affecting streamflow magnitude and timing motivates the need to understand how water resources management may need to adapt. Across the western United States (U.S.) declines in late summer streamflow magnitude (Luce and Holden, 2009; Safeeq *et al.*, 2013), altered flood risk (Hamlet and Lettenmaier, 2007), and shifts

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[2]Civil Engineer (Danner), Lower Colorado Regional Office, U.S. Bureau of Reclamation, P.O. Box 61470 (LC-6232), Boulder City, Nevada 89006-1470; Assistant Research Scientist (Safeeq), Sierra Nevada Research Institute, University of California-Merced, Merced, California 95343; Research Hydrologist (Grant), Pacific Northwest Research Station, U.S. Forest Service, Corvallis, Oregon 97331; and Assistant Professor (Wickham), Department of Statistics, Professor (Tullos), Department of Biological & Ecological Engineering, Former Graduate Student (Danner), Former Postdoctoral Scholar (Safeeq), and Associate Professor (Santelmann), College of Earth, Ocean and Atmospheric Sciences, Oregon State University, Corvallis, Oregon 97331 (E-Mail/Danner: adanner@usbr.gov).

to earlier streamflow timing of the center of mass (Stewart *et al.*, 2005) have been observed. With warming temperatures (IPCC, 2007), winters may be wetter and dry season streamflow may be lower (Tague and Grant, 2009; Safeeq *et al.*, 2013) as a result of more winter precipitation falling as rain rather than snow (Knowles *et al.*, 2006; Feng and Hu, 2007; Safeeq *et al.*, 2016). These changes may significantly affect the timing and magnitude of streamflow and thus could have important implications for reservoir management (Nolin and Daly, 2006).

Operations of dams and reservoirs are particularly vulnerable to climate change due to their sensitivity to variability in reservoir inflows (Stakhiv and Schilling, 1998; Palmer *et al.*, 2008; Flatt and Tarr, 2011). The storage and release trajectory of a reservoir that is realized in a given year is dependent both on inflow, which varies with weather and climate, and the reservoir's operational objectives, described by a set of operational targets and constraints. These may include target dates for achieving storage goals, minimum and/or maximum outflow requirements, target rates of filling or emptying, and limits on how quickly storage volume or outflows may change. Deviations from the "ideal" operational trajectory due to inflow variability are common, and a range of trajectories may successfully fulfill overall operational objectives. Under circumstances of changing climate, however, these deviations can become too large and/or compromise the ability of reservoir operators to achieve operational objectives.

Assessment of climate change impacts on water resources systems generally follows either a scenario-driven or scenario-neutral approach. A scenario-driven impacts assessment typically uses general circulation model (GCM) projected temperature and precipitation scenarios, followed by hydrologic modeling and reservoir operation simulations to investigate future reservoir operations for specific future climate change scenarios (*e.g.,* Christensen *et al.*, 2004; Payne *et al.*, 2004; VanRheenen *et al.*, 2004, 2011; Tanaka *et al.*, 2006). However, assessing impacts in relation to specific climate change scenarios has limitations. These downscaled GCM-driven scenarios typically have only a few decades to a century of projected inflow data with which to run operational scenarios, meaning that operational performance must inevitably be interpreted in the context of specific sequences of inflows (*e.g.,* Christensen *et al.*, 2004). A series of dry or wet periods in a short inflow dataset can skew results or make it difficult to draw generalized conclusions about effects of climate change. This is especially problematic for reservoir systems with multi-year carryover storage. Additionally, scenario-based studies also quickly become dated as new projections are developed, since new projections may have different magnitude and variability in future climate conditions. Despite these limitations, the scenario-based approach is commonly applied because it provides useful and easily understood information on the responses of water resources systems to changes in climate, with respect to historical climatology, and the potential timelines of those responses. In addition, a variety of methods is available for expanding the number of inflow sequences and range of projections beyond what is typically included in a scenario-based study. Stochastic techniques allow large numbers of inflow sequences to be generated from a few hydrologic model simulations (Sharma *et al.*, 1997; Srinivas *et al.*, 2001; Nowak *et al.*, 2011; Lanini *et al.*, 2014), thereby increasing the number of years of data beyond the length of a hydrologic model simulation and introducing additional variability in event sequencing. Large multi-model ensembles can introduce a greater range of potential future climate scenarios (Beyene *et al.*, 2010; Vano *et al.*, 2010). Perturbing an existing reservoir inflow dataset can also provide a wider range of reservoir inflows without using additional model projections (Vicuna *et al.*, 2007).

As an alternative to scenario-based studies, scenario-neutral assessments examine the likelihood of exceeding thresholds for reservoir performance as a function of climate parameters by examining relationships between operational performance and climate parameters (Brekke *et al.*, 2009; Prudhomme *et al.*, 2010; Brown *et al.*, 2012). A wide range of climate inputs and reservoir inflow sequences is desirable to provide the broadest possible range in operational performance. The scenario-neutral approach is less dependent on the method of developing reservoir inflows and operations, and instead focuses on identifying generalized relationships and performance thresholds between hydrology and operations.

The objective of this analysis is to explore the ability of concurrent application of scenario-based and scenario-neutral approaches to provide complementary information about future reservoir operations. A case study of Cougar Dam in Oregon, U.S. assesses impacts of climate change on a multipurpose flood control dam to characterize the sensitivity of reservoir operational performance to changing hydrology.

CASE STUDY AREA

Cougar Dam is a multipurpose dam and reservoir located on the South Fork of the McKenzie River (SF McKenzie), a tributary to the McKenzie and then

Willamette Rivers in western Oregon, U.S. (Figure 1). The McKenzie River originates on the western slopes of the Cascade Mountains and flows into the Willamette River near Eugene, Oregon. Cougar Dam was completed in 1963 and consists of a 138 m tall rockfill dam with a 25 MW powerhouse (U.S. Army Corps of Engineers, 2009). At full pool, Cougar Reservoir has a storage capacity of 246 Mm^3 of water, approximately one-third of the mean total annual inflow. The project is operated by the Portland District of the U.S. Army Corps of Engineers (USACE) as part of the Willamette System of 13 multipurpose dams (Figure 1) to meet authorized purposes of flood damage reduction, irrigation, power generation, recreation, navigation, and downstream water quality improvements.

The case study region has a Mediterranean climate with a strongly seasonal distribution of precipitation that is influenced by marine airflow from the Pacific Ocean to the west. Most precipitation falls between October and May, and the wettest month (December) averages about 10 times more precipitation than the driest month (July). Annually, about 50-80% of precipitation falls as snow (Mote *et al.,* 2003), and the mix of rain *vs*. snow precipitation is highly dependent on winter temperatures (Nolin and Daly, 2006; Sproles *et al.*, 2013). This climatic regime results in rainstorms and rain-on-snow events in the fall and winter, a gradual, muted snowmelt peak in the spring, and a prolonged recession to low flows during the summer (Tague and Grant, 2009; Safeeq *et al.*, 2013). In the future, temperatures in the Pacific

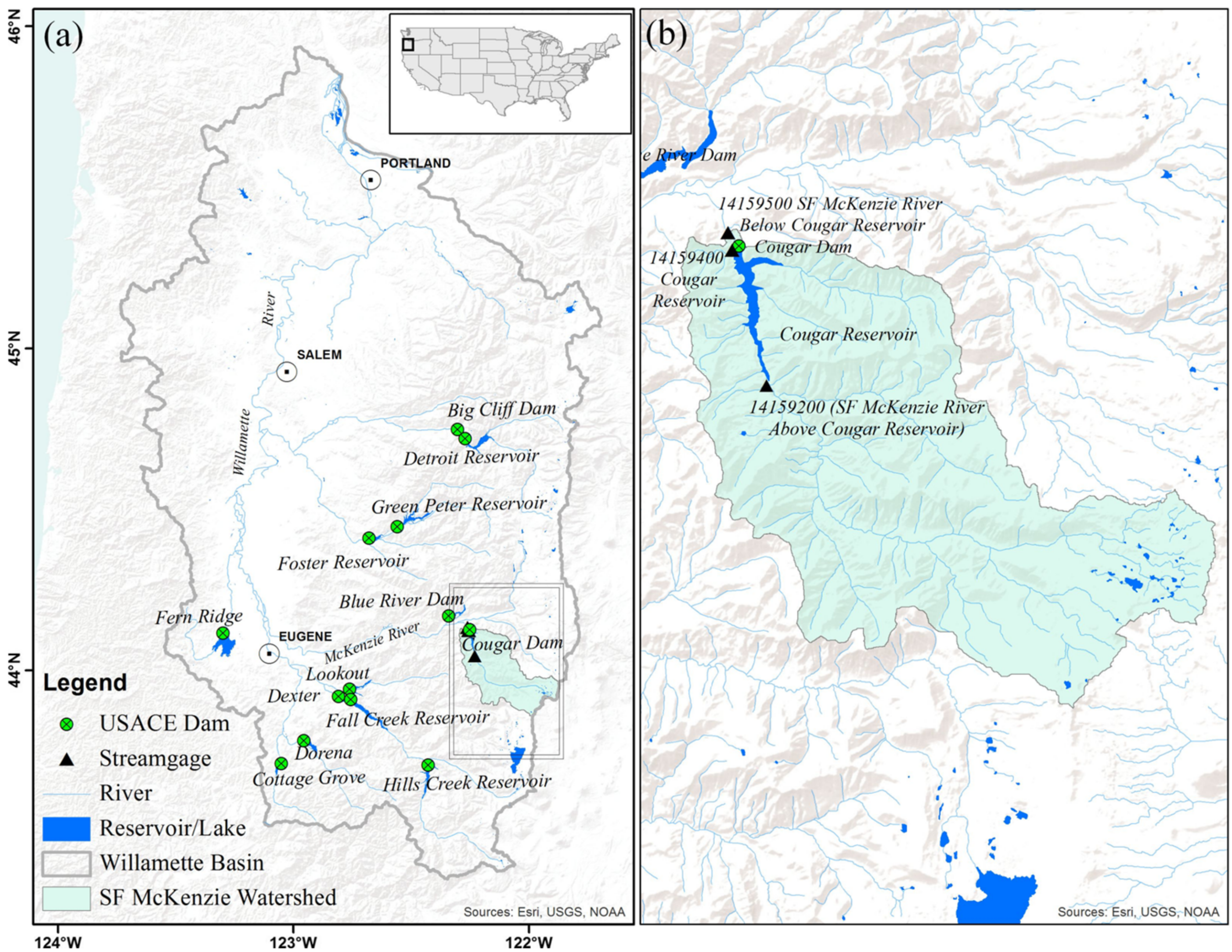

FIGURE 1. Willamette Basin System Dams Operated by the U.S. Army Corps of Engineers (USACE) (a) with Detail of Cougar Dam and Reservoir and U.S. Geological Survey (USGS) Gaging Stations Used to Develop the Historical Dataset Used for Bias Correction and Discussed in the Supporting Information (b).

Northwest are predicted to be warmer and, as a consequence, seasonal distributions of precipitation and streamflow are likely to change (Abatzoglou *et al.*, 2014). Changes in annual precipitation volumes may occur, but the direction and magnitude of these changes are uncertain (Mote and Salathé, 2010; Elsner *et al.,* 2010).

Operation of Cougar Dam is guided by operational policies that have remained essentially unchanged since the project was completed in 1963 (U.S. Army Corps of Engineers, 1964, 2009), except for the implementation of the Willamette Biological Opinion (BiOp) in 2008 (National Marine Fisheries Service, 2008). The reservoir regulation manual contains a set of operational targets and guidelines that are described by a rule curve and additional operating policies (Figure 2). The BiOp added constraints on rates of change of outflows, raised minimum outflow requirements, and added maximum flow targets immediately downstream of Cougar Dam on the SF McKenzie. Cougar Dam operations also contribute to meeting minimum flow and flood control targets at two downstream control points on the mainstem Willamette, along with the other reservoirs in the Willamette system.

Throughout the year, reservoir elevation generally varies between low pool at 467 m above mean sea level (MSL) and high (conservation) pool at 515.1 m above MSL (Figure 2). The rule curve specifies that Low Pool storage should be maintained in December and January, except when the storage volume is being used for flood control. Between February and May, storage is gradually increased as operations transition between winter flood control and summer conservation. During this period, flood control must be balanced with filling of the reservoir. High pool is maintained from May through September, although drawdown may begin earlier than September as a result of releases made to supplement outflows and meet mainstem Willamette flow targets at Albany and Salem (Figure 1). From September through November, water is gradually released to reach low pool for flood storage.

METHODS

Step 1: Develop Future Reservoir Inflows

The method implemented for the case study uses a small set of reservoir inflows to form the basis of a much larger set of projections that is used in both the scenario-based and scenario-neutral analyses. The smaller set of projections may come from a variety of sources, such as historical inflows or hydrologic model results simulated from one or more GCM projections. While we use a single GCM in the case study, it would be valuable to consider using a larger input ensemble to allow for a wider range and variability in possible results.

Case Study: Select, Downscale, Route, and Bias-correct Inflow Projections. For the case study, we used model projections of daily runoff and baseflow from the Columbia Basin Climate Change Scenarios Project (CBCCSP) (Hamlet *et al.*, 2010, 2013) as the basis for the reservoir inflow projections. From the options available in the CBCCSP project database, we selected the Hybrid Delta downscaling method, the A1B emissions scenario, and the CGCM3.1(T47) (CGCM) climate model. CGCM was one of the five GCMs that performed best in the Pacific Northwest (Hamlet *et al.*, 2010). It closely represents the ensemble mean streamflow conditions for the 2020s and is wetter than the ensemble mean for the 2040s and 2080s. Analysis of the 10 GCMs described in Hamlet *et al.* (2010, 2013), indicated that no significant difference exists between the ensemble mean streamflow between the A1B and B1 scenarios for the SF McKenzie basin. Thus, only results from the A1B scenario are presented here (see Supporting Information for further information on climate model and emissions scenario selection).

The hydrologic model results were provided as 91 years of gridded daily simulations for the average observed climate from 1915 to 2006 (historical) and three climate change scenarios representing average conditions for 2010-2039 (2020s), 2030-2059 (2040s), and 2070-2099 (2080s). The future projections had been downscaled with the observed historical climate (Hamlet *et al.*, 2010, 2013) to produce 91 years of daily gridded projections for each future climate scenario.

We routed the gridded projections of daily runoff and baseflow, using the unit hydrograph method (Lohmann *et al.*, 1996) to obtain simulated daily streamflow hydrographs. These hydrographs were bias corrected against calculated observed reservoir inflow, using a monthly quantile mapping technique (Piani *et al.*, 2010). Prior to bias correction, modeled streamflow consistently underestimated actual inflow to the reservoir by approximately 21%. Monthly errors were as high as −74% (August), and the months with the largest errors were July, August, and September. After bias correction, the observed and simulated reservoir inflows differed by +4.8% across all months.

Step 2: Generate Stochastic Inflow Sequences

A large set of inflow sequences is desirable in the scenario-based approach to alleviate some of the

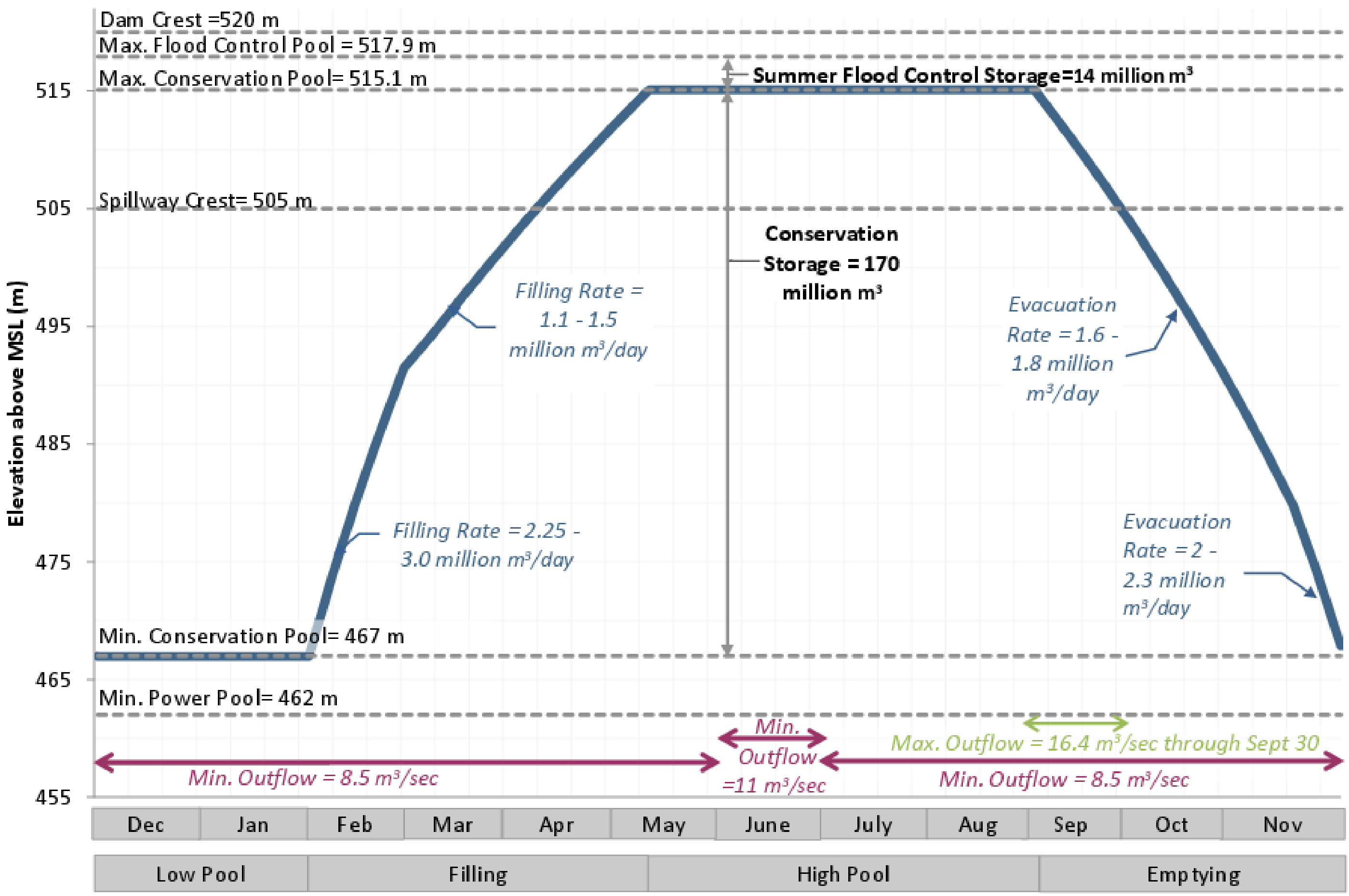

FIGURE 2. The Cougar Water Control Diagram as Implemented in the Reservoir Model. Operations were adapted from the Cougar Reservoir Regulation Manual (U.S. Army Corps of Engineers, 1964) and the Willamette BiOp (National Marine Fisheries Service, 2008). It summarizes operational policies for the reservoir, including the rule curve, minimum and maximum outflow rates, pool elevations above mean sea level (MSL) and storage volumes. Four reservoir seasons were defined for this analysis as Low Pool (November 30-January 31), Filling (February 1-May 7), High Pool (May 8-August 31), and Emptying (September 1-November 29). DOrY was defined for the analysis as Day Of the reservoir Year, starting from the beginning of Low Pool on November 30, with Filling beginning on DOrY 62 (February 1), High Pool beginning on DOrY 163 (May 10), and Emptying beginning on DOrY 277 (September 1), assuming a leap year.

uncertainties in modeled reservoir operations, such as problems with event sequencing and limited projection range. Options for generating additional inflow sequences include stochastic sequences, flow perturbation, and multi-model ensembles. Stochastic techniques allow large numbers of inflow scenarios to be generated from a few hydrologic model simulations, thereby increasing the number of years of data beyond the length of a hydrologic model simulation and introducing additional variability in event sequencing. Perturbing an existing reservoir inflow dataset can also provide additional scenarios beyond those projected by the GCMs, and corresponding operational responses for identifying generalized relationships. Large multi-model ensembles can introduce a greater range of potential future climate scenarios.

In the case study, we utilize a stochastic flow generation technique, described below, to generate a large number (1,000 years) of inflow sequences based on the historical inflow scenario and the future inflow scenarios for the 2020s, 2040s, and 2080s. Then we apply a projection perturbation technique to the future projections to add an additional scenario of future inflow.

Case Study: Generate Stochastic Reservoir Inflow Sequences. To increase the number of years of inflow data and to eliminate biases that can result from wet and dry periods within the historical or GCM records (*e.g.,* Christensen *et al.*, 2004), we stochastically generated 1,000-year sets of reservoir inflows based on each of the CGCM reservoir inflow projections (historical, 2020s, 2040s, and 2080s). The goal was to generate daily flow sequences that were (1) indistinguishable from the base projections in their statistical properties; and (2) includes more variety in annual inflow sequencing than the base projections. We adapted a monthly stochastic method described by Srinivas *et al.* (2001) to produce daily stochastic flows. The method produces a synthetic record of daily reservoir inflows through modeling and removing the mean, seasonality, and correlation in the daily flows, generating synthetic residuals by bootstrapping, and adding back the correlation, seasonality, and mean. We standardized the daily flows by taking their logarithms, and modeling the mean and standard deviation with a loess (local regression smoothing) fit (Cleveland *et al.*, 1991; Ripley, 1998). We pre-whitened the data to remove autocorrelation, using a periodic autoregressive [PAR(1)] model (Jones *et al.*, 1967). After pre-whitening, the PAR(1) residuals were resampled, using a moving block bootstrap method in blocks of one year to create a new series of residuals. The new residuals were then post-blackened to add back the mean and seasonality, resulting in 1,000-year synthetic flow sequences that represent a scenario of reservoir inflows for each time period (historical, 2020s, 2040s, and 2080s).

The stochastic model produced sequences of synthetic reservoir inflows that had approximately the same statistical properties as the base CGCM inflow projections used to develop them. For a verification simulation, there was a 0% difference between annual mean and a −4% difference in annual standard deviation. Monthly errors ranged between −3% and +9% for the mean and between −8% and +16% for the standard deviation.

Case Study: Perturb for Additional Inflow Range. The CGCM model flow under A1B is well within the range of flow predicted by other GCMs and also closely follows the 2020s ensemble mean flow for both the A1B and B1 emissions scenarios. However, for the 2040s and 2080s, CGCM predicts wetter conditions than the ensemble mean (see Supporting Information). To account for this potentially wetter future, we created a "dry spring" scenario that mimics the lower bound of GCM predictions for the 2020s and 2040s and the ensemble mean for the 2080s, as described below.

The perturbed flow scenario was identified as the "dry spring scenario" and the unperturbed CGCM projection was the "wet spring scenario" (Figure 3). Multiplicative factors were chosen to create a scenario in which the increase in future volumes of spring reservoir inflows would be smaller than the increase projected by CGCM while including the timing shift from CGCM. CGCM projects a 49% increase compared to an increase of 10-30% for the Willamette Basin predicted by Jung and Chang (2011) based on eight climate models and two emissions scenarios. We specified a factor of 1/1.3 for March 15th-April 15th so that wet spring (unperturbed) scenario flows would be 30% higher than dry spring (perturbed) flows, and we specified a factor of 1 (no change) between May 15th and February 15th. We used linear interpolation to create gradually changing perturbation factors for each day between February 15th-March 15th and April 15th-May 15th. Spring flow changes are greater for the wet

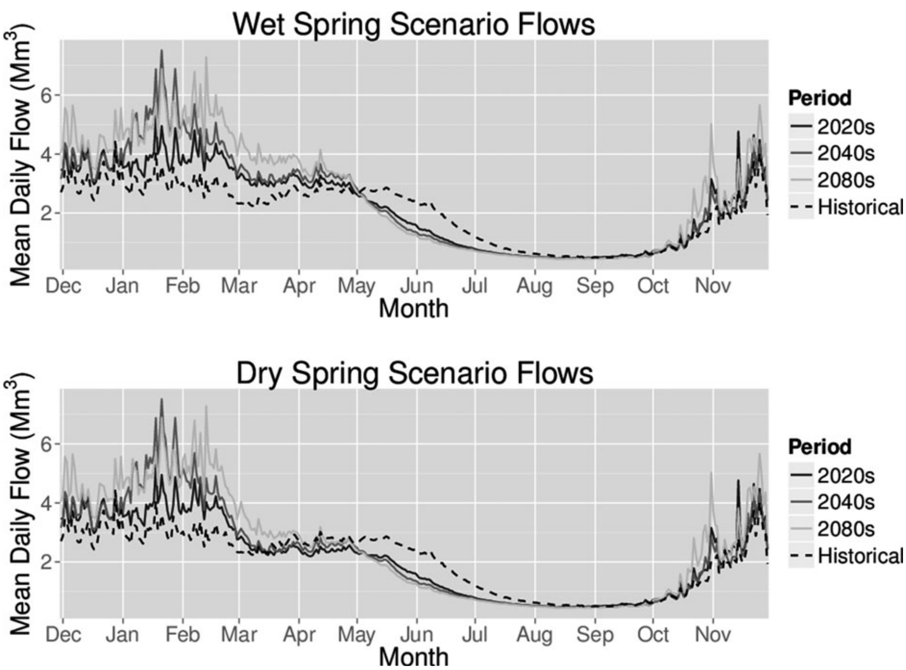

FIGURE 3. Wet Spring and Dry Spring Scenario Inflows (after bias correction) for the 2020s, 2040s, and 2080s with Reference to Historical Inflows. Mean inflows were computed by averaging daily stochastic 1,000-year inflows for each day of reservoir year.

than dry spring scenario. March flows in the wet spring scenario are about 55% larger by 2080 than in the historical record and April flows are 15% higher. In the dry spring scenario, March flows are 23% higher and April flows are 8% lower. Changes in February and May flows are small because the adjustment factors are meant to blend the step change for March and April into the unchanged projections for the rest of the year. Compared with streamflow projections from the other GCMs from the CBCCSP, the dry spring scenario represents the lower bound of ensemble mean streamflow for 2020s and 2040s and the ensemble mean for the 2080s (see Supporting Information).

Step 3: Model Reservoir Operations

Similar to other climate impacts studies, the method applied for this study uses a reservoir operations model to simulate reservoir storage and outflow. In contrast to typical scenario-based studies, simulations are run with the inflow scenarios resulting from a large number of stochastic inflow sequences (*e.g.,* 1,000 years), rather than the shorter inflow sequences resulting directly from a hydrologic model (*e.g.,* 91 years).

Case Study: Develop, Verify, and Simulate a Reservoir Model. For the case study, we developed a reservoir model in the R statistical programming language (R Development Core Team, 2008) that simulated operations at Cougar Reservoir on a daily time step under a range of historical and plausible future reservoir inflows. The model was based on the policies described by the rule curve for Cougar Reservoir as well as other targets and flow requirements in the Cougar Reservoir Regulation Manual (U.S. Army Corps of Engineers, 1964) (Figure 2). The model simulated reservoir operations independently of any other dams in the system, although in reality, the dam is operated in conjunction with other dams in the Willamette system. The minimum and maximum flow requirements from the Willamette BiOp were implemented in the model, although they were not in place in the historical record. We verified the general model behavior by simulating reservoir operations with the 1963-2003 historical inflow time series and comparing to observed operations. As expected based on the assumptions of the model, simulated results sometimes differed from measured operations. For flood control, the model simulations and observations showed similar increases in reservoir storage during periods of high flows, but the model did not fully eliminate outflows above flood stage as in the observed operations. During filling, measured and modeled operations were generally similar, indicating that the simplified model captures the general filling behavior of the reservoir. During conservation operations, the model began drawdown at a similar time to the observations but the number of days that the reservoir spent below the rule curve was almost twice as large in the model as in the observations. These differences due to the simplified representation of the system by the model prevent direct application of the results of this case study to conclusions about the values of particular operational metrics under future climate scenarios. However, the general trends can be used to infer how climate change might affect future operations of Cougar Reservoir, and the model is adequate for demonstrating the analytical approach for combining scenario-based and scenario-neutral analyses. See Supporting Information for further discussion of model verification and measured *vs*. modeled reservoir operations.

Running the reservoir model with the 1,000-year sequences of simulated reservoir inflows for the four time periods (historical, 2020s, 2040s, and 2080s) and two spring scenarios (dry and wet) produced daily reservoir storage volume, storage change, and outflow values.

Step 4: Analyze Using Scenario-Driven and Scenario-Neutral Techniques

The final step in the method is to analyze the reservoir operations results. The analysis is done both separately by scenario and time period as in a typical scenario-based analysis, and also with the scenarios and time periods lumped together for a scenario-neutral analysis.

Case Study: Quantify Reservoir Inflow and Operational Performance with Metrics. For the case study, two reservoir inflow metrics (Q1, total inflow and Q2, timing of the center of mass of total inflow (CT)) (Stewart *et al.*, 2005) described reservoir inflow characteristics and 14 reservoir operations metrics described reservoir operations based on reservoir storage and outflow. The 14 reservoir operation metrics were subdivided into three groups by the operational objective that they measured: flood control (storing and releasing high flows), filling (timing and consistency of filling from low to high pool), and conservation (fulfillment of drawdown and minimum flow objectives). The metrics were calculated on both an annual and seasonal basis (Table 1).

Case Study: Analyze Results Using Scenario-Driven and Scenario-Neutral Approaches. Consistent with scenario-driven impact assessments, projected changes in reservoir inflow and reservoir

TABLE 1. Metrics Used to Quantify Reservoir Inflow and Operations.

Metric	Name	Operational Objective	Description
Q1	Total inflow	Inflow	Sum of inflow (Mm^3)
Q2	CT	Inflow	Timing of the center of mass of total inflow (DOrY)
R1	10% above	Flood	Number of days more than 10% above the rule curve (days)
R2	10% below	Conservation	Number of days more than 10% below the rule curve (days)
R3	Above rule curve (RC)	Flood	Number of days at or above the rule curve (days)
R4	Min. outflow not met	Minimum outflow	Number of days minimum outflows are not met (days)
R5	Mean outflow deficit	Minimum outflow	Mean volume by which minimum outflows are not met (Mm^3)
R6	Consecutive days above RC	Flood	Maximum consecutive days above the rule curve (days)
R7	Max reservoir storage	Flood	Maximum reservoir storage (Mm^3)
R8	Outflow above flood stage	Flood	Number of days outflow is above maximum recommended outflow (days)
R9	Return to RC	Flood	Maximum number of days to return to the rule curve after flood control operations (days)
R10	Fill anomaly	Filling	Number of days before or after the target fill day that the reservoir fills (days)
R11	Storage change not met	Filling	Number of days daily storage changes described by RC are not achieved (days)
Fill %	Fill %	Filling	Percent of years that the reservoir fills
R12	Drawdown anomaly	Conservation	Number of days before or after the target drawdown day that reservoir elevation drops below high pool elevation (days)
R13	Below RC	Conservation	Number of days at or below rule curve (days)
R14	Boat ramp September 1	Conservation	Number of years pool elevation on September 1 is above boat ramp (years)

operations in the future were compared to simulated historical operations. Keeping the reservoir metrics separated by spring scenario (wet, dry) and time period (historical, 2020s, 2040s, 2080s), the absolute and percent changes in the mean of reservoir metrics were calculated by scenario and time period. One-way ANOVA was used to evaluate significant differences between metrics ($p < 0.05$).

For the scenario-neutral impacts assessment, the differences between time periods and scenarios were disregarded and all model results (wet spring, dry spring, historical, 2020s, 2040s, and 2080s) were lumped together. Scatterplots of climate *vs*. reservoir metrics were then generated to explore generalized relationships between reservoir inflow and reservoir performance. Linear regression r^2 values indicated correlation and $p < 0.05$ for the slope coefficient indicated evidence of a trend. Threshold relationships were identified by inspection of the plots.

RESULTS

Case Study: Scenario-Driven Impacts Assessment

Future Changes in Reservoir Inflow Magnitude and Timing. Changes in reservoir inflow magnitude and timing are predicted for the SF McKenzie based on the modeled climate scenarios. Compared to simulated historical inflow, total annual inflow is predicted to increase over the next hundred years by up to 30% ($p < 0.001$, Figure 4a) and the CT may shift earlier by up to 15 days ($p < 0.001$, Figure 4b). Seasonally, total inflow may increase during the Low Pool and Filling seasons, but decrease during the High Pool season. Increases in Low Pool total inflow may be as much as 53%, increases during the Filling season may be as much as 30-49% depending on the spring scenario, and increases during the Emptying season may be as much as 36%. Decreases in High Pool total inflow may be as much as 37-39%. CT may shift up to six to eight days earlier during the Filling season, but is not likely to change considerably in other seasons. Due to the method by which the spring scenarios were constructed, changes in total inflow are predicted to be larger for the wet than for the dry spring scenario both annually and during the Filling season, but there are no significant differences between annual or seasonal CT changes for the wet and dry scenarios.

Flood Control. Comparing the values of flood control metrics over time reveals that flood control storage volume may be used more often in the future (R1, R7, and R9, Figures 5a, 5b, and 5d), and outflows may exceed the recommended maximum outflow more often (R8, Figure 5c). Reservoir storage during the Low Pool season may be above the target volume for Low Pool storage as many as 84% more days (R1), and maximum reservoir storage may increase by as much as 25% (R7). It may take up to 70% more time for the reservoir to return to the rule curve after a flood (R9) and there may be twice as many days per year of higher than recommended outflows (R8).

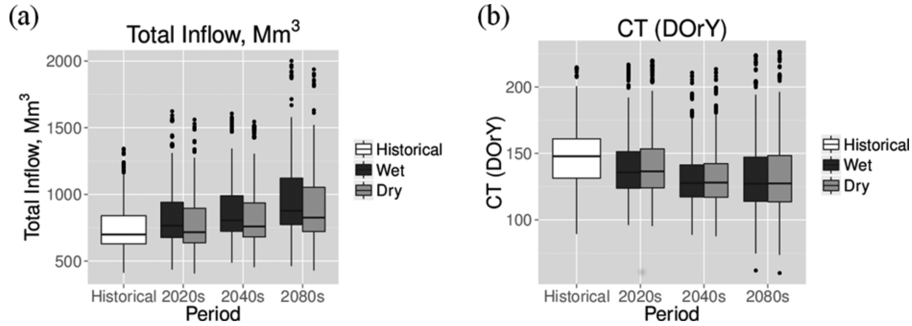

FIGURE 4. Total Annual Inflow (a) Is Projected to Increase and CT (b) Is Expected to Decrease from the Historical Period to Three Future Time Periods (2020s, 2040s, and 2080s) for Both Wet and Dry Spring Scenarios. Metrics were calculated on the 1,000-year stochastic simulated and perturbed inflows.

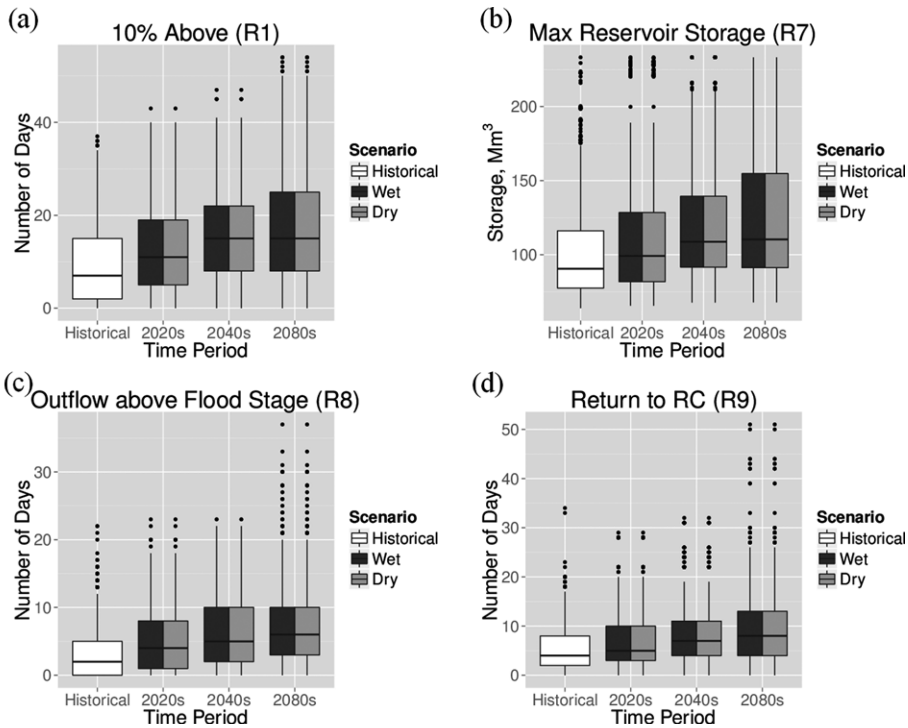

FIGURE 5. Decreasing Flood Control Performance over the Next 100 Years Is Indicated by Increasing Values of Low Pool Reservoir Metrics for Future Time Periods, Including (a) R1, Number of Days More Than 10% above the Rule Curve and (b) R7, Maximum Reservoir Storage (c) R8, the Number of Days Outflow Is Above Flood Stage, and (d) R9, the Maximum Number of Days the Reservoir Takes to Return to the Rule Curve after a Flood. Wet and dry spring scenarios are alike because flows during the Low Pool season were not perturbed. Metrics were calculated on the 1,000-year reservoir model simulations.

Filling. Reservoir filling performance, including whether or not the reservoir fills, the timing of filling, and how consistently filling occurs each day, depends on the type of changes in spring inflows. With simulated historical hydrology, the reservoir fills about 78% of the time, but in the future, this percentage may either increase or decrease (Table 2). In the dry spring scenario, the filling rate drops to 70% in the 2020s, to 69% in the 2040s, and to 66% for the 2080s. In the wet spring scenario, the rate of filling increases to 87% in the 2020s, then decreases to 84% in the 2040s and 82% in the 2080s. In the historical period, filling occurs an average of seven days late relative to the fill target specified by the rule curve (R10, Figure 6a). For the dry spring scenario, the fill anomaly increases from seven days to thirteen days in the 2020s, but then decreases to eight days in the 2040s and to six days in the 2080s. For the wet spring scenario, the fill anomaly first increases to nine days in the 2020s, then decreases to two days in the 2040s, then increases to four days in the 2080s. The direction of change in the number of days that

TABLE 2. Means and Percent Changes from Historical over Three Future Time Periods for Filling Metrics.

					2020s		2040s		2080s	
Metric	Metric Description	Season	Hist. Mean	Scenario	Mean	% Change	Mean	% Change	Mean	% Change
R10	Fill anomaly	Annual	7	Dry	13	81	8	9	6	−16
			7	Wet	9	19	2	−68	4	−51
R11	Number of days daily storage change is not achieved	Filling	62	Dry	65	4	62	1	62	0
			62	Wet	57	−9	56	−10	56	−10
Fill %	Percent of years that the reservoir fills	Annual	78%	Dry	70%	−10	69%	−11	66%	−16
			78%	Wet	87%	11	84%	7	82%	5

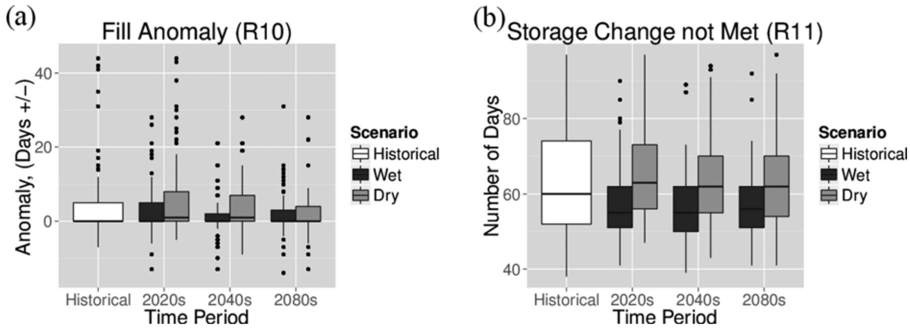

FIGURE 6. Future Changes in Filling Performance Depend on the Spring Scenario. Both scenarios have smaller values of metric R10, the fill anomaly, by the 2080s, but the pattern of change differs between the wet spring and dry spring scenarios (a). The direction of change in metric R11, Filling season number of days daily storage changes are not achieved, is sensitive to the spring scenario, either increasing or decreasing (b) depending on the scenario. Metrics were calculated on the 1,000-year reservoir model simulations.

daily storage changes are not met also depends on the reservoir inflow scenario (R11, Figure 6b). For the wet spring scenario, daily storage changes are met more often than in the historical period. However, for the dry spring scenario, they are met about the same number of days.

Conservation. For conservation metrics, the model results indicate that there will be negative impacts to both reservoir drawdown timing and minimum outflows. Under future climate change, there is likely to be earlier initiation of reservoir drawdown (R12, Figure 7a) resulting in increases in the number of days that the reservoir is below the rule curve (R13, Figure 7b). The start of reservoir drawdown shifts earlier in both wet and dry spring scenarios, from the historical anomaly of 35 days early to between 50 and 70 days early in the future. The number of days that minimum outflows are met is not likely to change (R4, Figure 7c), but there is evidence of a difference in mean outflow deficit volume (R5, Figure 7d). The direction of the change depends on the scenario.

Case Study: Scenario-Neutral Impacts Assessment

Using the scenario-neutral assessment methodology, we examined general climatic thresholds and trends for performance. Flood control metrics are strongly correlated with Low Pool inflow, with r^2 values between 0.49 and 0.87 (Table 3). The strongest correlation is between total low pool inflow and the number of days outflow is above flood stage (R8, Figure 8a). For Filling performance, there is a threshold effect of inflow over the total Filling season. Above a value of approximately 500 Mm^3 there are no years when the reservoir does not fill (Figure 8b). Between a threshold of 300-400 Mm^3, the fill anomaly reaches zero. The number of days that storage change is not achieved appears to level out to a value of approximately 50 days around 400 Mm^3. There also appears to be a varying threshold relationship between total inflow and the number of days that minimum outflows are not met (R4, Figure 8c). When total inflow is 1,200 Mm^3 or more, the number of days on which minimum outflows are not met is never more than four days. When total inflow is between 600 and 1,200 Mm^3, there may be as many as 13 days on which minimum outflows are not met; and there appears to be a threshold for total inflow at around 500 Mm^3 or less that in some cases leads to more than 30 days on which minimum outflows are not met. Late summer conservation performance is related to total inflow during the High Pool season. Drawdown begins earlier in years with lower high pool inflow (r^2 = 0.45). There is a threshold for late summer conservation

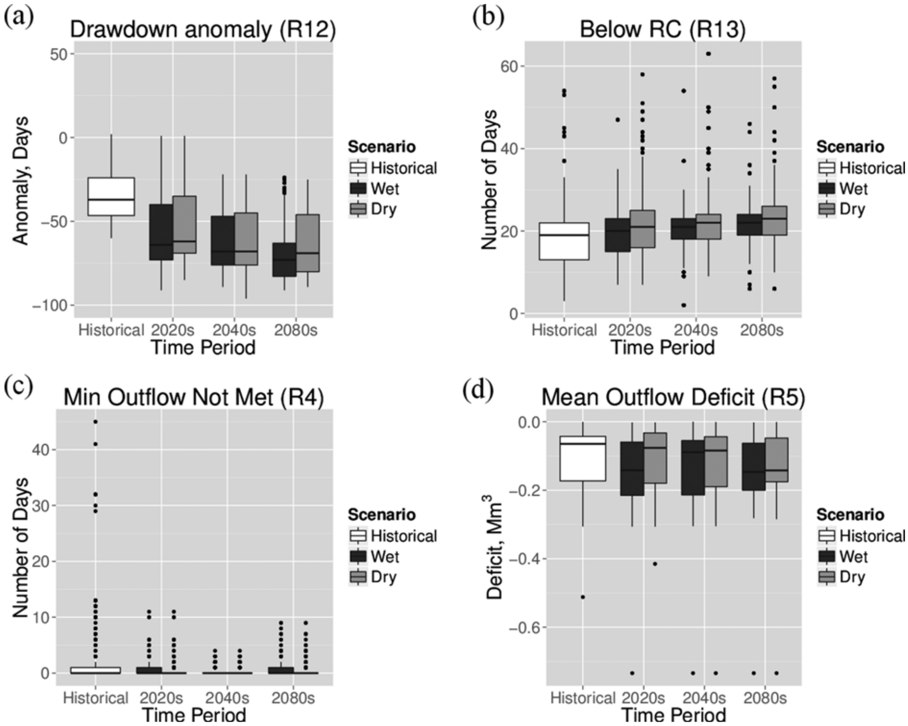

FIGURE 7. Conservation Performance Is Likely to Decrease over the Next 100 Years, with (a) Earlier Drawdown, R12, (b) and Larger Number of Days at or Below the Rule Curve during the Emptying Season (R13), and (d) Larger Annual Mean Outflow Deficit (R5). There is little evidence of a change in the number of days that minimum outflows are not met (R4, c). Metrics were calculated on the 1,000-year reservoir model simulations.

performance at 100 Mm^3 of High Pool inflow. The number of days at or below the rule curve (R13, Figure 8d) and the number of days more than 10% below the rule curve level off above 100 Mm^3, a value high enough to maintain access to the boat ramps. In general, there are linear relationships for flood control metrics and threshold relationships for filling and conservation metrics.

DISCUSSION

The case study results indicate that reservoir operations are likely to be affected by changing hydrology. There is a strong linear relationship between total inflow and flood control performance. Thus, increasing inflow during the Low Pool season may result in greater use of the reservoir for flood storage (R1, R7) and more frequent high flows downstream of the dam (R8). More frequent use of the reservoir for flood control in future modeled scenarios is not problematic in and of itself. However, coupled with the fact that returning the reservoir to Low Pool storage (R9) is projected to take longer in the future, such trends indicate that operators may have less flexibility to store incoming high flows if higher inflows require the reservoir to be partially filled more frequently than in the historical climate.

The differences in filling performance between the dry and wet spring scenarios, along with the generalized relationships between filling metrics and inflow, indicate that understanding of future filling performance is hindered by uncertainty in spring inflow. Spring inflow magnitude and timing influence whether and when the reservoir fills, but the uncertainty in how those changes will manifest and the sensitivity of filling operations to spring inflows make it difficult to forecast future filling performance. Historically, the high percentage of days that the daily storage change is not achieved (R11) suggests that there are many days when inflow has not been sufficient to fill the reservoir at the rate described by the rule curve. Thus, spring flood flows or flows late in the Filling season may be important for filling. We attribute the variation in fill anomaly (R10) between time periods to the alignment of inflow timing with the rule curve. If the projected increases in winter flows extend into the spring, then filling may occur more often and closer to the target fill date. Conversely, if snowmelt occurs earlier and there is limited spring rainfall to offset the earlier snowmelt timing, the reservoir may fill less often and later.

TABLE 3. Relationships between Inflow and Reservoir Metrics.

Metric	Metric Type	Metric Name	Relationship with Inflow	r^2
R1	Flood	10% above	Linear relationship	0.77
R2	Conservation	10% below	Threshold at ~100 Mm^3 total High Pool inflow	–
R3	Flood	Above RC	Linear relationship	0.67
R4	Conservation	Minimum outflows not met	Varying threshold	–
R5	Conservation	Mean outflow deficit	–	–
R6	Flood	Consecutive days above RC	Linear relationship	0.49
R7	Flood	Max reservoir storage	Linear relationship	0.7
R8	Flood	Outflow above flood stage	Linear relationship	0.87
R9	Flood	Return to RC	Linear relationship	0.58
R10	Filling	Fill anomaly	Threshold at ~300-400 Mm^3 total annual inflow	–
R11	Filling	Storage change not achieved	Threshold at 400 Mm^3 total annual inflow	–
R12	Conservation	Drawdown anomaly	Linear relationship	0.39
R13	Conservation	Below RC	Threshold at 100 Mm^3 total High Pool inflow	–
R14	Conservation	September 1	Threshold at 100 Mm^3 total High Pool inflow	–

r^2 values are listed for describing the strength of the linear relationships with inflows.

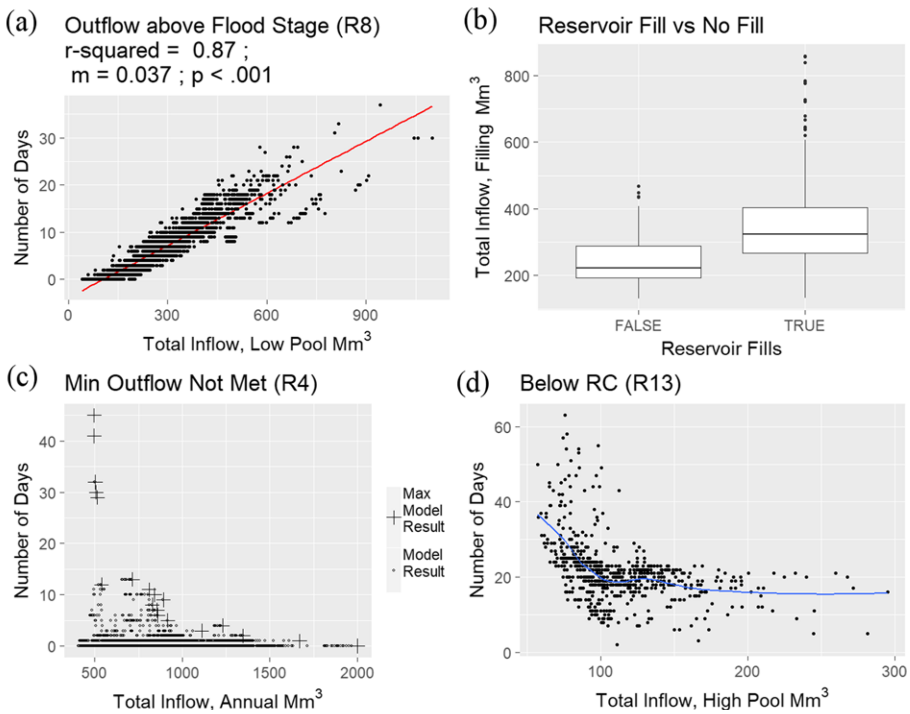

FIGURE 8. Generalized Relationships between Inflow and Reservoir Metrics. (a) Linear relationships like the increasing trend between Low Pool inflow and R8, the number of days above flood stage, are typical of flood control metrics. (b) Threshold relationships at 400 Mm^3 of inflow are typical of filling metrics. Conservation metrics have a variety of relationships types. They may (c) have a varying threshold like the relationship for R4, the number of days minimum outflows were not met or (d) may have a constant threshold relationships at approximately 100 Mm^3 of High Pool inflow like R13, the number of days at or below the rule curve, or they may have a linear relationship. In (c), cross symbols (+) approximate the inflow threshold for meeting minimum outflows on a specific number of days each year and dots are other data points.

Based on the scenario-neutral analysis, a threshold spring inflow volume of 500 Mm^3 is required to fill the reservoir. As the higher future filling percentage from the wet spring scenario indicates, the CGCM climate projection supports a conclusion that filling will occur more often in the future. However, before relying on this conclusion of higher fill percentages in the future, it will be important to consider other future reservoir inflow projections for this basin.

Similar to findings by Payne *et al.* (2004), conservation operations are likely to be negatively affected by climate change due to the dependence of conservation storage and drawdown on total High Pool inflow, and daily inflow volume, which are projected to decrease. The number of days when minimum outflows are not met (R4) is not likely to change, but the magnitude of the deficit (R5) may increase, likely due to the connection between outflow deficit and inflow volume. Drawdown may occur earlier (R12) and more days may be spent below the rule curve (R13), again because of lower High Pool flow volume. Early drawdown is not necessarily problematic, except when it conflicts with late summer regulation of water quality or recreation, which can have important economic impacts (Moore, 2015). Furthermore, the impacts of early drawdown due to climate change may be exacerbated by system-wide objectives, such as mainstem minimum flow targets for water quality or recreation purposes that may need to be met earlier than minimum flow targets on the South Fork McKenzie that are only met by Cougar.

Broader Applicability

The broader applicability of this approach to other dams is related to the analytical approach, the performance metrics and their relationships to inflow, and the case study results. Analytically, the combined scenario-based and scenario-neutral approach to evaluating climate impacts could be transferred to other reservoir systems. Examining climate impacts in the context of specific climate scenarios provides information about the types and timing of future changes in performance while the scenario-neutral analysis produces a set of relationships between climatic or hydrologic changes and operational performance that can be applied beyond the specific climate scenarios used in the analysis. The types of metrics used here could also be adapted for other reservoir systems, either directly for other multipurpose flood control systems, or indirectly for systems focused on water supply, recreation, navigation, or environmental purposes. The seasonal approach to quantifying reservoir operations, which allows examination of how changes in inflows during specific portions of the year may affect operational performance, could also be applied to other systems.

Cougar Reservoir represents a class of large multipurpose dams found throughout the western U.S. and beyond that are operated for both flood control (winter) and flow augmentation (summer). More broadly, Cougar Reservoir represents the widespread, engineering approach to ameliorating streamflow extremes in a Mediterranean climate where precipitation is out of phase with water demand (too much in winter, too little in summer). Qualitatively, the key findings (*i.e.,* climatic-operational relationships) from Cougar Reservoir should apply to the many other reservoirs throughout the western U.S. with similar objectives and operations.

Potential Adaptation Responses

Based on the modeled changes in reservoir inflow and the projected changes in operational performance, the operational policies of Cougar Dam may need to be modified in the future and the changes will likely require tradeoffs among operational objectives. The greatest challenges for adaptation are likely to involve conflicts between filling and flood control and between recreation and downstream conservation uses. If operational policies remain the same and Filling season inflows increase, the reservoir may fill more often (82% of the time for the wet scenario in the 2080s compared to 78% of the time in the historical period). However, there also may be greater chances of a flood occurring when the reservoir does not have enough available storage volume to fully reduce outflows. During the Filling season, the number of days that the reservoir is above the rule curve is projected to increase by as much as 13 days by the 2080s compared to the historical period. The number of days above flood stage may increase from one day in the historical period to five days in the 2080s. This may motivate more conservative filling practices, such as keeping the reservoir at low pool longer and shifting filling later. However, the likely shift to earlier reservoir inflow timing and less snowmelt, coupled with a later filling period, could result in lower frequency of filling the reservoir. In contrast, if springs are drier than they have historically been, the reservoir may fill less often. The dry spring scenario fill rate drops to 66% by the 2080s *vs.* 78% in the historical period. A potential policy change could shift the rule curve so that filling starts earlier to take advantage of late winter storms. However, this change in operations could also conflict with flood control operations (Payne *et al.*, 2004). The storms that would be used to fill the reservoir could also lead to higher flows downstream if they cannot be fully controlled when storage volume is limited by earlier filling.

In late summer, recreation may be the most impacted conservation objective. Maintaining minimum flows downstream for environmental and water quality reasons will likely continue to take precedence over recreation in the future. The results suggest that the historical level of performance for meeting minimum outflows can be maintained under climate change scenarios due to reservoir storage, but the resulting reservoir drawdown will occur approximately 35 days earlier by the 2080s. This will likely result in more limited recreation opportunities in late summer. A change to operating policies is unlikely to be implemented to resolve this tradeoff. The current minimum outflows were established by the 2008 Willamette BiOp, which requires a variety of measures for the protection of threatened salmon species in the Willamette Basin (National Marine Fisheries Service, 2008). A possible policy change could redefine the drawdown target date and rate to more closely match past observations and future projections (*e.g.,* move the target drawdown date from September 1st to late July and draw down at a more gradual rate). However, this change would only redefine performance, and would not have any tangible effect on operations. Demand reductions such as those explored by Christensen *et al.* (2004) and VanRheenen *et al.* (2004) are also unlikely to affect performance of Cougar Dam, due to the limited priority of water supply in the operations relative to flood control and in-stream flow targets. Alternatively, operating the reservoirs by applying variable rule curves could improve performance by modifying the target operational trajectory based on hydrologic and basin conditions (Maher, 2011).

Future Work

Climate projections other than the CGCM projection used in this study may produce somewhat different future operational performance, motivating the use of the generalized relationships between reservoir inflow and reservoir performance. Reservoir inflow magnitude changes could be larger or smaller in other climate projections, and timing shifts may be more or less drastic. For Cougar Dam, based on the linear relationships between total inflow and flood control performance, if winter runoff increases by 30%, as shown by Jung and Chang (2011) from an average historical value of 200 Mm^3 to a future value of 260 Mm^3, the number of days that outflows will be above flood stage is likely to increase from approximately four to seven. The generalized linear and threshold relationships we have developed would need further verification for application to reservoir planning, but they can provide estimates of future operations and sensitivity to a wide range of reservoir inflow changes.

CONCLUSIONS

Scenario-driven and scenario-neutral approaches can be successfully combined for assessing climate change impacts. They are complementary approaches for examining future reservoir operations, and can be applied concurrently to address the limitations of each.

The scenario-driven approach is particularly valuable in determining when performance may drop below a tolerable value, indicating that policy or expectations may need to change. For example, in the case of Cougar Dam, if basin stakeholders cannot tolerate more than five days per year above flood stage (R8), then changes will have to be made in the 2020s. If the tolerance can be extended to seven days per year above flood stage, changes will not have to occur until the 2040s.

The scenario-neutral approach provides improved understanding of thresholds of performance and the factors that could influence operator ability to meet operation objectives, providing inputs to risk-based decision making (Brekke *et al.*, 2009; Prudhomme *et al.*, 2010; Brown *et al.*, 2012). As demonstrated in the case study, threshold effects identified with the scenario-neutral analysis for inflow can be used to estimate potential performance under a wider range of climate scenarios, even without additional extensive modeling.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: A comparison of A1B and B1 emissions scenarios, a description of historical observed operational performance, and a comparison of measured and modeled historical operations.

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