

Reliability, Sensitivity, and Vulnerability of Reservoir Operations under Climate Change

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Abstract: Climate change may critically impair the performance of reservoirs in meeting operational objectives, but reservoirs may also aid in adapting to climate change. To understand how the reliabilities, sensitivities, and vulnerabilities of reservoir operations vary across hydrogeologic settings, a bottom-up approach was applied to investigate the reliability of two water resources systems in the future. To represent the uncertainty associated with future streamflow, global climate model projections were integrated with a formal Bayesian uncertainty analysis and groundwater–surface water hydrologic modeling. Finally, the effectiveness of variable rule curves for mitigating the effects of climate change was evaluated. Increasing air temperature appeared to reduce the reliability of meeting summer environmental flow targets in the future by 42 and 12% for the groundwater basin and surface water basin, respectively, but had negligible impacts on reservoir refilling and flood regulation. Variable rule curves mitigated the impact of climate change on summer flow target reliability without compromising flood risk reduction. Differences in subbasin sensitivity to changing climate were evident across the two hydrogeologic settings, and uncertainty associated with modeling groundwater resources and decision thresholds were identified, with implications for reliability assessments in other basins. DOI: [10.1061/\(ASCE\)WR.1943-5452.0000742](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000742). © 2016 American Society of Civil Engineers.

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Introduction

Reservoir operators may need to adapt operations to address hydrologic nonstationarity and uncertainty that are caused in part by a changing climate (Vonk et al. 2014; Watts et al. 2011). Increased temperatures projected for the Pacific Northwest (PNW) (Mote et al. 2005) are expected to reduce snowpack, shift spring snowmelt to earlier in the year, increase winter flooding, and reduce summer flows (Okkonen and Kløve 2011; Tague and Grant 2004, 2009). These hydrologic changes may contribute to the failure of reservoirs to meet operational objectives. For example, reductions in summer low flows projected for the PNW (Mote et al. 2005) may increase competition for water supplies (IPCC 2007), increasing competition between releases for hydropower production at the beginning of the summer, reservoir storage to secure releases for environmental flow targets at the end of the summer (Payne et al. 2004), and storage requirements for recreation purposes (Herrera et al. 2014). Wetter and shorter winters may result from the transition from snow to rain, potentially increasing flood risk (Payne et al. 2004; Vonk et al. 2014; Watts et al. 2011) and leading to larger flood storage requirements (Brekke et al. 2009). Reduced snowpack can lead to earlier and reduced spring runoff (Safeeq et al. 2013; Tague and Grant 2004), which may affect the reliability and timing of spring refill and decrease water supply and deliveries

to water users (Anderson et al. 2008; Brekke et al. 2009). In addition, earlier spring runoff may prompt operators to refill reservoirs earlier to ensure adequate storage for summer water supply, although early refill can reduce flood storage capacity and potentially increase spring flood risk. Although these tradeoffs already exist between reservoir priorities, the projected changes in climate and runoff patterns may exacerbate the frequency of and degree to which conflicts arise.

However, the frequency and degree of conflict between competing priorities is likely to vary between basins because hydrogeology may make some basins more responsive to climate change than others (Vano et al. 2015). Basins with permeable layers that allow the subsurface storage and discharge of precipitation exhibit smaller winter peak flows and higher summer baseflows, relative to less pervious systems dominated by surface water runoff (Conlon et al. 2005; Safeeq et al. 2013; Tague and Grant 2004). Although groundwater-driven basins tend to maintain higher and more consistent baseflows compared with surface water-dominated basins, they can also experience greater reductions in streamflow in response to changing precipitation and temperature (Safeeq et al. 2013; Tague and Grant 2009). Therefore, hydrogeology plays an important role in the sensitivity of a basin to a changing climate, and thus on reservoir systems response to climate variability. In addition to subsurface geology, the degree that subsurface storage contributes to streamflows is related to the depth, timing, and spatial distribution of precipitation, land use and land cover, and snow cover thickness and snowmelt characteristics (Kløve et al. 2014). For example, in systems in which snowmelt is not a major component of the streamflow, warmer winter temperatures can diminish ground frost, resulting in greater infiltration and higher subsurface storage (Kløve et al. 2014). However, in snow-dependent systems, warmer winters can trigger snowmelt and earlier runoff, thus increasing groundwater levels during the winter period and decreasing groundwater levels during the spring and summer periods (Okkonen and Kløve 2010).

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Modifying reservoir operations offers an important opportunity for mitigating hydrologic responses to climate change. Currently, objectives for reservoir operations generally remain structured as a static set of rules, henceforth called historical rule curves (HRC), that control reservoir releases on the basis of historical streamflow records, design storage capacity, and assessments of natural variability (Vogel et al. 2007). These rules work well under the conditions represented by the historical streamflows but can fail when unpredictable changes in runoff, including both droughts and floods, occur (Moy et al. 1986). Modifying reservoir operations can be an effective strategy for reducing the impact of changes in water supply (Vonk et al. 2014), contributing to increased resilience of water management systems and ecosystem restoration (Watts et al. 2011). Options for modifying reservoir operations include implementing variable rule curves (VRC) based on earlier (Payne et al. 2004) or later reservoir refill and/or drawdown schedules, modifying reservoir storage allocations (Ward et al. 2013), and varying decision rules seasonally in wet and dry years (Vonk et al. 2014). However, the effectiveness of changes in reservoir operations is expected to vary with hydrogeology.

This study investigates the impacts of climate change on the reliability of reservoirs to meet operational targets and the tradeoffs of modifying reservoir operations. Historical and future streamflows were analyzed, taking into account the uncertainty associated with hydrologic modeling, and reservoir operational reliability between two reservoir systems with different hydrogeology and runoff patterns was compared. Global climate model (GCM) results were coupled with a groundwater–surface water (GW-SW) model and formal uncertainty analysis to assess if and how changes in the timing and quantity of water resources and in reservoir operations affect the reliability of reservoir systems. This study evaluates (1) how well climate information is able to capture historical conditions that push the reservoir system to a vulnerable state; (2) the effectiveness of implementing variable rule curves as an alternate reservoir operation strategy to mitigate the effect of climate change; and (3) the tradeoffs between reservoir priorities under climate change and variable rule curves.

Methods

Study Area

This study is conducted along and downstream of two tributaries to the Santiam River Basin (SRB), which can be discretized into three primary hydrogeologic settings (Fig. 1): (1) groundwater (GW) snow precipitation (High Cascades) located at 1,200 m or higher; (2) surface water (SW) rain and snow precipitation (Western Cascades) located between 400 and 1,200 m; and (3) mixed SW-GW rain precipitation (alluvial areas) located at 400 m or lower (Jefferson et al. 2008; Tague and Grant 2004). The South Santiam Basin (SSB) is entirely sourced by the Western Cascades (WC) geology, with steep drainage network, relatively impermeable rock, and rapid subsurface flow. The North Santiam Basin (NSB) is sourced by the High Cascades (HC), representing higher elevations and lower relief than the WC, and deep groundwater and spring-dominated drainage (Tague and Grant 2009). Relative to the HC, the WC drain more rapidly (Safeeq et al. 2013; Tague and Grant 2004), resulting in higher winter peaks and lower summer baseflows in the SSB than the NSB. In contrast, NSB streams are less flashy, with more uniform flow throughout the year because of substantial groundwater contribution during summer low flows and muted and delayed timing of response to winter recharge (Jefferson et al. 2008; Tague and Grant 2004).

The analysis focused on the Detroit/Big Cliff reservoir system in the NSB and the Green Peter/Foster reservoir system in the SSB. Both reservoir systems are part of a system of 13 multipurpose dams and reservoirs in the Willamette River Basin operated by the U.S. Army Corps of Engineers (USACE). The primary operating objective for these multipurpose reservoirs is flood risk reduction, which are jointly operated to maintain water elevations at downstream control points (e.g., Salem) below bankfull. For example, when elevations at high-priority control points downstream are approaching bankfull stage, operators reduce releases from the NSB dams before reducing releases from dams in the SSB, resulting in differences in downstream flood stages in individual basins while satisfying flood stage at the control point (USACE 1953, 1968). Additionally, as secondary purposes, the reservoirs produce hydropower and supply water for irrigation, municipal and industrial, recreation, and water quality purposes (Risley et al. 2012).

Detroit Reservoir (Fig. 1) is operated primarily for flood control with a storage capacity of 561 Mm³ and 100 MW of installed capacity. This reservoir also has a high demand for recreation, which results in operators maintaining the pool as high as possible through the first week of September for Labor Day and rarely drafting the reservoir for flow augmentation in the summer (USACE 1953). Big Cliff Reservoir, with a storage capacity of 8 Mm³ and 18 MW of installed hydropower capacity, is a re-regulating reservoir, which reduces streamflow variability associated with peak power releases from Detroit Dam. Green Peter and Foster reservoirs have a storage capacity of 528 and 75 Mm³, respectively, and hydropower generation potential of 80 and 20 MW, respectively (USACE 1968). Foster Dam is also a re-regulating project, which regulates releases from Green Peter Dam to provide a more uniform streamflow in the SSB.

Study Approach

The vulnerability, reliability, and sensitivity of both basins were analyzed under eight GCM projections and two reservoir operational scenarios: HRC and VRC. The bottom-up decision-scaling framework (Brown et al. 2012) was applied to explore reservoir system vulnerabilities, with vulnerability defined as the probability of operational failure as opposed to the magnitude of operational failure (Hashimoto et al. 1982). Operational failure was defined by thresholds consistent with the bottom-up decision-scaling framework. Bottom-up decision scaling analyses use historical records and stakeholder input to first identify the decision thresholds that lead to unacceptable impacts and then applies GCM projections to identify the likelihood of the system being pushed beyond those thresholds into a vulnerable state (Brown et al. 2012). Top-down approaches use GCMs to generate a range of future climate scenarios, the outputs of which are used to estimate operational impacts, which are then presented to stakeholders for decision making, with the GCM scenarios driving the vulnerability assessment (Wilby and Dessai 2010). The two approaches most fundamentally vary in what drives the assessments. In the bottom-up decision-scaling approach, the assessments are driven by the relevance of climate to decision pathways, whereas assessments with the top-down approach are driven by GCM scenarios, which are subject to large uncertainties.

The study also analyzed system reliability and sensitivity. Operational reliability was defined as the frequency of the reservoirs meeting minimum summer flow, flood regulation, and refill targets (Hashimoto et al. 1982). Reliability thresholds, subsequently described in more detail, were established to identify when a system was in a vulnerable state, assessed as a condition of being below an acceptable performance threshold. The sensitivity of the two basins

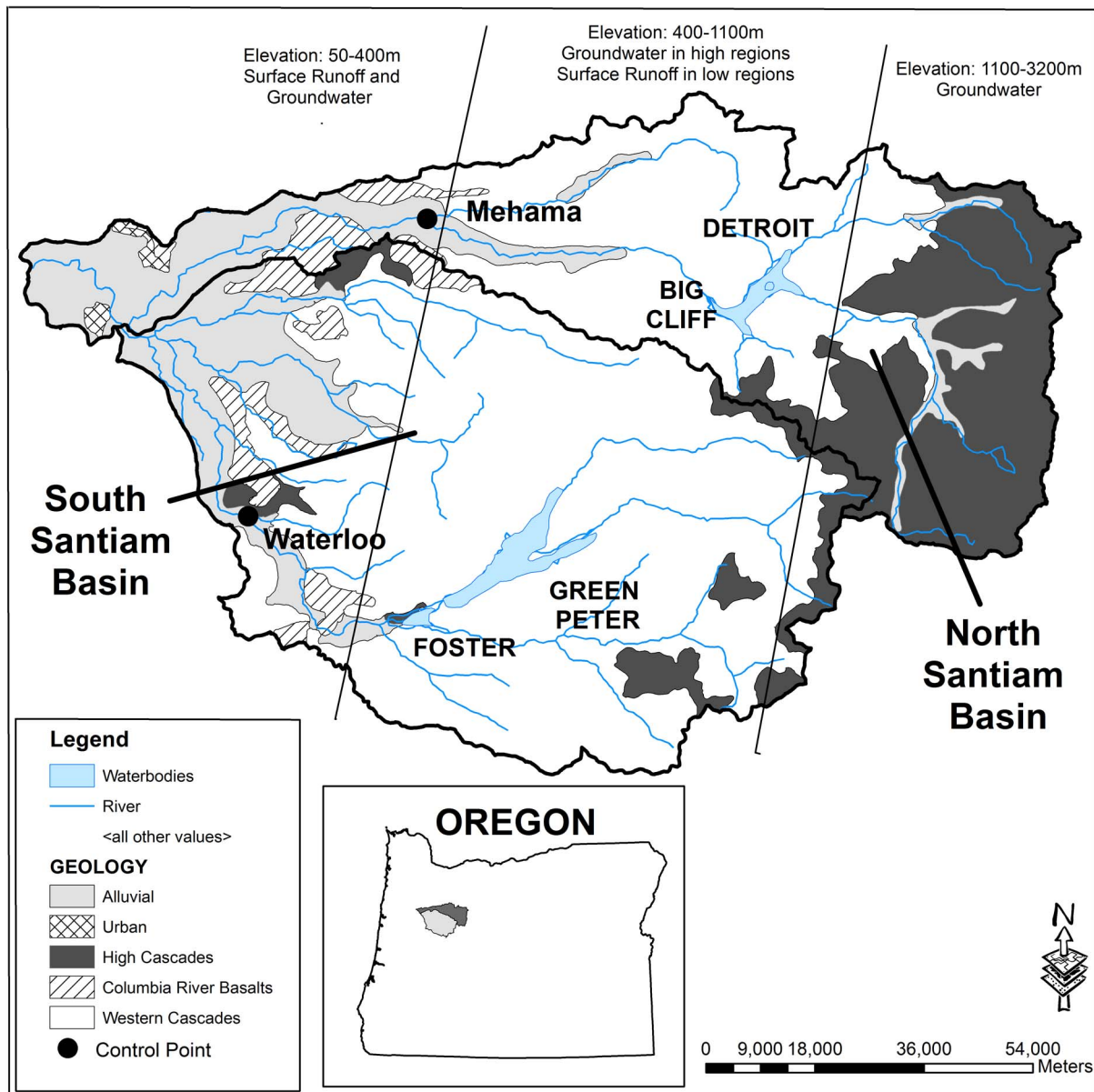


Fig. 1. Santiam River Basin hydrogeology and water resources infrastructure (reprinted from Mateus et al. 2015, © 2014 American Water Resources Association)

to changes in runoff and reservoir operations was assessed according to the degree of change in reliabilities under different climatic and operational conditions. Rather than a quantitative analysis of percent change in response to changes in input variables, the sensitivity of a basin to hydrologic changes was evaluated as the relative degree of change between the two basins.

Data Sources for Historical and Future Hydrology

Hydrologic data were analyzed as three periods: (1) historical period from 1960 to 2000 under observed historical (OH) and simulated historical (SH) records; (2) near future (NF) period from 2030 to 2060; and (3) far future (FF) period from 2070 to 2100. The OH records were obtained from the USGS National Water Information System (USGS 2013) and the Oregon Department of Water Resources surface data for Oregon (OWRD 2014). For the SH records, streamflow projections for the SRB (Surfleet and Tullos 2013) were derived from GSFLOW simulations, a hydrologic model that combines the modular groundwater flow (MODFLOW) model

(Harbaugh 2005) and the precipitation-runoff modeling system (PRMS) to simulate surface water flow (Leavesley et al. 1983).

Future runoff was modeled in GSFLOW by using temperature and precipitation projections from eight GCMs. The A1B greenhouse gas (GHG) emission scenario projections from these eight GCMs were bias corrected and spatially downscaled by using the method of Wood et al. (2002) to provide meteorological inputs to the GSFLOW modeling on a daily time step at 1/16-degree-resolution grid points. The key advantage of this downscaling method is that, in addition to preserving the time series behavior and spatial correlations from the gridded temperature and precipitation observations, it transforms the entire probability distribution of the observations at monthly time scales on the basis of the bias-corrected GCM simulation (Hamlet et al. 2010).

To implement a parsimonious model and reduce the substantial simulation times, the groundwater model (MODFLOW) was only applied in the basins located in the HC geology and alluvial geology (Fig. 1), where substantial groundwater interactions occur.

Assuming that the groundwater remains in deep storage or discharges in the WC unit, and thus that the contribution to the WC streamflow is small, subsurface flows were not conveyed to surface flow downstream from the HC, where only the surface water model was simulated. Although the assumption of limited contribution of groundwater to streamflow is consistent with current understanding of the groundwater hydrology (Conlon et al. 2005), the model configuration may have resulted in an unknown underestimation of baseflow in the WC. Whereas the entire basin was calibrated to historical streamflow, alluvial areas in the lower reaches of the SRB were calibrated to both streamflow and well observations. The groundwater elevations from three wells located in the alluvial areas were used as boundary conditions in MODFLOW, but no well observations were available in the WC or HC.

To represent the uncertainty in hydrologic projections associated with model parameterization, Surfleet and Tullios (2013) applied the differential evolution adaptive metropolis (DREAM) approach to develop posterior parameter distributions of 13 hydrologic parameters. DREAM is a formal Bayesian parameter uncertainty analysis that applies the Markov-chain Monte Carlo-sampling algorithm to estimate the posterior probability density function of parameters (Vrugt et al. 2009). Ten of the parameters were used to calculate soil water transport and exchange of soil water between groundwater and surface runoff. The remaining parameters were monthly rain and snow adjustments and maximum and minimum air temperature lapse rates. The rain, snow, and air temperature lapse adjustments also represented corrections to the downscaled precipitation and air temperatures from GCMs. The distributions for the 13 parameters were estimated across hydrologic response units (HRUs), with a priori distributions for each parameter in each HRU developed in previous modeling efforts (Chang and Jung 2010). The separation of behavioral solutions from nonbehavioral solutions in DREAM uses a cutoff threshold, which is based on the sampled probability mass that is defined by the underlying probability distribution (Vrugt et al. 2009). The posterior distribution of the model parameters were developed for both dry summer and wet winter seasons for three subbasins that represent the three hydrogeologic regions for the SRB: the rain-dominated areas of the alluvial zone, the rain- and snow-dominated areas of the WC, and the snow-dominated areas for the HC. Posterior distribution from these three subbasins were extrapolated to the remaining subbasins of the SRB according to similar hydrogeologic characteristics, elevation, and precipitation patterns. The 2.5, 50, and 97.5 percentile values of daily streamflow were selected from the distribution with the best fit to the historical data for each GCM. These 2.5, 50, and 97.5 percentile values were used as inputs to a reservoir operations model to generate reservoir elevations and downstream discharges for each period.

The daily OH streamflow records were used for both model development and model verification. Nash-Sutcliffe efficiencies (NSE) of daily and monthly streamflow for the three directly parameterized subbasins were greater than 0.7 and 0.8, respectively (Surfleet and Tullios 2013). The model fit to observations varied across the subbasins to which parameter distributions were transferred and appeared to be associated with the proportion of basins draining the HC geology. Whereas modeled runoff for basins in the WC had a strong statistical fit to OH streamflows [0.75 NSE and 0.1 m³/s root-mean-square error (RMSE)], runoff in basins in the HC had a weaker statistical fit to observations (0.35 NSE and 0.8 m³/s RMSE) (Surfleet et al. 2012; Surfleet and Tullios 2013).

Reservoir Operations and Operations Model

Reservoir operations were simulated in *HEC-ResSim* (USACE 2013), which follows a set of operating rules (rule curves) that

control reservoir releases on the basis of inflows into the reservoirs, available storage in the reservoirs, and reservoir priorities. The model divides operating rules into five storage and elevational zones: top of the dam, flood control, conservation, buffer, and inactive. Each zone has specific rules, described in further detail subsequently, that defined the discharge to be released. The model establishes releases on a daily time step for the highest priority rule. For this study, reservoir operations were based on operations defined in the water control manuals for each reservoir (USACE 1968, 1953). In addition, rules were included for spring and summer environmental flow releases established under the Willamette River biological opinion (BiOp) to meet or exceed the minimum flows needed for spawning, rearing, egg development, and migration of Chinook salmon and steelhead trout (NMFS 2008). Spring and summer flow targets are based on flows at a control point (Salem, Oregon) on the mainstem Willamette River, and augmentation of flows at Salem occurs by jointly operating the 13 reservoirs across the Willamette River Basin. Thus, the relative amount of discharge released from the NSB and SSB reservoirs to meet BiOp requirements varies with operations of other reservoirs in the basin.

For the SRB reservoir system, the flood control rule curves dictate releases from November to January to maintain adequate capacity to store high winter and spring flow events. Flood control rules are different for each reservoir associated with the magnitude and timing of inflows, reservoir storage capacity, distance to downstream control points (Brekke et al. 2009), and other priorities (e.g., recreation) for the reservoir. As flood risk decreases in the spring, reservoirs begin to store more water during the refill season (February through early May) until they reach the top of conservation pool by May. The time and rate of refilling is a function of reservoir inflows and storage capacity and also varies between reservoirs. For example, whereas both Detroit and Green Peter reservoirs start refilling by February 7, the target dates for refill are May 5 at Detroit and May 9 at Green Peter (USACE 1953, 1968). Departures from refill rules may occur in years when snowpack above the reservoirs is exceptionally high, in drought years when water supply is extremely low supply, or when critical power generation is required (NMFS 2008). During the conservation storage period from May to the end of August, operational rules maintain the reservoirs levels at full pool for recreation purposes and to store water for late summer demands. Reservoir elevations are drawn down in September and October before the onset of the flood season.

Reservoir Reliability, Threshold Identification, and Vulnerability

Summer reliability was an estimate of the ability of the reservoirs to meet summer environmental flow targets defined to protect Chinook salmon and steelhead trout habitat and to meet water quality targets from July to October (NMFS 2008). Summer reliability under historical and future periods was evaluated. However the BiOp minimum summer flows were not implemented in reservoir operations until 2009; thus, the reservoirs during the OH period were not operated to meet those minimum flow targets. Therefore, a comparison of summer target reliability between OH and SH was not made. Summer reliability was calculated [Eq. (1)] at Mehama and Waterloo control points (Fig. 1) as

$$Su_{Rel} = 1 - \left(\frac{N_{Su}}{N} \right) \quad (1)$$

where Su_{Rel} = summer reliability; N_{Su} = number of days summer flow targets were not met in a given year; and N = total number of summer days (July–October) per year.

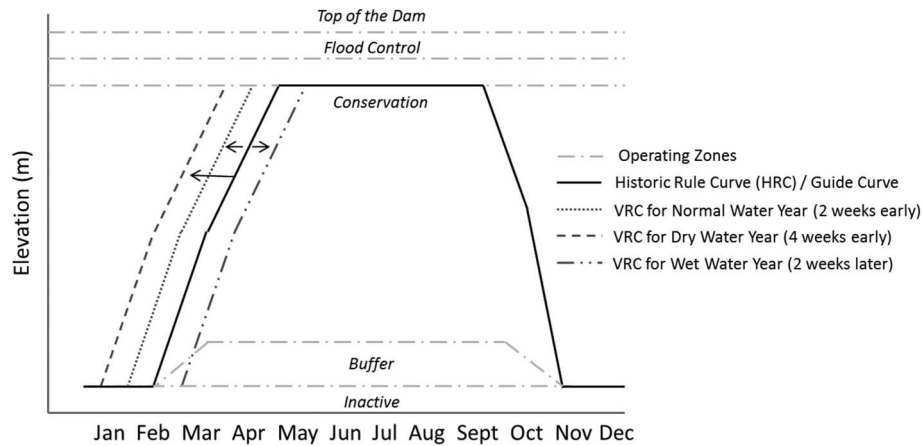


Fig. 2. Variable rule curves

Refill reliability (R_{rel}) was an estimate of the frequency of failure [Eq. (2)] of reaching the desired pool elevation calculated as the number of failures ($N_{Failure}$) for each period (T_{period}) (SH, NF, and FF). It is considered a failure when the simulated pool (S) is lower than the desired pool elevation (R_C). The percentage of failure in a given year was calculated [Eq. (3)] as the ratio of S to R_C on the refill deadline, established by each reservoir's rule curve. In the HEC-ResSim user's manual (USACE 2013), May 5 and 9 are the target dates for refill at Detroit and Green Peter, respectively

$$R_{rel} = 1 - \left(\frac{N_{Failure}}{T_{period}} \right) \quad (2)$$

$$R_{\%} = \frac{S}{R_C} \quad (3)$$

Flood control reliability [Eq. (4)] reflects the ability of a reservoir to regulate river elevations at downstream control points such that they remain below bankfull stage

$$FC_{Rel} = 1 - \left(\frac{N_{FC}}{N} \right) \quad (4)$$

where FC_{Rel} = flood control reliability; N_{FC} = number of days when flows were at or above bankfull stage in a given year; N = total number of days during the flood control period (January–May).

Under the assumption that the historical reliabilities reflect an acceptable condition to target in the future, performance thresholds for the decision-scaling approach were calculated as the median value for each reliability metric based on both the OH and SH streamflows. A system was determined to exhibit low reliability when values in any given year were below 0.9, without reference to the thresholds, and to be vulnerable when reliabilities were below the baseline thresholds. Probability distributions were calculated for each reservoir reliability metric and for each hydrologic scenario to estimate the likelihood that reservoir reliability was below the historical thresholds. The cumulative distribution functions (CDFs) were estimated by using a nonparametric empirical cumulative distribution with equal probability assigned to each observation (Brown et al. 2012). In interpreting the CDFs, rightward and downward shifts in the plots between scenarios were interpreted as an increase in reliability and thus lower probability of being vulnerable relative to the baseline threshold.

Assessment of Implementing Variable Rule Curves

The operational rules of VRC may be established in a number of ways, ranging from shifting between fixed curves for annual forecasts of wet, average, or dry years to a more dynamic varying of curves based on monthly or weekly evaluations of residual flow volumes stored in snowpack. Furthermore, VRC may be applied at various points within a year and the operational cycle (i.e., refill, drawdown). On the basis of evidence (Okkonen and Kløve 2011; Tague and Grant 2004, 2009) that warmer temperatures will lead to earlier spring snowmelt, VRC were simulated in this analysis by shifting the timing of spring refill in response to annual forecasts. This approach was applied because of its analytical simplicity, relevance to the anticipated effect of climate change, and anticipated impact on tradeoffs between operating objectives. Annual discharge data from 40 years of historical records (1960–2000) were used to classify each water year as (1) dry water years for the lowest quarter of the data; (2) normal water year for the middle half of the data; and (3) wet for the upper quarter of the data. Thus, taking into account the type of water year, the time that the reservoir refill would begin was simulated as (1) 2 weeks early in a normal water year; (2) 4 weeks early in a dry water year; and (3) 2 weeks later in a wet water year (Fig. 2).

Results

Observed versus Simulated Historical Hydrology

Comparisons of OH and SH streamflows illustrate that the hydrologic model did not fully capture OH summer baseflow conditions in the groundwater-dominated NSB. Upstream of the reservoirs, the simulated inflows into Detroit Reservoir in the NSB [Fig. 3(a)] were frequently lower than the observed inflows across all GCMs, whereas simulated inflows into Green Peter Reservoir in the SSB [Fig. 3(b)] were generally consistent with the observed inflows without a clear bias in overestimating or underestimating inflows. In addition, the uncertainty of inflows into Detroit was much higher than the uncertainty of inflows into Green Peter (shaded area in Fig. 4). Thus, the hydrologic model performed better in the basin with limited groundwater interactions, where uncertainties associated with modeling the groundwater were low.

Downstream of the reservoirs, the model consistently overpredicted summer discharge for both the NSB and SSB in the SH period (1960–2000) relative to OH flows (Fig. 4). The mechanism for this error was associated with reservoir operations. The simulated summer flow augmentation for the BiOp was not

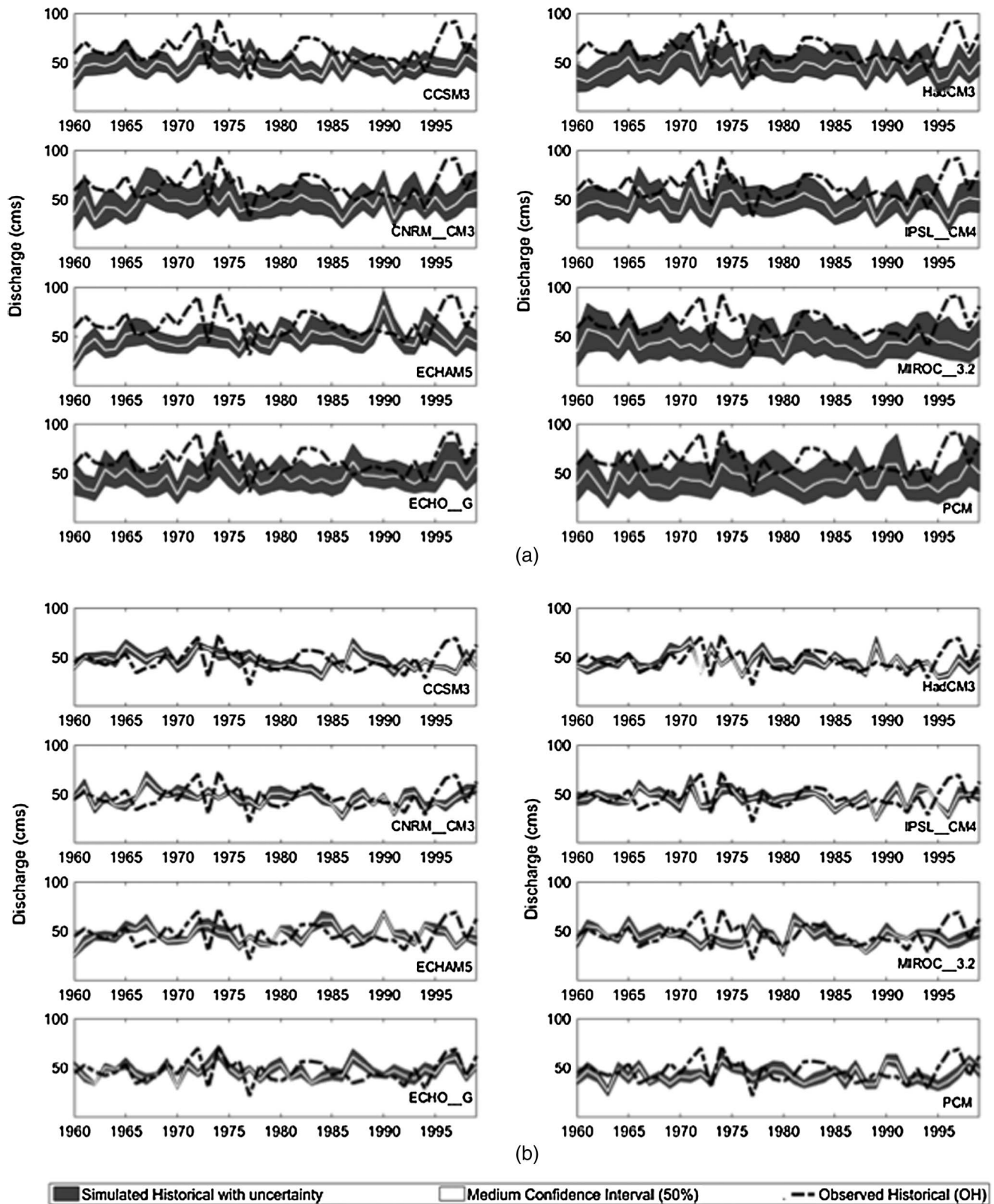


Fig. 3. Summer mean daily reservoir inflow under eight GCM projections: (a) Detroit Reservoir in the North Santiam Basin; (b) Green Peter Reservoir in the South Santiam Basin

implemented until 2009 but were included in the operations model, which resulted in higher discharge values for the SH record than occurred historically. In addition, differences between OH and SH summer flows downstream of the reservoir was higher in the SSB than in the NSB, which is associated with the prioritization of

releases between the two reservoirs for augmenting summer flows (USACE 2011). Because Detroit is a high-priority recreational reservoir during the summer, releases for augmenting mainstem flows in the summer are minimal, whereas Green Peter is used to augment summer flows by up to 42 cm.

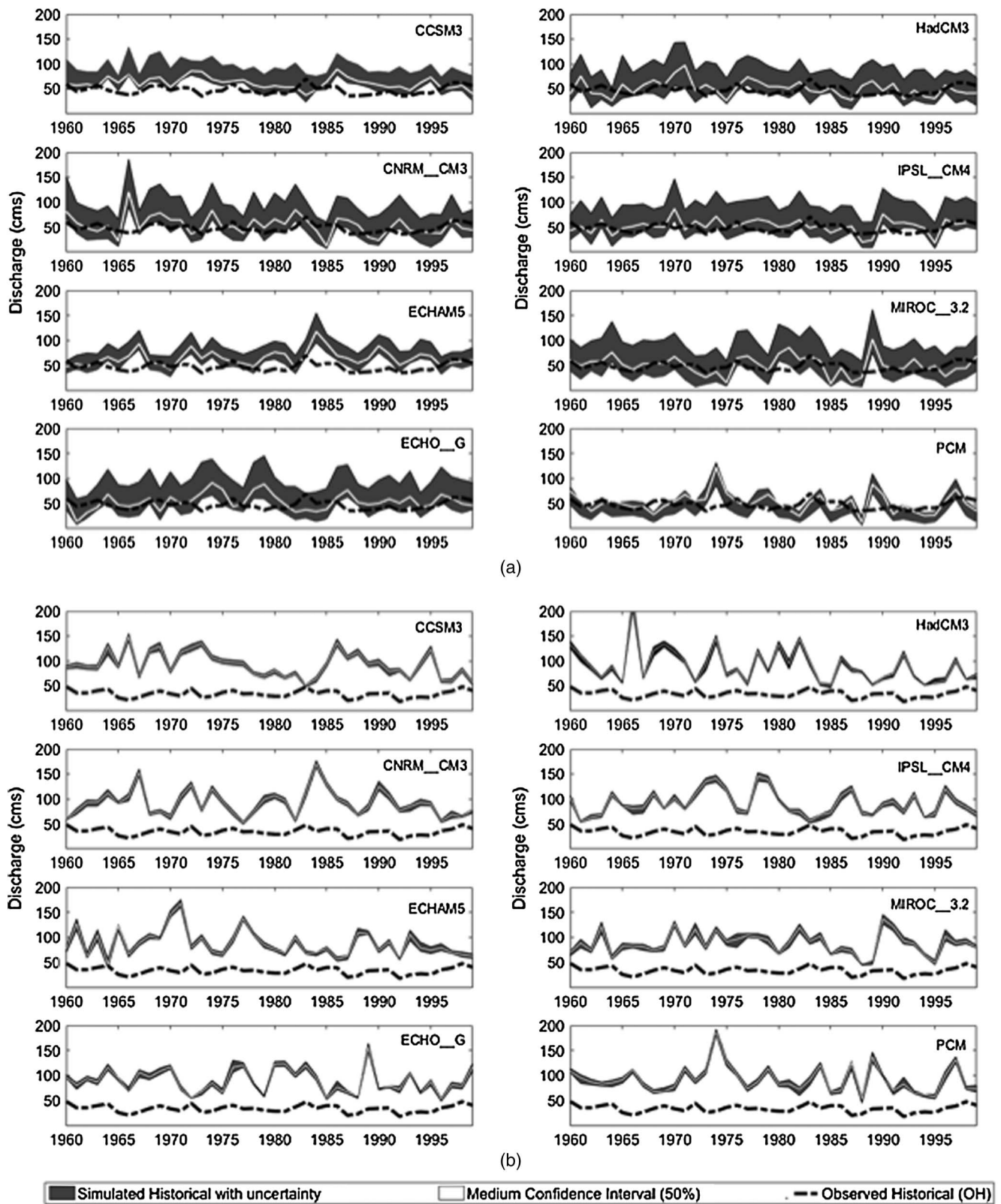


Fig. 4. Summer mean daily downstream flows under eight GCM projections: (a) North Santiam Basin at Mehama; (b) South Santiam Basin at Waterloo

Reservoir Reliability under Historical Rule Curves

Observed Historical versus Simulated Historical Reliabilities

The ability of reservoirs to refill by the May deadline under OH conditions was nearly 100% in both subbasins, with very low

variability and little differences between the two subbasins (Fig. 5). Reservoir refill thresholds were projected to be slightly lower under the SH records compared with the OH records for the SSB (Fig. 6), but the model generally produced a strong fit to historical conditions with respect to the reliability of reservoir refill.

The reservoirs reliably maintained flood elevations at downstream control points below bankfull levels in the past (Fig. 6), and the SH reasonably reproduced this finding. No differences between the upper and lower interquartile suggests zero variability related with flood control reliability under OH conditions. The differences between the SH and OH periods and across basins were negligible.

Despite the underestimation of reservoir inflows into the NSB, the SH hydrology reasonably reproduced OH reservoir performance. Refill and flood regulation reliability was historically very high, and differences between the basins are negligible. Because environmental flow targets were not implemented until 2009, OH and SH reservoir operational performances were not compared for the summer reliability.

Simulated Historical versus Future Reliabilities

For evaluating vulnerability, reliability thresholds based on the SH record were applied across all reliability metrics as the baseline against which future flows (NF and FF) were compared because the OH record did not represent summer flow augmentation targets that were implemented in the model.

Of the three performance measures, only summer flow target reliability appeared to be impacted by climate change. There was no trend in the median refill reliabilities at either Detroit [Fig. 5(a)] or Green Peter [Fig. 5(b)] reservoirs under NF or FF when uncertainties were considered. Individual GCMs indicated that a small decrease in refill reliability might occur in the FF at Green Peter Reservoir, although projected changes were within the uncertainty range, with similar uncertainties across the two subbasins. No impact of climate change was projected for median flood control reliability for both the NSB and the SSB (Fig. 6) despite higher uncertainty in the flood control reliability for the SSB than for

the NSB. Relative to SH, median summer flow target reliability was projected to decrease for the NF and FF periods in both basins (Fig. 7). Greater decreases in summer target reliability were projected for the NSB compared with the SSB, suggesting higher sensitivity to changes in temperature and precipitation for the NSB relative to the SSB. Uncertainty in summer flow target reliability was projected to increase for both basins in the future, with larger increases in uncertainty for the NSB over the SSB.

Impact of Variable Rule Curves on Vulnerability

Implementing the VRC reduced vulnerability by reversing the decline in reliability of reservoirs in meeting summer flow targets, with the degree of impact of the VRC varying across the basins (Table 1 and Fig. 8). For example, summer reliability for 50% of the projections at Mehama [Table 1 and Fig. 8(a)] were estimated as 0.91, 0.65, and 0.53 for the SH, NF, and FF, respectively, under the HRC, whereas the VRC resulted in reliabilities of 1.0 in the SH, NF, and FF. Similar patterns were observed for the SSB [Table 1 and Fig. 8(b)]. However, whereas reliability in summer flow targets increased in response to the change in the timing of refill based on the type of water year, it did not necessarily mean that the system was no longer in a vulnerable state. The SH threshold of 0.92 for summer flow target reliability in the NSB indicated that the probability of the basin being vulnerable during the FF period decreased from 66% under HRC to 41% under VRC [Fig. 8(a)]. Furthermore, implementing VRC compressed the range of expected reliabilities in meeting summer flow targets, especially in the NSB, as evident in the smaller range between the 10th and 90th percentiles under the VRC, relative to the HRC (Table 1). Finally, larger impacts of both climate change and VRC were projected for the FF, compared with NF, which highlighted that the impact of VRC on

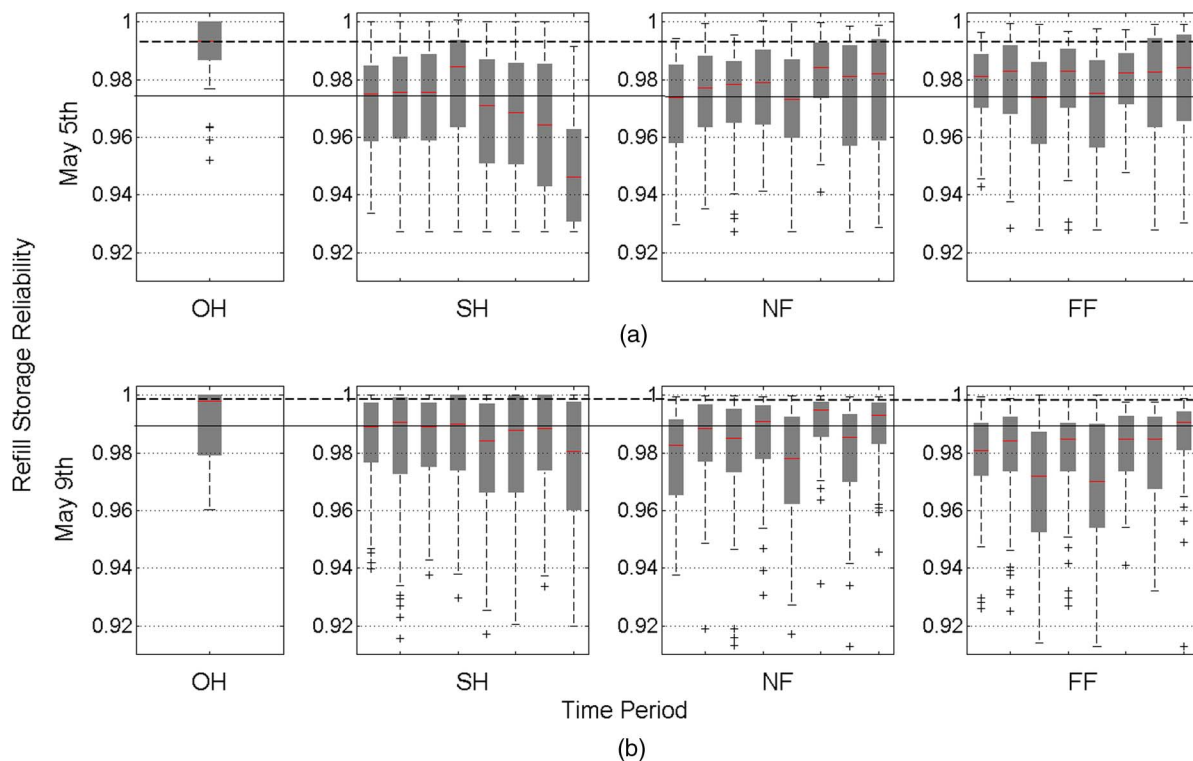


Fig. 5. Reservoir refill reliability for OH and simulated streamflow under eight GCM projections for simulated SH, NF, and FF periods; the refill reliability threshold from the OH period is represented by the horizontal dashed line, and the threshold from the SH period is represented by the horizontal solid line: (a) North Santiam at Deroit Reservoir; (b) South Santiam at Green Peter Reservoir

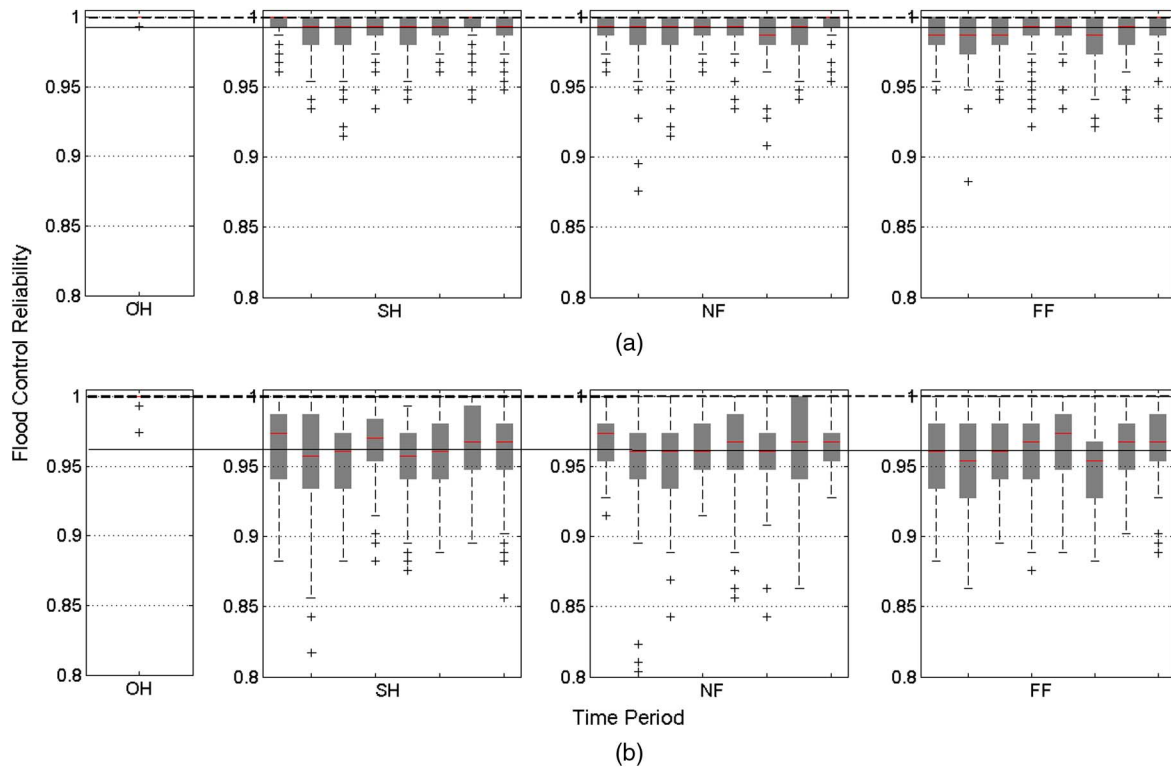


Fig. 6. Flood control reliability for OH and simulated streamflow under eight GCM projections for SH, NF, and FF periods; the summer reliability threshold from the OH period is represented by the horizontal dashed line, and the threshold from the SH period is represented by the horizontal solid line: (a) North Santiam Basin at Mehama; (b) South Santiam Basin at Waterloo

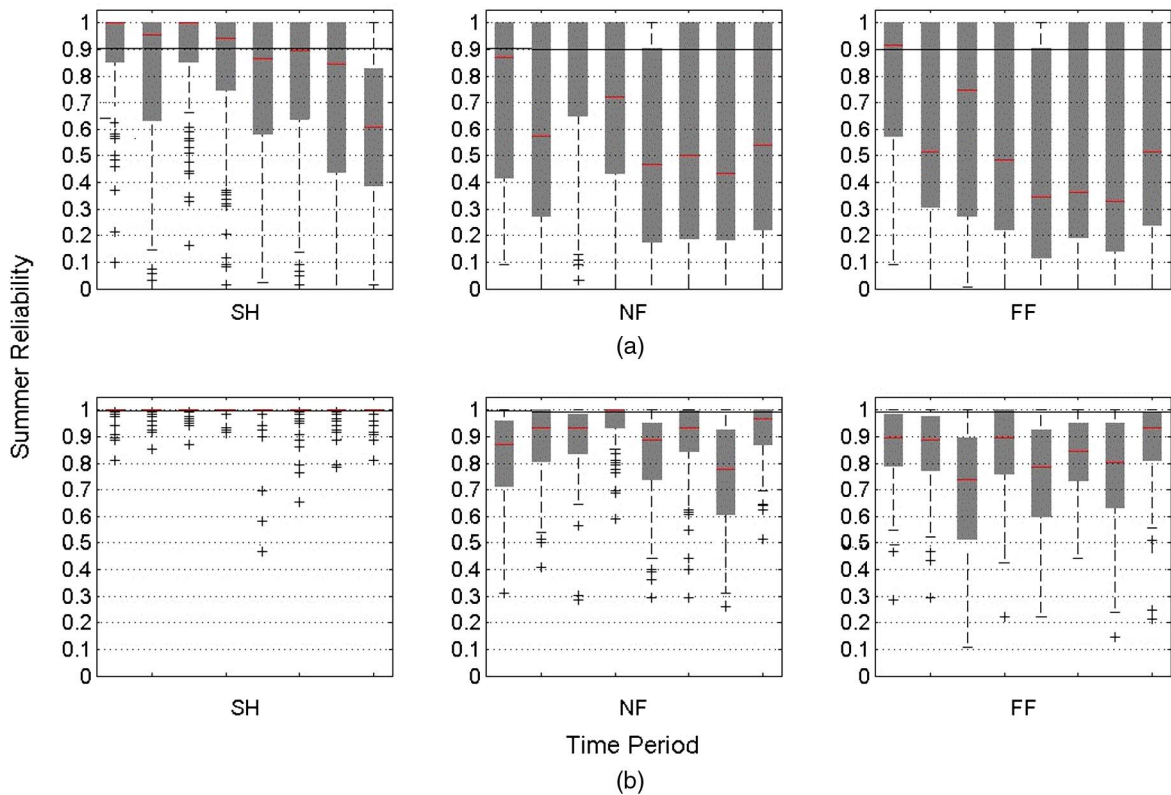


Fig. 7. Summer reliability for SH, NF, and FF periods under eight GCM projections; the summer reliability threshold from the SH period is represented by the horizontal solid line: (a) North Santiam Basin at Mehama; (b) South Santiam Basin at Waterloo

Table 1. Reliability Values for Summer, Refill, and Flood Control Metrics for the Upper, Median, and Lower Confidence Interval under Simulated Historical, Near Future, and Far Future Periods

Basin	Period	Curves	Reliability percentiles								
			Summer			Refill			Flood control		
			90th	50th	10th	90th	50th	10th	90th	50th	10th
North Santiam Basin	SH	HRC	0.09	0.91	-0.61	0.01	0.97	-0.04	0.00	1.00	-0.01
		VRC	0.00	1.00	0.00	0.00	1.00	-0.02	0.00	1.00	-0.01
	NF	HRC	0.35	0.65	-0.55	0.01	0.98	-0.03	0.00	1.00	-0.01
		VRC	0.00	1.00	-0.18	0.00	1.00	-0.01	0.00	1.00	-0.01
	FF	HRC	0.47	0.53	-0.47	0.01	0.98	-0.03	0.01	0.99	0.00
		VRC	0.00	1.00	-0.31	0.00	1.00	-0.01	0.00	1.00	-0.01
South Santiam Basin	SH	HRC	0.00	1.00	0.00	0.01	0.99	-0.04	0.02	0.98	-0.02
		VRC	0.00	1.00	0.00	0.00	1.00	0.00	0.02	0.98	-0.02
	NF	HRC	0.07	0.93	-0.28	0.01	0.99	-0.03	0.01	0.98	-0.02
		VRC	0.00	1.00	-0.06	0.00	1.00	0.00	0.01	0.99	-0.02
	FF	HRC	0.12	0.88	-0.34	0.02	0.98	-0.03	0.01	0.98	-0.02
		VRC	0.01	0.99	-0.07	0.00	1.00	0.00	0.02	0.98	-0.01

Note: The 50th percentile shows the median reliability value (bold), and the 10th and 90th percentiles shows the change in reliability from the 50th percentile.

summer flow target reliability was highest when reliabilities were the lowest.

Regarding refill reliability, the shift of the refill reliability distributions (Table 1 and Fig. 9) from HRC to VRC suggest a relatively

small decrease in vulnerability, represented by the increase in the ability of reservoirs to refill by the May deadline for both subbasins. The change in vulnerability was small because refill reliabilities were already so high for all scenarios. However, implementing VRC

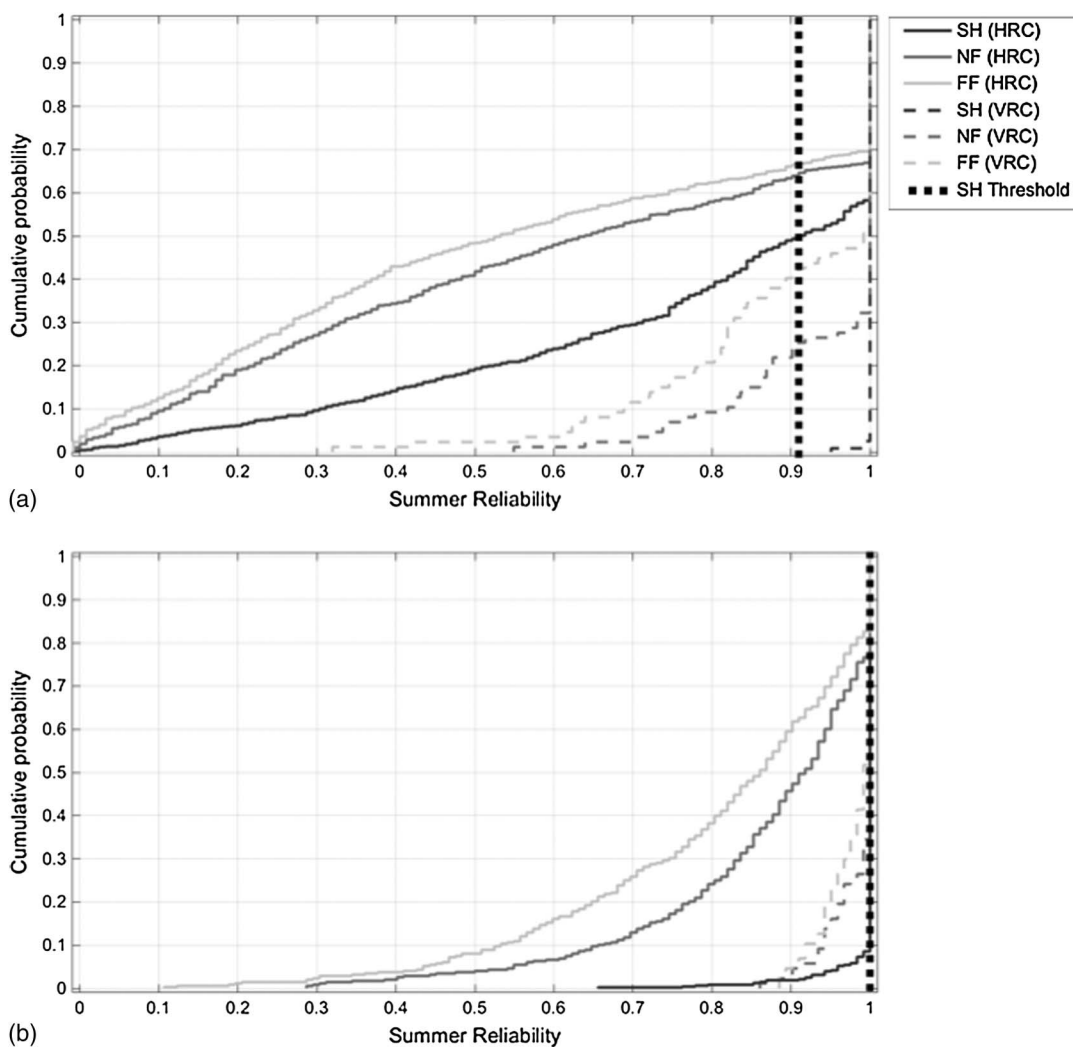


Fig. 8. System vulnerability of summer reliability from eight GCM projections for the upper, median, and lower confidence intervals for SH, NF, and FF; the x-axis range is 0–1: (a) North Santiam Basin at Mehama; (b) South Santiam Basin at Waterloo

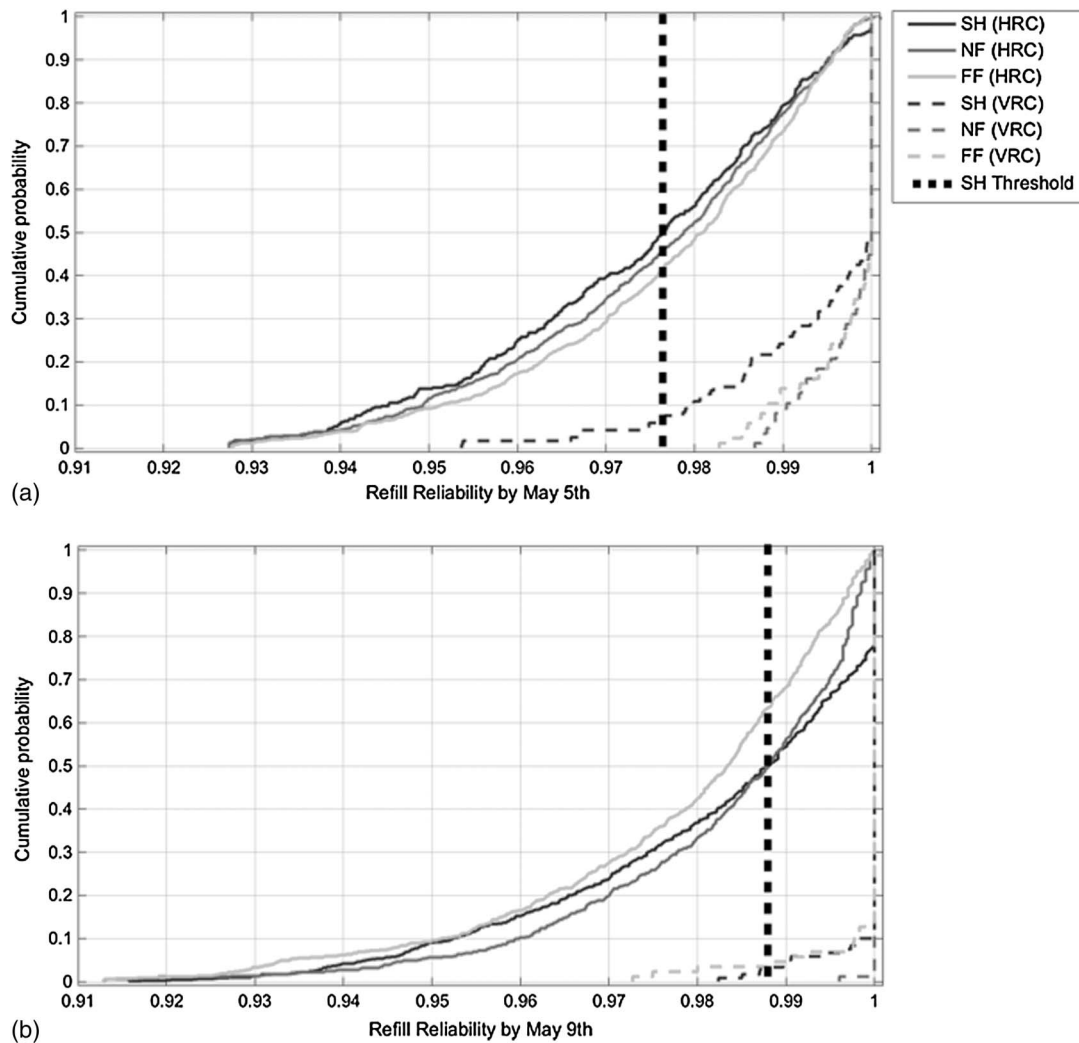


Fig. 9. System vulnerability of refill reliability from eight GCM projections for the upper, median, and lower confidence intervals for SH, NF, and FF; the x -axis range is 0.91–1.0: (a) North Santiam Basin at Detroit Reservoir; (b) South Santiam Basin at Green Peter Reservoir

appeared to compress the range of projections between the 10th and 90th percentiles (Table 1), suggesting that changes in the timing of refill was likely to reduce the uncertainty associated with refill reliability.

With respect to flood regulation, implementing VRC appeared to have a minimal effect on vulnerability across the two subbasins (Table 1 and Fig. 10) primarily because flood regulation was already very reliable and was not strongly affected by climate change. The differences in uncertainties across climate and operational scenarios were negligible.

Discussion

Impacts of Climate Change on Reservoir Reliability across Hydrogeologic Settings

The results indicated that climate change would only affect the reliability of meeting minimum flow targets during the summer, with greater impacts and thus higher sensitivity to changes in climate on the groundwater-driven basin compared with the surface-water driven basin. Across the entire SRB, relative to SH, summer reliability decreased into the future under HRC (Table 1) as a result of decreases in summer low flows projected for the basin (Surfleet and

Tullos 2013; Tague et al. 2008). However, a larger decrease in summer reliability was projected for the NSB than for the SSB, which corresponded to greater reductions in summer low flows (Surfleet and Tullos 2013; Tague et al. 2008). This trend is common in groundwater-driven systems relative to surface water systems (Kløve et al. 2014; Okkonen and Kløve 2010; Safeeq et al. 2013, 2014; Tague and Grant 2009), where larger changes can occur in groundwater systems for the same changes in temperature and precipitation. Relative to the SH period, the ability of both reservoir systems to maintain downstream control points below bankfull and to reliably refill did not change under the NF and FF periods.

Mitigating Impacts of Climate Change with VRC

Consistent with other studies (Vonk et al. 2014; Watts et al. 2011), changes in reservoir operations were found to be effective in mitigating the effects of climate change on the reliability of water resources (Table 1). However, this effect was only observed for summer flow targets because the reliability of flood regulation and refill were already high and not sensitive to climate change. Whereas implementing VRC increased summer reliability immediately in the NF, the benefits grew into the future when climate impacts were greater and reliability was lower. In addition, there was

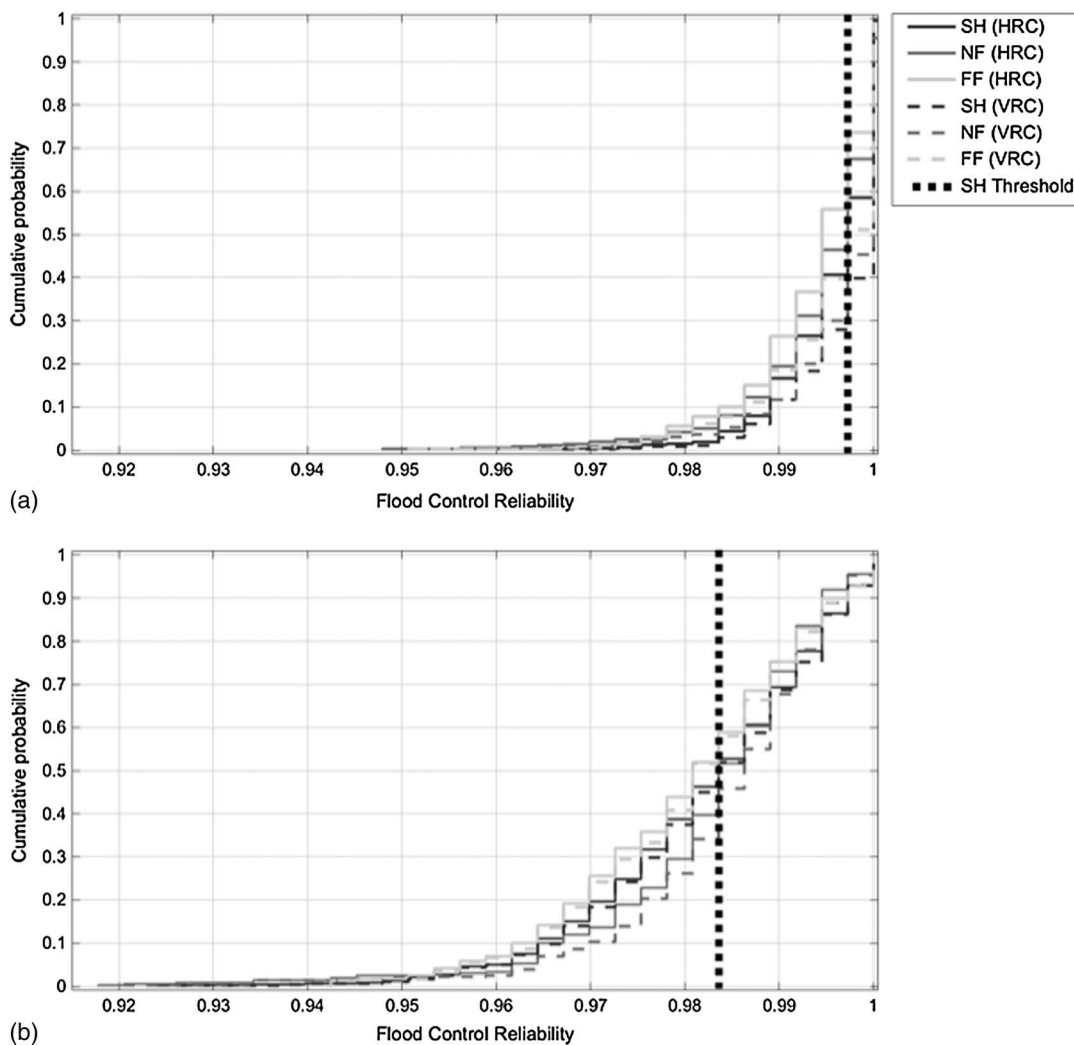


Fig. 10. System vulnerability of flood control reliability from eight GCM projections for the upper, median, and lower confidence intervals for SH, NF, and FF; the x -axis range is 0.92–1.0: (a) North Santiam Basin at Mehama; (b) South Santiam Basin at Waterloo

no evidence that VRC compromised the ability of reservoirs to maintain flood regulation at downstream control points or reliably refill, as suggested in other systems (Payne et al. 2004).

Implications of Analytical Uncertainties in Climate-Change Assessment and Decision Making

Consistent with other studies (Brown et al. 2012; Garcia et al. 2014), the results from this study highlighted some inaccuracies of streamflow projections in capturing historical hydrologic conditions and the thresholds that will determine if a system is in a vulnerable state (Table 1). The comparisons between OH and SH (Fig. 3) indicate that the hydrologic model often underestimated the historical inflows into the NSB reservoirs and always produced streamflows with higher uncertainty compared with the historical inflows into the SSB. The higher uncertainty is likely associated with the challenges of modeling groundwater interactions in a basin where streamflow is comprised of over 80% groundwater (Conlon et al. 2005). Potential sources of the uncertainty include those specific to this model, such as the lack of groundwater modeling in the WC and the assumption that the contribution of deep groundwater from the HC to the WC is small. This assumption is supported by previous field and modeling studies of groundwater hydrology in the basin (Conlon et al. 2005; Herrera et al. 2014), which document

the low contribution of groundwater to baseflow in the WC relative to the HC, and that the majority of HC groundwater following deeper and longer flow paths discharges in the HC unit where the impermeable basement confining unit is exposed (Conlon et al. 2005). In addition, this model is also subject to uncertainties consistent with other groundwater models in the Willamette River Basin, including the limited availability of data on the aquifer geometry and water level and fluxes over time and space (Herrera et al. 2014). Despite these modeling uncertainties, the results are consistent with previous studies that document greater decreases in summer streamflows for groundwater-dominated basins of the PNW than for runoff-dominated systems as a result of declines in snowpack with warming temperatures (Safeeq et al. 2013; Tague and Grant 2009).

Furthermore, the discrepancy between OH and SH has practical implications for bottom-up analysis of water resources under climate change. It is logical to assume that an acceptable outcome under climate change is no deviation from the past performance, resulting in the establishment of decision thresholds for system vulnerability based on historical records. However, the use of thresholds based on past performance can be problematic when simulated historical streamflows do not match observed historical streamflows. When OH and SH do not closely match, errors associated with the hydrologic modeling are conflated with the impacts of

climate change. To account for the discrepancies between historical and simulated conditions, decision-making thresholds that do not rely on historical streamflows are likely to be more valuable in evaluating the impact of climate variability and mitigation strategies on reservoir reliability. For example, identifying decision thresholds based on known changes of state in a system (e.g., the maximum number of days that summer flow targets can be missed without compromising fish growth or reproduction) will likely be more effective in establishing whether a need for an adaptive action (e.g., implement VRC) exists.

The vulnerability analysis presented in this study reflects only one of several approaches (Hashimoto et al. 1982; Acosta and Martínez 2014; Asefa et al. 2014; Goharian et al. 2016) to assessing system vulnerability, and further analysis may provide additional insight regarding the severity (magnitude of damage), exposure (occurrence of failure), and potential severity (represents adaptive capacity) of vulnerability to climate change. Furthermore, Goharian et al. (2016) conclude that vulnerability analyses based on severity of the failure alone may lead to misleading quantification of vulnerability. This analysis focused on frequency of failure as a key aspect of decision making about vulnerable water systems, but it is expected that the key findings surrounding which operational objectives (i.e., summer reliability) and which basins (i.e., ground-water dominated) were more sensitive to climate change, and the effectiveness of VRC in mitigating changes, would not change if a more comprehensive vulnerability analysis were conducted.

Finally, new climate-change projections (CMIP5) have been released since the hydrologic modeling was performed for this analysis. The major differences between the two models are associated with how emissions scenarios are represented and the greater number and finer resolution of GCMs applied in CMIP5. Despite these differences, a comparison (Rupp et al. 2013) between the two scenarios, based on 30 performance metrics, indicates that the model results are similar. Thus, it is unlikely that the key findings of this analysis would change substantially with the application of newer projections.

Conclusions

This study evaluated the sensitivity, reliability, and vulnerability of subbasin hydrogeology and reservoir operations to a changing climate and investigated the ability of variable rule curves to mitigate those responses in the Santiam River Basin in Oregon. The key findings included the following: (1) climate change may reduce the reliability of meeting summer flow targets but is unlikely to affect reservoir refill or flooding in the study basin; (2) the groundwater-driven basins exhibited higher sensitivity to hydrologic changes and to reservoir operations than the surface water-driven basins; (3) implementing variable rule curves effectively mitigated the impact of climate change on summer target reliability without compromising flood regulation; and (4) identifying practical thresholds that provide meaningful results to decision makers is critical, given the challenges in modeling historical streamflow and reservoirs operations. These findings emphasize the importance of hydrogeology in establishing the practical impacts of climate changes on summer baseflows and that reservoirs can play an important role in mitigating those effects.

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