Reliability, sensitivity, and uncertainty of reservoir performance under climate variability in basins with different hydrogeologic settings

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Abstract. This study investigates how reservoir performance varies across different hydrogeologic settings and under plausible future climate scenarios. The study is conducted in the Santiam River basin, OR, USA, comparing the North Santiam basin (NSB), with high permeability and extensive groundwater storage, and the South Santiam basin (SSB), with low permeability, little groundwater storage, and rapid runoff response. We apply projections of future temperature and precipitation from global climate models to a rainfall-runoff model, coupled with a formal Bayesian uncertainty analysis, to project future inflow hydrographs as inputs to a reservoir operations model. The performance of reservoir operations is evaluated as the reliability in meeting flood management, spring and summer environmental flows, and hydropower generation objectives. Despite projected increases in winter flows and decreases in summer flows, results provide little evidence of a response in reservoir operation performance to a warming climate, with the exception of summer flow targets in the SSB. Independent of climate impacts, historical prioritization of reservoir operations appeared to impact reliability, suggesting areas where operation performance may be improved. Results also highlight how hydrologic uncertainty is likely to complicate planning for climate change in basins with substantial groundwater interactions.

Key words: Uncertainty; reliability; sensitivity; climate change; reservoir operations; rule curves

1 Introduction

In addition to long-standing uncertainties related to variable inflows and the market price of power, reservoir operators face many new uncertainties related to hydrologic nonstationarity, changing environmental regulations, and increasing water and energy demands. A warmer

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atmosphere is expected to generate changes in the timing and quantity of streamflow as more precipitation falls as rain rather than snow, snowpack depths decline, and remaining snowpack melts earlier as a result of atmospheric warming (Mote et al., 2005). Of particular interest to water resources managers, projections for the PNW are that winter runoff periods will be shorter, spring runoff will occur earlier, and summers will be longer and drier (Chang and Jung, 2010; Tague and Grant, 2009). Given that snowmelt and groundwater discharge contribute substantially to summer streamflows in the PNW (Safeeq et al., 2014a; Tague and Grant, 2004), projected snowpack reductions and changes in the timing and quantity of streamflows may increase the scarcity and vulnerability of summer water supply (Jaeger et al., 2013). However, climate change impacts on hydrology will vary by basin's characteristic. For example, snowmelt-dominated basins are projected to shift towards mixed rain-snow dominated basins, resulting in increases in winter flow and reductions in summer low flows (Dalton et al., 2013). On the other hand, mixed rain and snow-dominated basins are projected to shift towards rain dominated basins experiencing less snow and more rain during the winter months (Dalton et al., 2013).

Projected hydrologic changes could have severe impacts on the performance of reservoir systems (Minville et al., 2009; Payne et al., 2004; Rheinheimer and Viers, 2014). For example, winter inflows to reservoirs may increase as a result of the snow-to-rain transition (Safeeq et al., 2013), which can increase the risk of flooding (Payne et al., 2004; Vonk et al., 2014; Watts et al., 2011). The greater winter inflows may also result in the need for greater flood space requirements during the winter period (Brekke et al., 2009) or require that operators refill reservoirs earlier in the season to ensure adequate releases will be available for summer water supply. However, these adjustments to operations can result in tradeoffs with other objectives for the reservoir. For example, earlier refill could increase flood risk if adequate flood storage is not available in the reservoir when a spring flood arrives (Payne et al., 2004). Earlier peak streamflow projected for the PNW may result in a decline in summer hydropower generation and an increase in winter hydropower generation (Dalton et al., 2013). However, atmospheric warming may force reservoir operators to maximizing hydropower generation during the summer months to meet peak electricity demand (Madani and Lund, 2010; Rheinheimer and Viers, 2014), potentially compromising adequate reservoir storage needed to meet summer supply, environmental flows and temperature targets at the end of the summer (Payne et al., 2004). Reservoir releases for late summer water demands and environmental targets may also compete with storage requirement for recreation purposes (Morris and Walls, 2009). Therefore, atmospheric warming may result in the need for tradeoffs between reservoir priorities. However, it is not yet clear which priorities and which basins will be most affected by projected change in hydrometerology.

Climate change is likely to affect basins differently based on an individual basin's characteristics. Changes in precipitation and temperature patterns for the Mediterranean climate of the PNW (Mote et al., 2005) are projected to have a limited effect on low flows in surface-water (SW) systems because they already experience very low summer flows (Nolin, 2012). On the other hand, GW systems and mixed SW-GW systems, and especially those that drain areas of the rain-snow transition, depend on delayed runoff due to snowpack storage and discharge of groundwater for sustaining base flow (Safeeq *et al.*, 2013; Tague and Grant, 2009). These basins are likely to experience greater magnitudes of change in summer low flows due to their dependence on snowpack accumulation and the projected shifts of streamflow to earlier in the season (Safeeq et al., 2013; Tague and Grant, 2009). While the steepness of the terrain, porosity, and permeability for the underlying geology determines how fast the water moves through the ground, how fast recharge, either as rain or snow, is transformed into discharge will determine how much water will be available in the future (Safeeq et al., 2013). In the Cascade range of the PNW, lower rates of recession and lower drainage densities in GW systems make them more sensitive than SW systems to changes in snowmelt amount and timing (Jefferson et al., 2008; Tague and Grant, 2009). More sensitivity for GW systems results from depletion of the storage and the magnitude of drop in the system, which after the lag of depleting the groundwater will be greater than the changes observed in the SW systems. Furthermore, greater decreases in snowpack accumulation due to more precipitation falling as rain rather than snow are projected for basins located at the rain and snow transitional elevations than areas at higher elevations characterized by snow precipitation (Jefferson et al., 2008; Tague et al., 2008). Thus, it is clear that increases in air temperature will affect basins differently based on the characteristics of individual basins, and that the simulation of basin response is prone to systematic errors (Safeeq et al. 2014). However, there are no studies that have taken the next step to evaluate how these differences in hydrogeology and elevation may drive the degree of response and tradeoffs that can be anticipated for the operational performance of reservoirs and the potential tradeoffs required in the benefits they provide.

Thus, while several studies have been published on the impacts of climate change on reservoir operations (Minville et al., 2009; Payne et al., 2004; Rheinheimer and Viers, 2014; Vano et al., 2010; Vonk et al., 2014) and the sensitivity of different hydrogeological conditions to atmospheric warming (Jefferson et al., 2008; Safeeq et al., 2013, 2014a; Tague et al., 2008), there is very little information on how hydrogeology and reservoir operations interact under climate change. In applying a coupled surfacewater-groundwater model, this study attempts to understand the interactions between hydrogeology, the sensitivity of basins to climate change, and the delivery of benefits provided by reservoirs in the Santiam River Basin (SRB) in Oregon, USA. Moreover, this study adds a novel analysis of hydrologic modeling uncertainty in the analysis of reservoir reliability under a warming climate. We couple GCM results with a coupled GW-SW model and a formal uncertainty analysis to assess whether and how changes in the timing and quantity of water resources affect the reliability of reservoir systems. This analysis is conducted on reservoir systems located in two different hydrogeologic settings: the North Santiam Basin (NSB), with high permeability and large groundwater storage, and the South Santiam Basin (SSB), characterized by low permeability, little groundwater storage and rapid runoff response. We evaluate: (1) how the performance of current reservoir operations, designed to provide flood regulation, hydropower production, water supply, and environmental flows, changes under future 2.5, 50 and 97.5 percentile streamflow projections for the two hydrologic settings; (2) which operating system (NSB or SSB reservoirs) is more sensitive to hydrologic variability associated with climate change, and; (3) the sensitivity of different elements of reservoir operations to climate variability.

2 Methods

2.1 Study area

The Santiam River Basin (SRB) encompasses approximately 4,700 km^2 of the eastern portion of the Willamette River Basin (WRB) and drains the Western and High Cascade Range (Fig. 1, left inset). The basin is primarily forested at the headwaters. Precipitation patterns are highly influenced by temperature and elevation and about 80% of precipitation falls between November and March. Precipitation primarily falls as rain at elevations lower than 400 m, rain and snow at elevations between 400 m to 1,200 m, and snow at elevations higher than 1,200m (Jefferson et al., 2008; Tague et al., 2008; Tague and Grant, 2004).

We focused our study in two reservoir systems that both include coupled flood control and re-regulating dams, located in sub-basins with different hydrogeologic systems within the SRB: Detroit and Big Cliff located in the North Santiam Basin (NSB) dominated by the High Cascade geology, and Green Peter and Foster located in the South Santiam Basin (SSB) dominated by the Western Cascade geology. While the primary operating objective for both dams is to reduce flooding during winter and spring, the reservoirs also provide hydropower, recreation, and regulate water quality (Risley et al., 2012).

The North Santiam sub-basin drains approximately 2,000 km^2 and flows west from Mount Jefferson, passing through Detroit and Big Cliff dams into the Santiam River (SR) just upstream of the city of Jefferson (Sullivan and Rounds, 2004). The basin elevation ranges from 3,200 m at the summit of Mount Jefferson to 66 m on the Willamette Valley floor (Risley et al., 2012). Over 50% of the watershed is in public ownership and is administered primarily as the Willamette National Forest by the US Forest Service (ODEQ, 2006a). The basin is sourced by the High Cascades, characterized by highly porous and permeable volcanic layers that contribute to high groundwater recharge and low drainage densities (Tague and Grant, 2004), which sustain base flow during the dry summer months (Chang and Jung, 2010; Tague et al., 2008).

Detroit dam is located at river km 98 on the North Santiam River at 477 meters above the sea level. It maintains 561 Mm^3 of storage capacity and includes a total powerhouse capacity of 100 megawatts (MW) from two turbines (Table 1) (USACE, 1953). In addition, Detroit reservoir has extensive public recreation facilities operated by the US Forest Service and Oregon Parks and Recreation Department. Due to the high demand for recreation, the pool at Detroit is maintained as high as possible through the first weekend of September to accommodate Labor Day recreation and is rarely drafted for flow augmentation at Salem in the summer (USACE 1953). Big Cliff dam is located 4.5 km downstream from Detroit dam at 369 meters above the sea level. It has a storage capacity of 8 Mm^3 (Table 1) and regulates peak power releases from Detroit to ensure steady streamflows in the NSB (USACE 1953). Big Cliff dam has three spillways and one 18 MW capacity power generating unit (USACE 1953). Together, Detroit and

Big Cliff generate more hydroelectric power than any other USACE facility in the WRB (Buccola et al., 2012). In addition to the principal functions of flood control and power production, Detroit and Big Cliff dams are required to operate to improve downstream water temperature and total dissolved gas in response to Reasonable and Prudent Alternative (RPA) 5.1.1 in the 2008 Biological Opinion (BiOp) (NMFS, 2008).

The South Santiam sub-basin drains 2700 km^2, the majority of which is in private ownership, with federal and state ownership accounting for 30 to 40% of the total land use in the sub-basin (ODEQ, 2006b)**.** The elevation in the basin range from 67 m to 1,700 m (ODEQ, 2006b). The basin is predominantly Western Cascade geology (Tague et al., 2008) with steep, well-developed drainage networks (Tague and Grant, 2004). The basin is characterized by shallow subsurface storm flow that generates rapid runoff responses, high peak flows, high flow variability, and little groundwater storage (Tague and Grant, 2004).

Green Peter dam, with inflows from Quartzville Creek and the Middle Santiam River (MSR), and Foster dam, with inflows from the South Santiam River, are located in the SSB. Both Green Peter and Foster dams provide flood control, power generation, water quality, and recreation benefits. Green Peter dam is located at river km 9 on the Middle Santiam River at 310 meters above the sea level, with a storage capacity of 528 Mm^3 and hydropower generation potential of 80 MW from two generating units (Table 1) (USACE 1968a). Storage at Green Peter can reduce downstream flood stages by regulating 48 percent of the total drainage area above the mouth of the South Santiam River (USACE 1968a). Foster dam is located 13 km downstream of the Green Peter dam in the South Santiam River (SSR) at 165 meters above the sea level and regulates releases from Green Peter to provide a more uniform streamflow in the SSR. Foster dam has 75 Mm^3 of water storage capacity and two generators capable of producing 20 MW (Table 1) (USACE 1968b). Foster reservoir is a popular recreation resource in the SRB, thus the lake is rarely drafted for flow augmentation at Salem. Foster spring spills are required from April 15 through May 15 each year to facilitate passage of juvenile and kelt winter steelhead and juvenile spring Chinook salmon (USACE 2000). Approximately 3 to 7 cms (0.2 to 0.5 meters of water depth), depending upon reservoir elevation and inflow, is spilled on a daily basis from 0600 through 2100 hours.

2.2 Study Approach

We applied streamflow projections (Hamlet et al., 2010a; Surfleet and Tullos, 2013) as inputs to a reservoir operation model (HEC-ResSim) to analyze reservoir system reliability, sensitivity, and uncertainty under future climate. Reservoir system reliability is defined as the probability of failure to achieve some target demand or level of flood protection (Watkins and McKinney, 1995). The range of output (2.5, 50, and 97.5 percentiles) from the hydrologic modeling resulted from climate model projections is presented as a demonstration of uncertainty of the future streamflow projections. We evaluated reservoir performance sensitivity to hydrologic variability as the change in the ability of a reservoir to (a) store a flood of a certain magnitude, (b) maintain downstream control points below bankfull, (c) refill to the top of Conservation pool, (d) meet environmental flow targets, and (e) produce maximum hydropower capacity. A system is considered to be sensitive to changes in climate when reservoir performance is projected to increases or decreases in the future. Uncertainty of the estimated changes in streamflow and reservoir reliability measures is estimated based on a Bayesian approach from which we compare the range between the 97.5 and 2.5 percentiles.

We perform the analysis for the Simulated Historic (SH) time period (1960- 2000), the Near Future (NF) time period (2030- 2060), and the Far Future (FF) time period (2070-2100). To avoid conflating errors due to the hydrologic model with the impacts of climate change and to maintain the emphasis on comparison across basins, we present the simulated historical as the reference against which simulated future is compared, rather than the observed historical observations, to evaluate the impacts of changing climate and reservoir operations.

2.2.1 Estimates of future water supply

To assess the effects of climate change on various objectives of reservoir operations, we applied streamflow projections from two hydrologic models as inputs in HEC-ResSim (USACE, 2013), a reservoir operation model (Fig. 2). We simulated the reservoir operations model for all 13 multipurpose dams and reservoirs located in the WRB (Fig. 1; right inset) since they operate as a system to maintain downstream control points (e.g. Salem) below bankfull. Inflows for the SRB were obtained from GSFLOW (Surfleet and Tullos, 2013), a coupled groundwater-surface water flow model (Markstrom et al., 2008). Inflows for the other reservoirs in the WRB were obtained from Variable Infiltration Capacity (VIC) (Hamlet et al., 2010a, 2010b), a spatial-distributed surface water model (Liang et al., 1994). Climate change projections for the basin were simulated within GSFLOW for the SRB and within VIC for the rest of the WRB using the same eight GCMs projections, two GHG emission scenarios, and downscaling method. The eight GCMs from which we obtained the temperature and precipitation projections are: CCSM3, CNRM_CM3, ECHAM5/MPI-OM, ECHO_G, UKmo-HacCM3, IPSL_CM4, MIROC_3.2, and PCM. The A1B and B1 GHG emissions scenarios were chosen because they are the most frequently used by the global modeling groups for future climate change simulations and impact assessments (Chang and Jung, 2010; CIG, 2010). A1B presents a higher emissions scenario, whereas B1 reflects a more conservative estimate of GHG emissions as a result of reduction in population growth and transitioning industries. GCM simulations were statistically downscaled using the Hybrid Delta approach (Hamlet et al., 2010a) to provide metereological data for input to the hydrologic model 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 behaviour and spatial correlations from the gridded temperature and precipitation observations, it transforms the entire probability distribution of the observations at monthly time scales based on the bias corrected GCM simulation (Hamlet et al., 2010a).

We analyze the performance of reservoir operations for the reservoirs located in the SRB only because the GSFLOW simulations, available only for the SRB, include a groundwater component and distributions of streamflows that represent the uncertainty attributed to hydrologic modeling parameters. The GSFLOW projections (Surfleet and Tullos, 2013) used for this analysis combines the US Geological Survey (USGS) Precipitation-Runoff Modeling System (PRMS) simulating surface-water flow (Leavesley et al., 1983) with the USGS Modular Groundwater Flow Model (MODFLOW) simulating groundwater flow (Harbaugh, 2005) and the Differential Evolution Adaptive Metropolis (DREAM) (Vrugt et al., 2008), a formal Bayesian uncertainty assessment of model parameters that cascades GCM uncertainty through hydrologic model uncertainty. The algorithms underlying the DREAM approach apply a Markov Chain Monte Carlo sampling algorithm to estimate the posterior probability density function of parameters. DREAM runs multiple chains simultaneously, automatically tuning the scale and orientation of the *a priori* distribution during the evolutions to the posterior distribution. The separation of behavioural solutions from nonbehavioural solutions uses a cut-off threshold, which is based on the sampled probability mass that is defined by the underlying probability distribution (Vrugt et al., 2009).

The groundwater model (MODFLOW) within GSFLOW was applied only for the sub-basins in the High Cascades and the alluvial geology (Fig. 1) due to the substantial groundwater interactions that occur in those areas. For computational efficiency, only the surface water model was simulated for sub-basins draining the Western Cascades due to the limited groundwater interactions there. Subsurface flows were not transferred as surface water flow to lower sections in the basin based on the assumption that the groundwater remains in deep storage and does not appreciably contribute to streamflow in the Western Cascades (Herrera et al., 2014). In addition, the groundwater contribution for the alluvial areas at the lower reaches of the model does not originate from the High Cascades.

The uncertainty assessment focused on 13 parameters using the DREAM uncertainty parameter approach (Surfleet and Tullos, 2013; Vrugt et al., 2008), ten of which are used in the calculation of soil water transport and exchange of soil water between groundwater and surface runoff. Each of the 13 parameters were estimated across hydrologic response unit (HRU), each with similar elevation, geology, soil type, slope and aspect (Surfleet and Tullos, 2013). The *a priori* distribution of each parameter for each HRU was determined from parameter sets developed for the Willamette River Basin (Chang and Jung, 2010). Posterior distributions of the 13 hydrologic model parameters were developed for both dry summer and wet winter seasons for three sub-basins, henceforth referred to as parameter sub-basins, that represent the three hydrogeologic settings of the SRB: mixed SW-GW rain dominated (alluvial areas), SW rain and snow dominated (Western Cascades), and GW snow precipitation (High Cascades). Posterior distributions from these three parameter sub-basins were then extrapolated to the remaining sub-basins of the SRB based on similar hydrogeologic characteristics, elevation and precipitation patterns. Five hundred of the parameter combinations with the best fit for each GCM and GHG emission scenario were used to obtain the 2.5%, 50% and 97.5% daily values. While the uncertainty analysis was conducted for each of the eight GCMs, the daily mean of all eight GCMs, for the 2.5^{th}, 50^{th} and 97.5^{th} percentiles, were used as inflows in HEC-ResSim to reduce the number of reservoir operations model simulations required.

In addition to the daily precipitation, maximum and minimum air temperature (NOAA COOP, 2010; NRCS SNOTEL, 2010) under to develop the model, historical daily streamflow records (USGS NWIS, 2010), from 1973 to 2012, were used for both model development and validation. In addition, well observations were used to validate the groundwater model in the alluvial areas of the basin. Fit of model to the observed historic (1960-2006) streamflow for the three parameter sub-basins is high for both daily and monthly record, with Nash Sutcliffe Efficiencies (NSE) greater than 0.7 and 0.8, respectively (Surfleet and Tullos 2012). The model fit to observations varies for the sub-basins to which parameter distributions were transferred. For example, strong statistical fit was observed in basins with high proportions of the Western Cascades, with NSE values of 0.75 and Root Mean Square Error (RMSE) value of 0.1 m^3/s. In contrast, one basin with substantially larger area draining the High Cascades than the parameter sub-basin produced a weak statistical fit to observations, with NSE value of 0.35, reflecting an RMSE of 0.8 m^3/s (Surfleet and Tullos, 2013). The model output fit differences for the areas where parameters were transferred is likely due to may result from the proportion of the basins draining the High Cascades geology.

For the rest of the WRB we used the median ensemble mean of all the GCMs from VIC projections (Hamlet et al., 2010b). Results from the same eight GCM projections and GHG emission scenarios used in GSFLOW were applied in VIC projections. Daily minimum and maximum temperatures and precipitation data were gridded at 1/16-degree spatial resolution from (Elsner and Hamlet, 2010; Hamlet et al., 2010a). VIC model was validated and calibrated on a monthly time step to available natural or unregulated streamflow data from eleven large basins located east of the Cascade mountain divided within the Columbia River Basin (Elsner and Hamlet, 2010). The NSE for the Willamette River Basin was 0.89 for the calibration period (1975 to 1989) and 0.91 for the validation period (1960 to 1974) (Elsner and Hamlet, 2010). Model calibration was based on adjusting infiltration, Ds, Ws, Dsmax and soil depth using the MOCOM-UA autocalibration tool to fit monthly data. For greater detail on VIC model calibrations and validation please see Elsner and Hamlet (2010). Infiltration, runoff, and baseflow processes are simulated in VIC model based on empirical derived relationships that characterize the average grid cell condition (Liang et al., 1994). The VIC model does not explicitly represent the storage and movement of groundwater, which limited its applicability for comparing climate change response across hydrogeologic conditions. Thus, VIC projections were only used as inputs to remaining nine reservoirs in the WRB located upstream from Albany (Fig.1; right inset) to simulate the entire reservoir network.

To match both GSFLOW and VIC streamflow projections and use them as inputs for HEC-ResSim, we calculated annual discharges to classify the water year into a) dry (lowest ¼), b) normal (middle ½), and c) wet (upper ¼) water years. Streamflow projections from both datasets are compiled into Simulated Historic (1960- 2000), Near Future (2030- 2060), and Far Future (2070-2100) time periods. Within each time period, wet, normal and dry water years are randomly selected from VIC streamflow projections to match with wet, normal, and dry water years from GSFLOW streamflow projections.

2.2.2 Reservoir operation modeling description

We applied the same rule curves implemented in the U.S. Army Corps of Engineers' (USACE) 2010 Willamette Basin HEC-ResSim model, which includes Biological Opinion (BiOp) operations for spring and summer flow releases for the seasonal life histories for Chinook and Steelhead (NMFS, 2008), in addition to winter flood control operations from the Water Control Manuals (WCMs) for each reservoir. The reservoirs are operated by a set of operation objectives or rule curves (Fig. 3) originally designed (USACE, 1953; 1968a; 1968b) based on assessments of natural variability, historical streamflow records, design storage capacity and the minimum releases. Reservoir release decisions are based on a set of rule curves within a zone that schedule releases from the lowest to the highest priority. There are five zones in ResSim: Top of Dam, Flood Control, Conservation, Buffer, and Inactive. Each zone is based on pool storage and elevation levels for each day of the year. HEC-ResSim calculates a reservoir's release at each time step to meet the highest priority rule called Guide Curve (GC), which is the Conservation Pool Rule Curve for the analysis presented herein. When the reservoir's pool elevation is above the GC, within the Flood Control (FC) zone (Fig. 3), the reservoir will release more water than is entering the pool. In contrast, when pool elevation is below the GC, the reservoir will release less water than is entering to the pool.

The storage and release schedule varies for each reservoir (Fig. 3). Detroit reservoir starts releasing water in September to create storage capacity for flood control, dropping the reservoir elevation from 477 m to 442 m by December (USACE, 1953). As flood risk decreases across the winter season, the reservoir is allowed to refill, beginning January 31st to reach maximum Conservation pool at 477 m by May 4th at a rate of 5 Mm^3 per day during February and 3 Mm^3 per day during March. The elevation in Big Cliff reservoir is maintained year round at 365 m of elevation, with the pool level varying ~7 m on a daily cycle due to hydropower generation (USACE, 1953). Green Peter reservoir starts releasing water to generated flood storage capacity in September, lowering the reservoir from 308 m at Conservation pool to 280 m by December. It stays in the flood control zone until February, when the outflows are reduced to refill the reservoir by May 9th (USACE, 1968a). Foster reservoir generally has two refilling periods due to the small amount of flood control storage associated with historical and unrealized plans for a second flood control project upstream of Foster Dam. Special flood-regulations schedules for Foster Dam refill the reservoir up to 190 m by March 28th. The reservoir is then is lowered back to 187m by April 15th. For the period of April 15th to May 15th, a 29 cms spill is released through the spillway gate for downstream juvenile fish passage, with the reservoir kept at minimum Flood Control pool until refilling up to 194 m at maximum Conservation pool by May 30st (USACE, 1968b).

Since the two reservoir systems in the SRB, Detroit/ Big Cliff and Green Peter/Foster are part of the (USACE) thirteen multipurpose dams and reservoirs in the WRB (Fig. 1, right inset) they all operate as a system to maintain downstream control points (e.g. Salem) below bankfull by storing water. While bankfull stage is considered to be a non-damaging level, it is a stage where action is required (USACE, 2011). Thus, reservoir releases depend on the river stage at the downstream control point with the highest priority. For the WRB, and thus the SRB, the Salem control point on the mainstem of the Willamette River (Fig. 1, right inset) has higher priority over the upstream Harrisburg and Jefferson control points, which contribute discharge to the Salem control point. The control point at Jefferson is located below the confluence of the North Santiam and South Santiam rivers and thus is regulated by both the NSB and SSB reservoir systems. If the stage at Jefferson goes above bankfull, operators will regulate releases from the Detroit-Big Cliff complex before regulating releases from Green Peter and Foster. Flows at Jefferson are usually regulated to bankfull stage by reducing releases from Detroit long before it is necessary to control releases from Green Peter and Foster. Green Peter reservoir provides the principal flood regulation in the SSB (USACE, 1968a). Foster serves as a re-regulating reservoir for power peaking at Green Peter and has limited capacity to store high winter floods from Green Peter releases and flows from the South Santiam River at Cascadia (USACE, 1968b), resulting in historical flows at Waterloo often being at or above bankfull levels.

Hydropower is generated at all four of the dams, and the maximum power release rule curve is always the top priority rule in each of the five zones in each reservoir. Releases are prioritized through the penstocks, as opposed to the spillway and re-regulating outlets, to generate power during regulation for flood control and environmental flows.

2.3 Reservoir Operation Performance Measures

To investigate the nature and importance of climate-related uncertainties and hydrologic variability in the context of dam operations, we evaluated the reservoirs' operational performance under the 2.5, 50, and 97.5 percentiles of streamflow projections. The two reservoir systems under study are adjacent in space but are sourced from basins of different hydrogeological characteristics and elevations. Inflows to Detroit-Big Cliff reservoir system are entirely sourced by the High Cascade geology and are located at higher elevations compared to the Green Peter-Foster reservoir system sourced entirely by the Western Cascade geology at lower elevations. Reservoir performance measures were chosen based on reservoir primary functions, including flood risk, hydropower production, environmental flows and probability of refill. Uncertainties in reservoir reliabilities related with streamflow projections are represented by the range between the 2.5 and 97.5 percentile output. The 2.5, 50, and 97.5 percentile values for each metric are calculated from the outflows and reservoir elevations generated from simulations of the entire study period using the 2.5, 50, and 97.5 percentile inflows to the reservoirs.

2.3.1 Flood Risk Analysis Measures

We analyzed the reliability of flood risk reduction using two measures, one based on the adequacy of the reservoir capacity for storing floods of different recurrence intervals, and a second based on the frequency of flooding at downstream control points in the systems. The adequacy of the flood storage capacity was evaluated as the ability of the reservoir to store a 3-day annual flood event of a 1-year (1yr), 2-year (2yr), 5-year (5yr), 25-year (25yr), 50-year (50yr), 100-year (100yr), and 200-year (200yr) recurrence interval (RI). We performed a flood frequency analysis using Log-Pearson Type III (LP3) distribution to obtain the flow (Q) associated with each RI, as outlined in the federal Guidelines for Determining Flood Flow Frequency (i.e. Bulletin #17B) (U.S. Department of the Interior, 1982), for each GCM separately. We then calculated the mean flow from the eight GCMs for each RI to obtain the Flood-Storage (St) ratio (Equation 1), which provided an estimate of the magnitude of potential inadequacy in flood storage. The Flood-Storage ratio was calculated as the ratio of the volume for a 3-day event at each RI (Q_{RI}) to the maximum reservoir storage (R_{st}) (Equation 1).

$$S_t = \frac{Q_{RI}}{R_{ST}} \qquad Equation\ 1$$

where, S_t is the reservoir flood-storage ratio; Q_{RI} is the 3-day runoff volume (m^3) for a given recurrence interval, and; R_{ST} is the maximum reservoir flood storage capacity (m^3). A value of one indicated a reservoir's maximum flood storage capacity levels and values less than one indicates that reservoirs will effectively store floods of a given RI, assuming no previous floods were being stored in the reservoir. When above one, a higher ratio reflected a larger inadequacy for storing a given RI event.

To evaluate the frequency of flooding at downstream control points, we evaluated the time reliability of flood control (F_C) (Equation 2) as the ability of the reservoirs to operate as a system to maintain elevations at control points below bankfull level (Hashimoto, 1982; McMahon et al., 2006). We calculated the number of days per year bankfull stage was exceeded at Mehama in the NSB, Waterloo in the SSB, and Jefferson in the mainstem of the Santiam River for each time period.

$$F_C = \frac{N_{FC}}{N} \qquad Equation\ 2$$

where, F_C is the time reliability of flood control; N_{FC} is the total number of days that flows exceed bankfull at downstream control points, and; N is the total number of days in the time period.

2.3.2 Reservoir Refill

We calculated reservoir refill as the percentage of the Conservation pool elevation achieved by the beginning of the Conservation season: May 4th for Detroit; May 9th for Green Peter, and May 30th for Foster (Equation 3). A reservoir was considered to be 100% refilled if it achieved maximum Conservation pool elevation by the beginning of the Conservation season. The percentage of reservoir pool elevation was calculated for each year and then averaged by decade.

$$R = \frac{S}{R_C} * 100 \qquad \textit{Equation } 3$$

where, R is the reservoir refill (%); S is reservoir pool elevation (m) at the beginning of the Conservation season, and; R_c is the desired Conservation pool elevation based on the rule curve.

2.3.3 Environmental Flows

To determine the frequency that the system does not meet minimum spring and summer flow targets over a period of time, we calculated the time reliability (Hashimoto, 1982; McMahon et al., 2006; Milutin and Bogardi, 1997) for spring (S_{PR}) (Equation 4) and summer (S_{UM}) (Equation 5) minimum flows for the North Santiam River at Mehama and South Santiam River at Waterloo. Minimum spring flow targets were defined by the 2008 BiOp to be released from April to June for assisting with downstream migration of juvenile salmonids. Summer flow targets released from July to October were established for fish habitat and meeting water quality targets. These BiOp minimum flow recommendations are slightly higher than historical levels because it takes into account increases in diversions downstream of the dams relative to historical observations (Bach et al., 2013; NMFS, 2008).

$$S_{PR} = \frac{N_t}{N} \qquad \textit{Equation } 4$$

$$S_{UM} = \frac{N_t}{N} \qquad \textit{Equation } 5$$

where, N_t is the total number of days the targets were not met during the spring (S_{PR}) or summer (S_{UM}) season, and; N is the total number of days in the time period.

2.3.4 Hydropower Efficiency (P_e)

To analyze the ability of reservoirs to produce the maximum amount of energy the power plants are capable of producing over the course of an average year (efficiency) and its sensitivity to climate variability, we calculated the ratio of averaged annual power generated to generation capacity (Equation 6) at each reservoir, where power generated is estimated from the head and discharge at each time step (Equation 7).

$$Pe = \frac{P}{PC} \qquad \textit{Equation 6}$$

$$P = \rho\, \eta\, Q\, g\, h \qquad \textit{Equation 7}$$

where, P is hydropower production (MW); ρ is the water density (kg/m3); η is turbine efficiency (assumed 90 %); Q is water discharge (cms); g is acceleration of gravity (m/s2), h is the falling height (m), and; PC is generation capacity. A value of one indicated that the reservoir is capable of producing the total hydropower capability, whereas values less than one indicate the degree to which the power plants are generating under capacity.

3 Results

We first provide an overview of hydrologic projections in the SRB and then present results on the impacts and uncertainties of streamflow changes for reservoir performance measures. The study was made for A1B and B1 GHG emission scenarios; however, for clarity of the figures and because differences between the two GHG emission scenarios were insignificant, we only plotted results for A1B scenario to show the worst-case scenario.

3.1 Water Supply Estimates

Streamflow projections from GSFLOW simulations (Fig. 4) for the SRB indicated the two sub-basins will undergo similar responses to projected warming, characterized by increases in winter flows and reductions in summer flows relative to simulated historic hydrology.

However, the degree of differences varied between the basins. For example, increases in December median inflows, relative to simulated historical flows, were projected to be 17% higher at Detroit reservoir in the NSB (Fig. 4a) than at Green Peter reservoir in the SSB (Fig. 4b). Conversely, reduction in August median runoff was projected to be 13% higher at Green Peter reservoir than Detroit reservoir. Additionally, streamflow projections suggested that uncertainty in streamflows were higher during the winter months (Fig. 4c-d) compared to the summer months at both locations, and higher uncertainty was projected for NSB streamflows into Detroit reservoir relative to SSB inflows to Green Peter reservoir.

Results indicated that floods of small magnitude were likely to increase in the future for both NSB and SSB while floods of greater magnitude were likely to decrease slightly or not change in the future (Fig. 5). While inflows of 5yr or lower RI were projected to increase into the future for all three reservoirs, the response of larger magnitude floods, such as the 100yr or 200yr RI, was to not change or to decrease, with variability across the reservoirs. However, projected changes in winter inflows entering the reservoirs were greater for Detroit reservoir than for Green Peter and Foster reservoirs. Flood events up to the 25yr RI were projected to be higher than simulated historical at Detroit when uncertainty was considered, while flows up to only the 5yr RI at Foster and Green Peter reservoirs were projected to increase over simulated historical. For the larger events, projected changes were small. The largest, 100yr flood events were not projected to change at Detroit and Green Peter when uncertainties were considered, and the arrival of 100yr events to Foster were projected to decrease only by 2% for the lower confidence interval under both NF and FF time periods. For the 200yr flood, both Detroit and Foster decreased 2% for the lower confidence interval under both NF and FF time periods, and Green Peter was not projected to change when uncertainties were considered.

3.2 Reservoir Operation Performance Measures

3.2.1 Flood Risk Analysis Measures

The ability of Detroit and Green Peter reservoirs to store a three-day event of a particular recurrence appeared to be high now and in the future (Fig. 6). Despite the projected changes in the size and frequency of smaller floods entering the reservoirs (Fig. 5), impacts of warming on the flood storage ratio were negligible. The ratio remained below one at both Detroit and Green

Peter under all time periods and scenarios, indicating that both reservoirs will be able to reliably store the analyzed floods under the simulated future. The flood storage ratio remained constant into the future, presumably because increases were projected only for floods of small magnitude, which are generally easy to regulate. Like the inflows (Fig. 4), uncertainty in the flood storage metric was high for the NSB and very low for the SSB. While the range between the 2.5 and 97.5 percentile predictions for the flood storage ratio at Green Peter was close to zero, Detroit ratios for the 2.5 and 97.5 percentile were + 0.05 and - 0.15 relative to the median for almost all RIs.

Under all time periods, the control point at Waterloo in the SSB was projected to experience higher risk of winter flows exceeding bankfull stage than other control points in the SRB (Fig. 7). Simulated river elevations at the Jefferson control point, located on the mainstem of the Santiam River, and the Mehama control point, located in the North Santiam River, were below bankfull stage under all time periods and scenarios. In contrast, river elevations at Waterloo, located in the South Santiam River, exceeded bankfull stage during at least a few years under all time periods. When uncertainties were considered, Waterloo bankfull target was exceeded for 18 of 40 years during the SH time period, with 1 to 5 days above bankfull stage in each of those years. For the NF time period, the bankfull target was exceeded in 11 and 0 of the 30 years during A1B and B1 scenarios, respectively, with 1 to 4 days above bankfull stage in each of those years. In the FF time period, the bankfull target was exceeded in 17 and 13 of 30 years during the FF time period under A1B and B1 respectively, with 1 to 3 days above bankfull stage. In general, the impact from uncertainty related to GCM and hydrologic model parameters on estimates of flood control at downstream control points was relatively large, based on the comparison of 0 to 4 days above flood stage in any given year against an interquartile range of 2 to 3 days. Results suggested no clear impact of climate change on the reliability of flood control of the Green Peter-Foster reservoir complex. Instead, it appeared that bankfull stage levels at Waterloo were likely a result of reservoir operation priorities.

3.2.2 Reservoir Refill

For both the simulated historical and future inflows, the reservoirs did not reliably refill to maximum Conservation pool (Fig. 8) by their respective deadlines in May (Fig. 3), and the impact of a warmer climate appears to be negligible, particularly when uncertainty is considered.

For both historical and future scenarios, while the reservoirs failed to reliably refill by their May deadlines, they often reached water levels very close to maximum Conservation pool (Fig. 9) and refilled within 15 days of the refill deadline in 90% of the years, based on median runoff scenarios. Relative to historical, the future appeared to have an initially higher but declining refill reliability, though the differences were all within the range of uncertainty. Thus, despite not refilling by the deadline each year, the reliability of reservoirs to eventually refill, both in the past and future, was high and does not appear to be appreciably impacted by a warming climate.

Some variability between basins was observed, as illustrated by a wet and dry water year under the simulated historical scenario. While Detroit reservoir in the NSB may never refill during a dry water year (e.g. 1996 for the simulated historical time period) (Fig. 9), reaching only ~94% of maximum Conservation pool under the lower confidence interval, it may refill ~10 days after the May 4th deadline during a wet water year (e.g. 1998 for the simulated historical time period) (Fig. 9d). Pool elevation at Big Cliff reservoir is constant throughout the year with fluctuations no bigger than ± 1 meter each day in the course of re-regulating flows from Detroit power plant, therefore it was not considered in this metric. At Green Peter reservoir in the SSB, refill reached maximum Conservation pool ~20 days after the May 9th deadline during the same dry water year (Fig. 9b) and met the refill deadline during the same wet water year (Fig. 8e). Foster reservoir appeared to refill to maximum Conservation pool by May 30th deadline during both dry (Fig. 9c) and wet (Fig. 9f) water years. Uncertainties with reservoirs' ability to refill were large for Detroit reservoir in the NSB relative to the observed change in refill for the other reservoirs, with differences of 2 to 3% between the 2.5 and 97.5 percentiles (Fig. 8). In contrast, Green Peter and Foster uncertainties were small relatively to the observed change, with an interquartile range no larger than 1.5%. This range of uncertainty appeared to decline in the future for the SSB reservoir system but stays about the same for the NSB reservoir system.

3.2.3 Environmental Flows

Results indicated that the reliability of meeting spring flow targets (Fig. 10) was generally high under both historical and future scenarios and in both the NSB and SSB, though reliability was lower in the NSB when uncertainties were considered. While both basins met spring flow targets every year for the SH time period, the NSB did not meet the spring flow targets in the NF and FF time periods for the 2.5 percentile flows for A1B scenario and in the NF for B1 scenario. The lower reliability in the NSB was associated with higher uncertainty for the NF_A1B scenario, where 13 out of 30 years were projected to experience a minimum 8 days when flows are below targets for the upper confidence interval. In years with the lowest performance, spring flow targets were not met for up to 42 days. The uncertainty was lower for the FF_A1B scenario, where only 6 years experienced up to 30 days with flows below spring targets under the lower confidence interval. For the B1 scenario, only the NF time period experienced 4 years of flows below target for less than 10 days under the lower confidence interval, whereas spring flow targets were met throughout the B1 FF time period. Thus, while spring flow targets were generally met in both basins, uncertainty in the spring flow reliability was higher in the NSB and indicated that the reliability of spring targets may be compromised in the future during periods of low flow.

Reservoirs' ability to meet summer flow targets and the uncertainty in those estimates, varied across the two basins, but projections indicated that decrease in summer flow reliability may occur into the future for both basins (Fig. 11). From the simulated historical record, summer flow targets were met in 100% of days for the SSB, while both the number of days of inadequate flows and the uncertainties in those estimates were higher in the simulated historical NSB. With failure defined as a year in which all confidence intervals for the number of days below a target were non-zero, the SSB failed to meet summer targets in 2 of the 30 years for the near future under the lower confidence interval for both A1B and B1, indicating that reliability may decrease from simulated historical. Reliability in the NSB also decreased from historical to the near future, with only 1 year above zero under the lower confidence interval for the NF_B1. For the far future time period, the SSB failed to meet flow targets for 18 and 8 years in the 30 year simulation period under A1B and B1 scenarios, respectively, whereas the NSB only failed during 2 and 1 years. However, uncertainties in the NSB flows were high relative to the SSB, with differences between the upper and lower confidence interval of up to 120 days in some years for both simulated historical and future time periods. Thus, the frequency of future failures in meeting summer targets was higher for the SSB, though the reliability of meeting summer flow targets was far more uncertain for the NSB relative to the SSB.

3.2.4 Reliability of hydropower production

The impact of a warming climate on the reliability of producing hydropower appeared as a decline in power production, though the effect was within the uncertainty limits of the model (Fig. 12). For the simulated historical period for the median flows, the NSB reservoirs operated at between 40-50% of maximum power production. This range appeared to drop to 30%-40% for by the FF time period, though the differences were generally within the lower confidence interval of the simulated historical data. The SSB reservoirs operated at ~60% or 90% for Green Peter and Foster reservoirs, respectively, for this simulated historical period. Those ranges dropped for Green Peter reservoir in the future, but not for Foster reservoir, though most future projections were within the uncertainty of future projections. Thus, the impacts of a warming climate on power production at the largest two reservoirs were small declines in production, relative to capacity, though the differences were rarely larger than uncertainties. Decreases in hydropower capability for Detroit and Green Peter were likely a result of more water being released through the spillway rather than the penstocks. For example, based on the median confidence interval, the number of days water was released through the spillway increased by ~3% and ~5% for the Far Future time period at Detroit and Green Peter respectively.

4 Discussion

4.1 Reservoir Performance under a changing climate

By applying a reservoir operations model to distributions of simulated future runoff impacted by climate change, we found limited evidence of a response in reservoir operations performance to a warming climate. Despite projected increases in winter flow and decreases in summer low flows, only the ability to meet summer flows in one of the two study basins was conclusively impacted by the simulated future climate, suggesting that reservoir operations may adequately accommodate hydrologic changes in the Santiam River basin, without compromising the ability to meet operating objectives. However, independent of climate impacts, the results highlight areas where operations performance may be improved and how hydrologic uncertainty may impact uncertainty in evaluations of reservoir performance.

While some studies have suggested the need to modify reservoir operations to mitigate the effects of climate changes (Watts et al., 2011) or to reduce the impact of climate change on water systems (Vonk et al., 2014; Watts et al., 2011), our results indicated that the projected changes in hydrology were not large enough to generate substantial changes to the performance of reservoir operations in the Santiam River. The projected changes in inflows did not affect the ability of the reservoirs to store a three-day event of any recurrence interval (Fig. 6) or to maintain downstream control points below bankfull (Fig. 7). Furthermore, and contrasting the results of other studies on climate change impacts on reservoir refill (Payne et al., 2004), the changes in hydrology did not appear to appreciably affect the ability of the reservoirs to refill (Fig. 8), or the ability to meet spring environmental flow targets (Fig. 9). While results indicated that hydropower production could decrease in the future (Fig. 12), consistent with other studies (Schaefli et al., 2007; Vonk et al., 2014), the changes were rarely larger than uncertainties. Thus, reduction in the reliability of meeting summer flow targets (Fig. 11) provided the only evidence of climate change impact suggesting that large hydrologic changes may be required for other operating objectives to be impacted.

Regarding the comparison in sensitivity between the two basins due to hydrogeology, the three distinguishing features between the basins were the sensitivity of the SSB to the hydrologic changes associated with summer low flow, differences in prioritization around flood risk reduction, and the uncertainty in streamflow in the NSB, which lead to uncertainty in several of the reservoir performance metrics. The increase in the frequencies of floods for low return intervals (1-yr) and decreases in frequencies of high return intervals (200-yr) were greater for the groundwater basin reservoir system compared to the surface water basin reservoir system (Surfleet and Tullos, 2013). The warmer and wetter winters with more rain than snow precipitation (Mote *et al.*, 2005) for the Detroit-Big Cliff reservoir systems explains the predicted increases in small flood events. In contrast, high flood events have been associated with rain on snow events in which warm air temperatures leads to more rain precipitation creating rapid snow melt and runoff (Marks et al., 1998). Thus, decreases in snowpack accumulation projected in the area (Surfleet and Tullos, 2013) could be associated with greater decreases in high flood events for the groundwater reservoir system.

For sensitivity to summer low flow, only the ability to meet summer environmental flow targets appeared to decline in the future (Fig. 11). Across the two sub-basins, the frequency of future failures in meeting summer targets was higher for the surface water basin (SSB) relative to the groundwater basin (NSB), though the reliability of meeting summer flow targets was far more uncertain for the groundwater basin. This discrepancy between the NSB, with higher elevations and greater groundwater connectivity, and the SSB, with a more limited snow zone and more rapid runoff, is consistent with other studies (Nolin and Daly, 2006; Safeeq et al., 2013) that found summer low flows in basins at higher elevations with snow precipitation may be less sensitive to changes in climate than basin at lower elevations located along the rain-snow transition zone (Fig. 4). However, this discrepancy between the NSB and SSB summer flow target reliability may also be related to the high uncertainty in streamflow projections in the NSB, which generated higher uncertainty in the reliability of meeting summer flow targets. From a water management perspective, the ecological implications of not meeting these BiOp minimum flow recommendations could put aquatic species at risk (NMFS, 2008). For example, maintaining a baseflow from June to August of 28-34 cms in the North Santiam river (Big Cliff releases) and 20-34 cms in the South Santiam river (Foster releases) is intended secure rearing habitat for chub and juvenile salmonids, upstream migration of Chinook adults, protect steelhead redds from stranding, and maintain temperatures appropriate for species targets (Bach et al., 2013). At this point, it is unclear how longer duration of sub-target flows impact the survive and recovery of fish, and thus the ecological significance of the projected lower performance in meeting summer flow targets is unknown. While historical unregulated flows were as low as 12 cms and 15 cms on the North Santiam and South Santiam Rivers (Risley et al., 2012), respectively, the availability of side channel habitats and cold water refugia likely facilitated their survival during low flow conditions. With the removal of 22 percent of side channel habitat along the Willamette River over the past century (Gregory et al., 2002), the historical unregulated base flows may not be a relevant representation of minimum flows for fish survival today.

Regarding prioritization of flood risk reduction, existing operating priorities in the basin appeared as higher flood risk at Waterloo than at other control points in the Santiam River basin and lower hydropower production for the SSB, relative to the production capacity, at the reservoirs in the NSB. These results suggest that operating policies and priorities may need review, independent of impacts of climate change. However, warmer winters as a result of increases in air temperature should reduce winter power demand (Payne et al., 2004) suggesting that re-evaluation of reservoir operations and priorities taking into account changes in demands influenced by climate change could also benefit reservoir performance in the future.

Finally, relationships between climate projection uncertainty, system reliability, and system sensitivity in the NSB indicate that reservoir systems located in basins with groundwater interactions may be less predictable than reservoir systems located in surface water basins. Higher uncertainty for groundwater basins compared to surface water basins is likely a result of the uncertainty associated with modeling of groundwater for a number of reasons, including the a) transfer of model parameters in the groundwater model (Rosero *et al.*, 2010; Surfleet and Tullos, 2013), b) scarcity of information on the magnitude, timing, and direction of GW discharge and recharge in GW basins (Herrera et al., 2014, Safeeq et al. 2014a), and c) for this study specifically, the simulation of groundwater only where substantial groundwater interactions are known to occur (High Cascades). Despite a generally high model fit (Surfleet and Tullos 2012), this model configuration may have contributed to an underestimation of groundwater contributions to summer baseflow on the NSB, as has been reported in other studies (Safeeq et al., 2014b). Higher resolution of groundwater cells, high quality information about the groundwater depths and flow paths may improve the ability of existing models to capture groundwater behavior.

We summarize the results of this study in a graphic (Fig. 13) that illustrates our key findings regarding interactions between hydrogeologic sensitivity to climate change, impacts to reservoir operations, and hydrologic modeling uncertainty. We find that the basin (NSB), with more substantial groundwater resources, is more sensitive to the warming projected for the basin when considering winter peak flows, where as the basin (SSB), where groundwater plays a smaller role in the hydrologic cycle, is more sensitive with response to the response of summer low flows. These sensitivities translate to significant impacts on reservoir reliability only for meeting summer flow targets, whereby the sensitivity of the SSB generates significant declines in the reliability of the reservoirs to meet summer targets. However, we also find that the response of the groundwater basin to warmer air temperature is more uncertain and thus that the impacts on reservoir reliability are also uncertain. These relationships represent hypotheses around the interactions between sensitivity, reliability, and uncertainty of SW and GW systems beyond the SRB and warrant further study to verify how and where systems deviate from these expectations.

4.2 Study limitations

This top-down climate change assessment was conducted to evaluate the impact and importance of climate-related uncertainties and hydrologic variability on reliability and sensitivity of reservoir operations in basins with contrasting hydrologic conditions. In addition to the uncertainties around modeling of groundwater, as discussed in Section 4.1, assumptions regarding stationarity, model integration, and performance measures could impact the transferability of key findings. For example, we acknowledge that our analytic approach assumed stationarity in relationships and interactions between climate and the landscape, as well as reservoir operations and priorities. This assumption may not be appropriate for some types of analysis, such as the design of hydraulic structures (Obeysekera and Salas, 2014). However, for the purpose of identifying key differences in the sensitivity of reservoir operations and priorities to a warmer climate, we do not believe the stationarity assumption substantively impacted our key findings.

Next, additional and undocumented uncertainty is associated with combining GSFLOW and VIC simulations in order to simulate all 13 reservoirs in the broader Willamette River basin. Our intent in simulating the entire system was only to reflect how operating rules within the Santiam basin may be impacted flows throughout the basin. We expect that these uncertainties associated with combining the models are greatest for evaluation of flood risk. While we classified the water years in wet, dry and normal water years for the two datasets, floods generated by VIC and GSFLOW may have occurred at different times. However, the impact of uncertainties in the basin-scale flows produced by VIC impacted our two study basins similarly, and thus, while the exact values of estimated uncertainties would be different if GSFLOW was applied to the entire Willamette River basin, we believe the relative differences between the NSB and SSB, which was the emphasis of this study, would not be substantially impacted.

Finally, the reservoir performance measures were selected based on their familiarity to local stakeholders and reservoir operations, and by their common application in the literature

(Hashimoto, 1982; McMahon et al., 2006; Milutin and Bogardi, 1997). However, other approaches to evaluating reservoir operations performance have been proposed and offer an important advancement in evaluating reservoir performance under climate change. For example, Raje and Mujumdar (2010) include partial failure analysis and adaptive policies to mitigate impacts of climate change on reservoir operations.

5 Conclusions

Given that reservoir systems' sensitivity to climate variability can be influenced by basin hydrogeology, operating rules, and available storage, we assessed the impact, sensitivity, and uncertainty of changing hydrology on hydrosystem performance across different hydrogeologic settings. We evaluated the changes in future performance of reservoirs in the Santiam River basin (SRB), including a case study in the North Santiam Basin (NSB), with high permeability and extensive groundwater storage, and the South Santiam Basin (SSB), with low permeability, little groundwater storage and rapid runoff response. Key findings included: 1) Projected reductions in summer flows and increases in winter flows for both basins, but at levels small enough that reservoir performance did not appear to be impacted, except in summer flow targets for the SSB; 2) The hydrologic uncertainty in the NSB resulted in uncertainty in the reliability of reservoir refill, spring and summer flow targets, and hydropower production, indicating that water resources may be less predictable in basins with substantial groundwater interactions; 3) Higher resolution of groundwater cells, high quality information about the groundwater depths and flow paths may improve the ability of existing models to capture groundwater behavior; and 4) Irrespective of climate change, historical prioritization of reservoir operations appeared to impact reliability, suggesting review of operations may be warranted to consider how flood risk could be reduced at Waterloo and power production could be prioritized on the NSB. Results highlighted how summer flows may be vulnerable to climate change in surface water basins, but that large changes may be required for other operating objectives to be impacted. In addition, hydrologic uncertainty is likely to complicate planning for climate change in basins with substantial groundwater interactions. Finally, assessment of climate change impacts may support the identification and modification of existing inefficiencies in system operations that are independent of a warming climate.

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	GREEN PETER	FOSTER	DETROIT	BIG CLIFF
Primary Function	Flood Control	Re-regulating	Flood Control	Re-regulating
Project Purposes*	F,N,HP,E,I,M,R	F,N,HP,I,M,R	F,N,HP,E,I,M,R	F,N,HP,I,M,R
Drainage Area (km^2)	717	1,279	1,134	1,171
Storage (m^3)	528,053,582	74,872,349	561,357,592	7,955,958
Storage space reserved for winter floods (m^3)	333,040,096	36,511,062	370,044,551	-
Normal Evacuation Rate (cms)	283	425	283	283
Maximum Evacuation Rate (cms)	368	510	481	481
Min. Power Pool (m)	275	186	434	360
Min. Summer Release (m/sec)	91	122	229	229
Spillway Crest (m)	295	182	470	354
Number of Spillways	2	4	6	3
Total Capacity at Max Cons. Pool (cms)	262	4,814	2,791	-
Total Capacity at Full Pool (cms)	283	5,663	4,127	5,069
Total Capacity at Max Pool (cms)	283	5,663	5,427	5,069
Number of Regulating Outlets	2	-	4	-
Total Capacity of all RO's at Max Pool (cms)	374	-	793	-
Total Capacity of all RO's at Min Pool (cms)	268	-	560	-
Number of Turbines	2	2	2	1
Total MW capacity at full pool	80	20	100	18
Capacity per Turbine at Min Pool (cms)	63	48	70	91
Capacity per Turbine at Max Pool (cms)	51	38	55	80
Total Cap. at Full Load at Min Pool (cms)	125	97	140	-
Total Cap. at Full Load at Max Pool (cms)	102	75	110	-

*F- Flood Control; N- Navigation; E- Environmental; HP- Hydropower; I- Irrigation; M- Municipal & Industrial; R- Recreation

Table 1 Reservoir characteristic

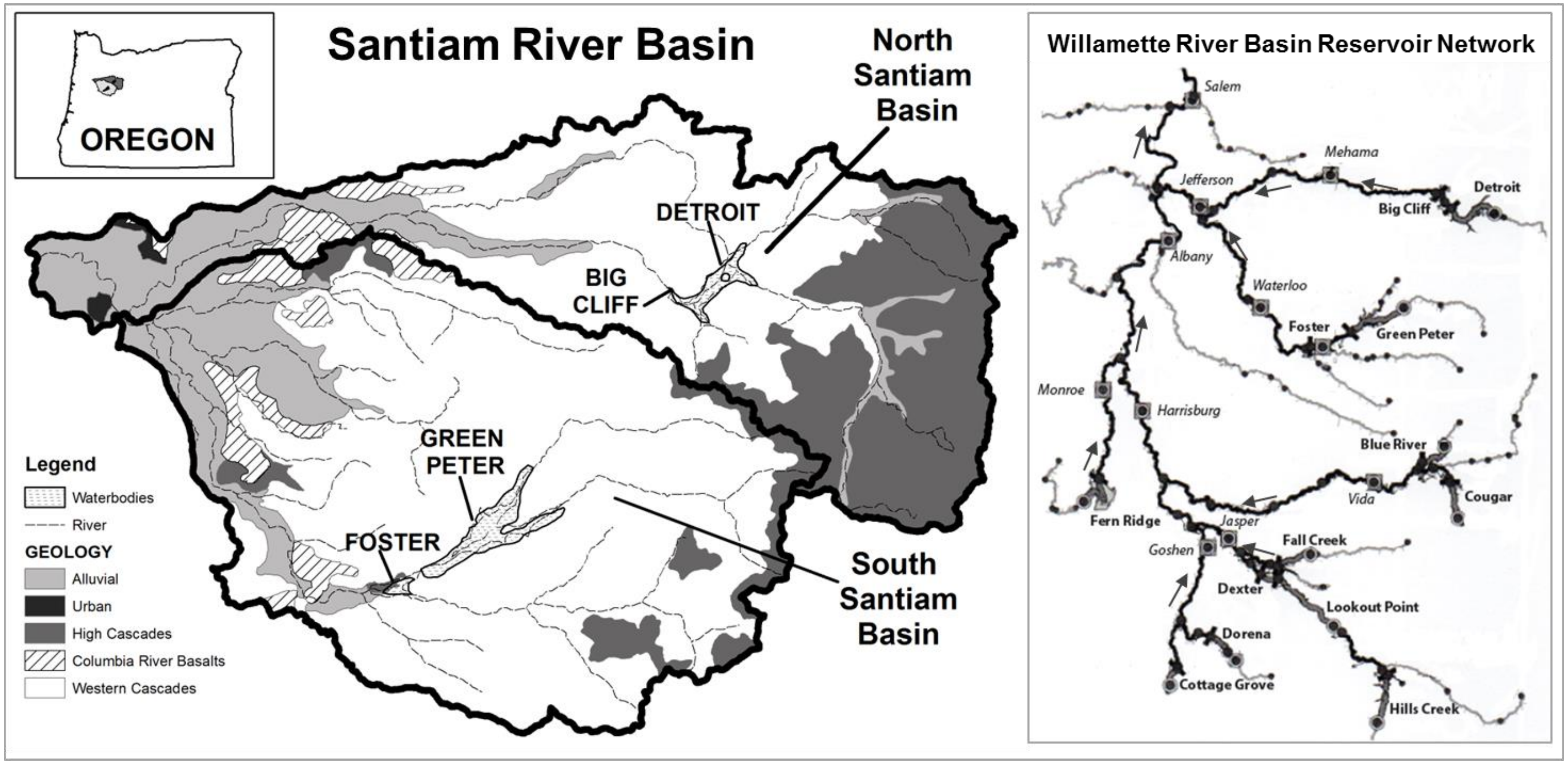


Fig. 1 Left inset: Santiam River Basin (SRB), reservoirs and geology. Right inset: Willamette River Basin Reservoir Network. Thirteen multipurpose dams and reservoirs (in bold) work as a system to meet downstream flow targets at control points (in italic). The arrows indicate the direction of the flow, the black dots represent stream nodes in the stream alignment, the black dots with gray circles represent computational points where streamflow projections are added to ResSim model, and the black dots with gray boxes represent control computational points for reservoir operation.

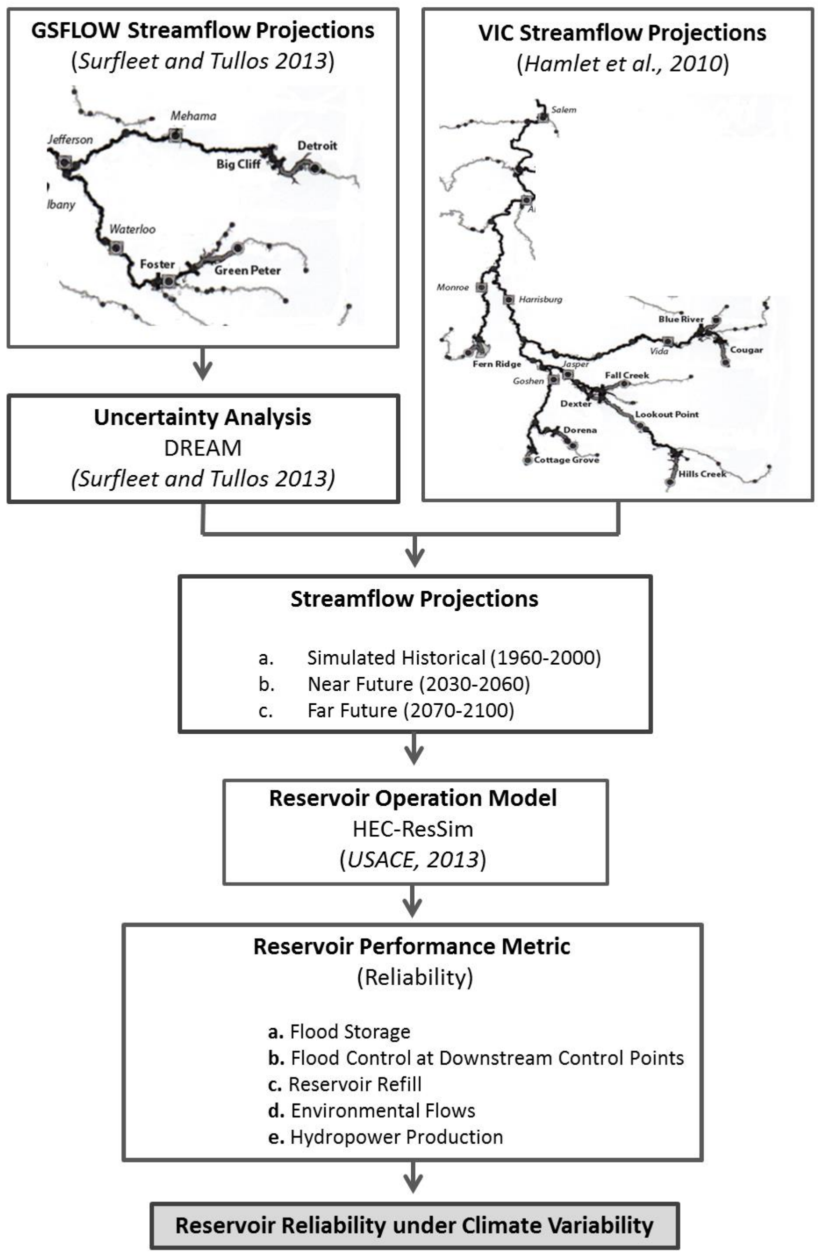


Fig. 2 Study Approach

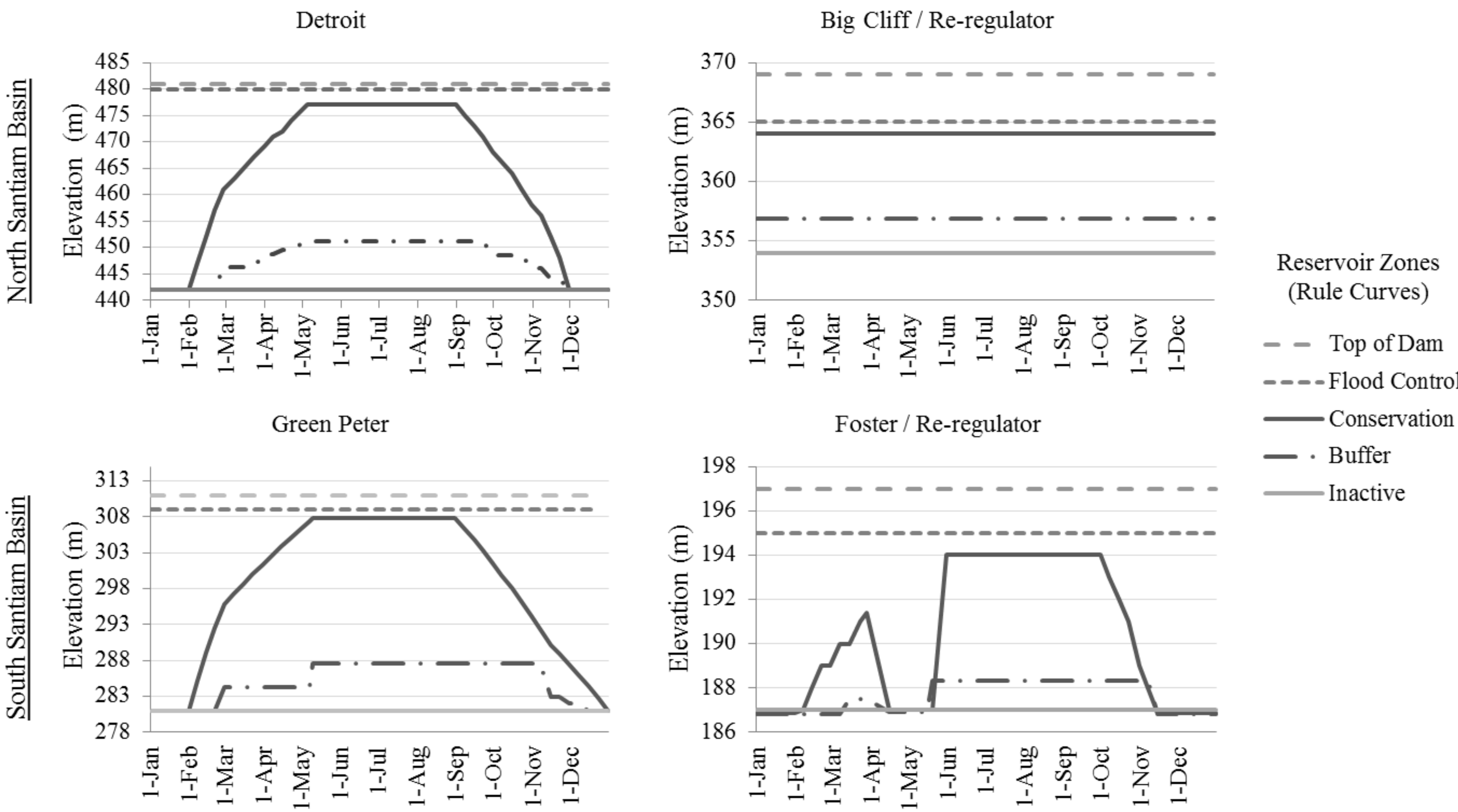


Fig. 3 Santiam Basin Reservoir Rule Curves.

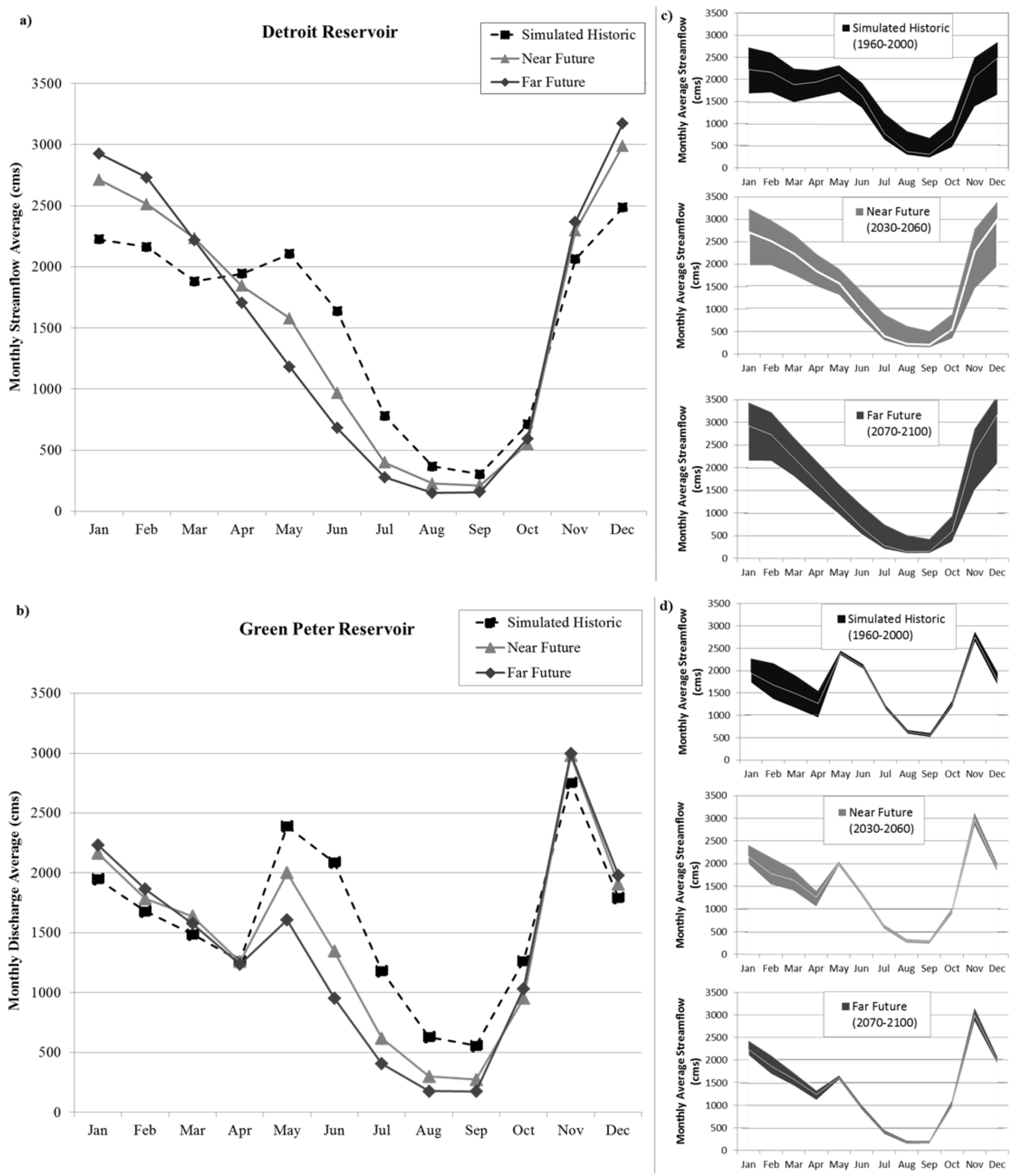


Fig. 4 GSFLOW streamflow inputs under A1B GHG emission scenario at Detroit reservoir and Green Peter reservoir. Figures a) and b) shows the median confidence interval for the Simulated Historical (SH), Near Future (NF) and Far Future (FF) time periods, and figures c) and d) shows the median confidence interval (white line) for each time period with its uncertainty (shaded area).

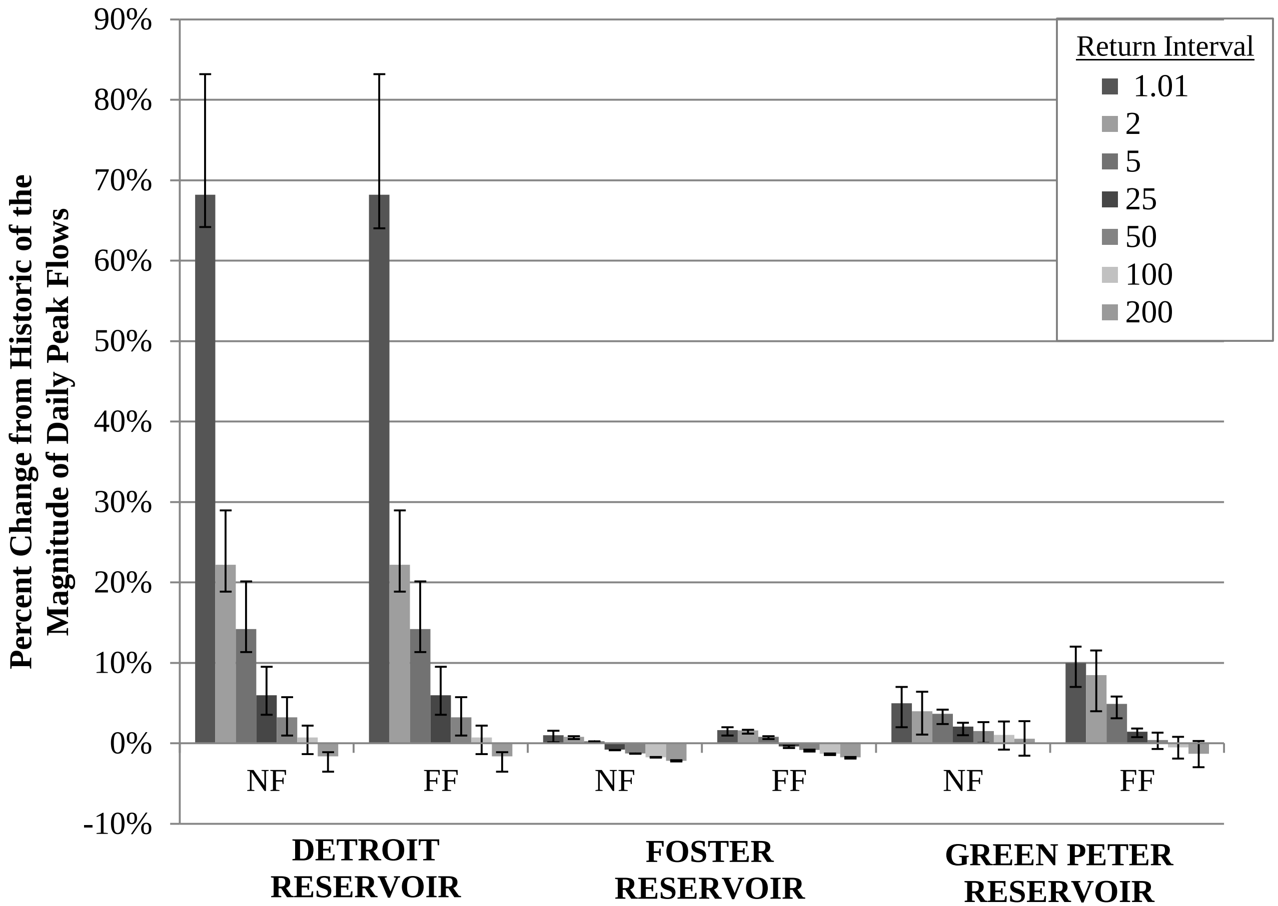


Fig. 5 Percent change from historic in the size and frequency of peak daily inflows (median) of 1yr, 2yr, 5yr, 25yr, 50yr, 100yr and 200yr recurrence intervals (RI). Error bars represent the upper and lower confidence interval. The likelihood of the various discharges as a function of recurrence interval is obtained using Log Pearson Type III distribution (Bulletin #17B (USGS) method for estimating quantiles.

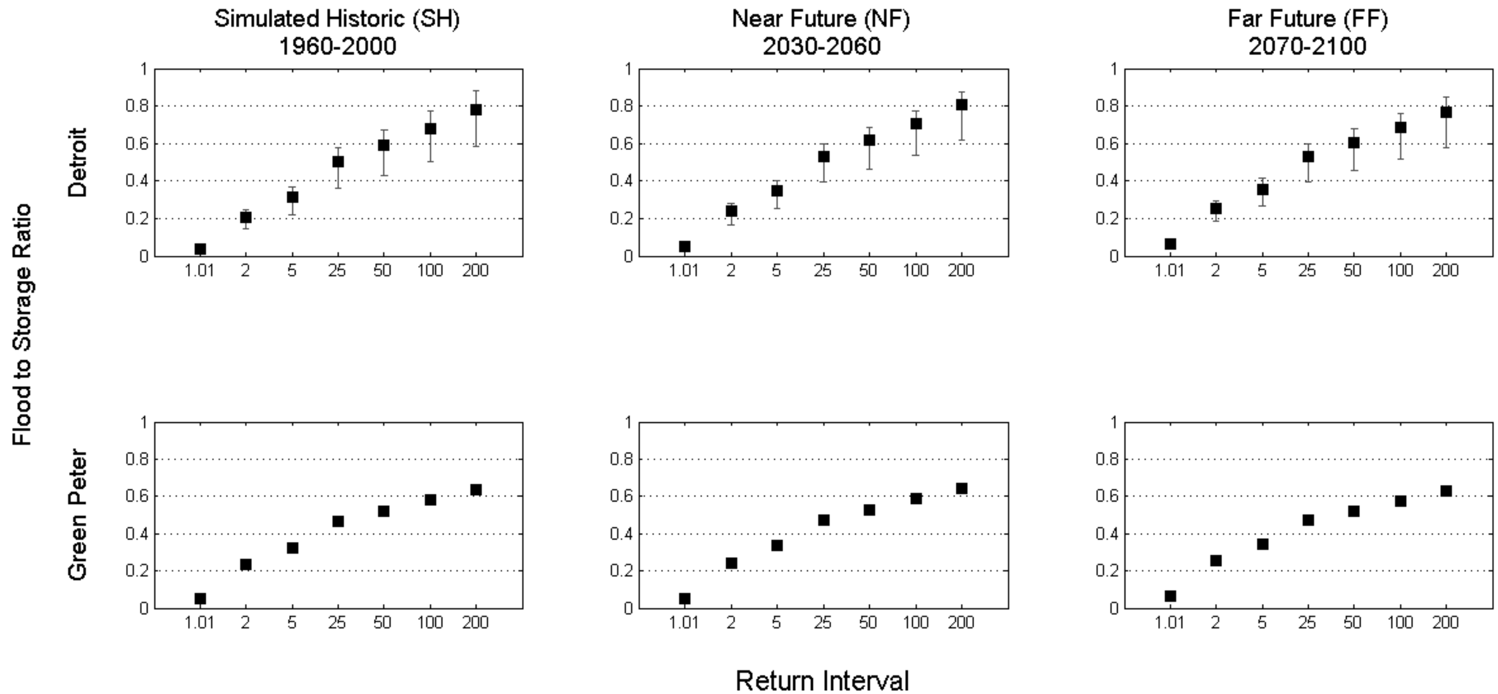


Fig. 6 Flood to storage ratio represented as the ability of a reservoir, on any given day to store a three-day event of a particular recurrence interval was calculated for Detroit, and Green Peter reservoirs for the Simulated Historical (SH), Near Future (NF), and Far Future (FF) time periods under A1B GHG emission scenarios. A higher ratio means a potentially larger failure to store high flood events.

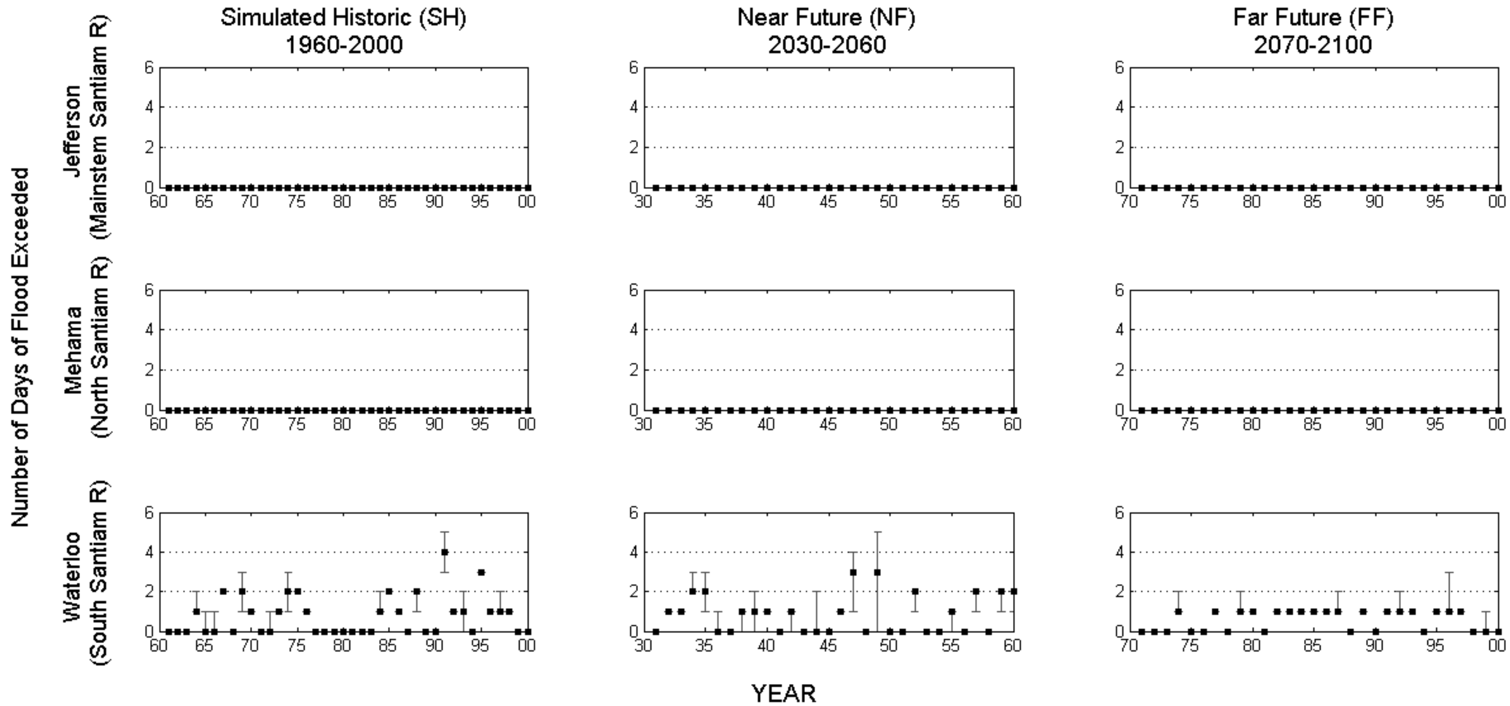


Fig. 7 Time reliability of flood control at downstream control points represented as the number of days flood exceeded at Jefferson control point in the mainstem of the Santiam River, Mehama control point in the North Santiam River, and Waterloo control point in the South Santiam River for the Simulated Historical (SH), Near Future (NF), and Far Future (FF) time periods under A1B GHG emission scenarios. Error bars represent the upper and lower confidence interval.

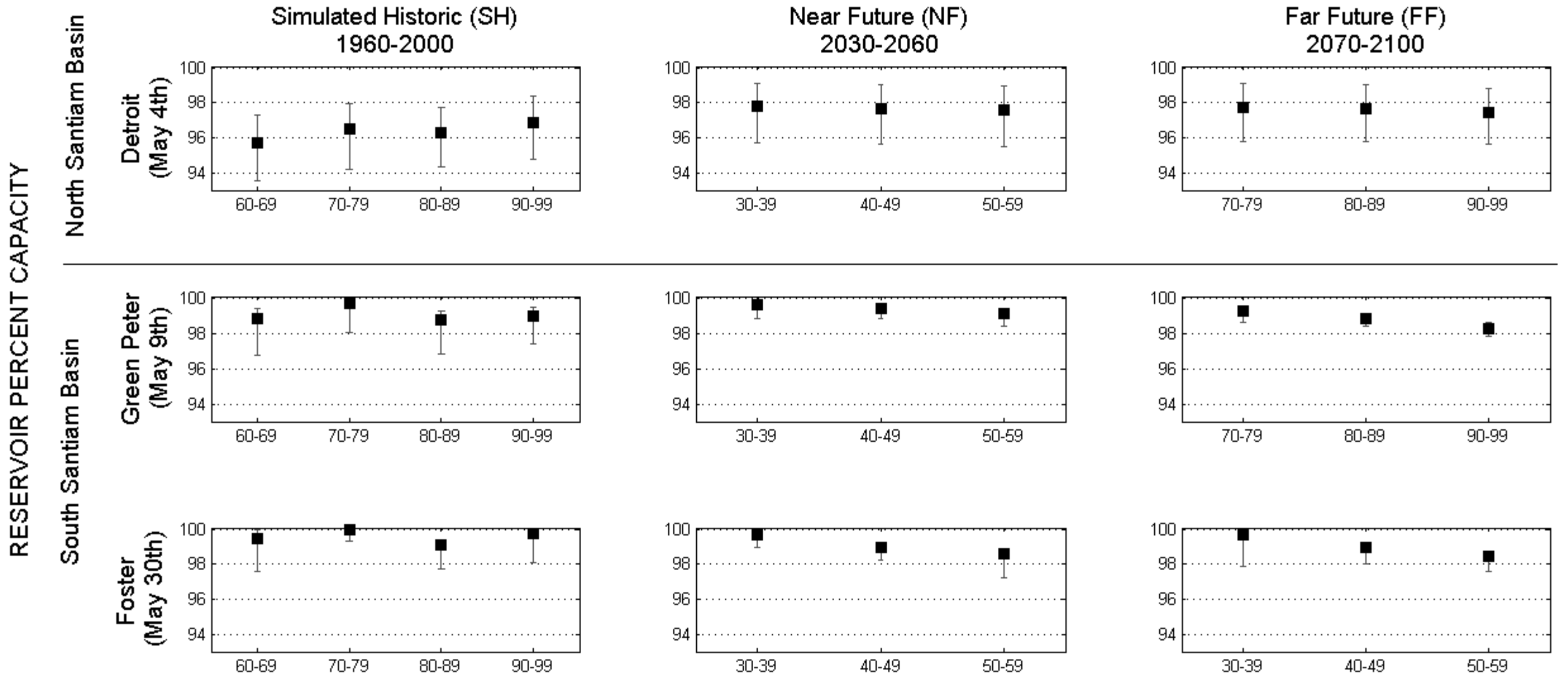


Fig. 8 Reservoirs ability to refill by decade to maximum conservation pool showed as percentage of water stored by May 4th at Detroit, May 9th at Green Peter and May 30th at Foster during the Simulated Historical (SH), Near Future (NF), and Far Future (FF) time periods under A1B GHG emission scenarios. Error bars represent the upper and lower confidence interval.

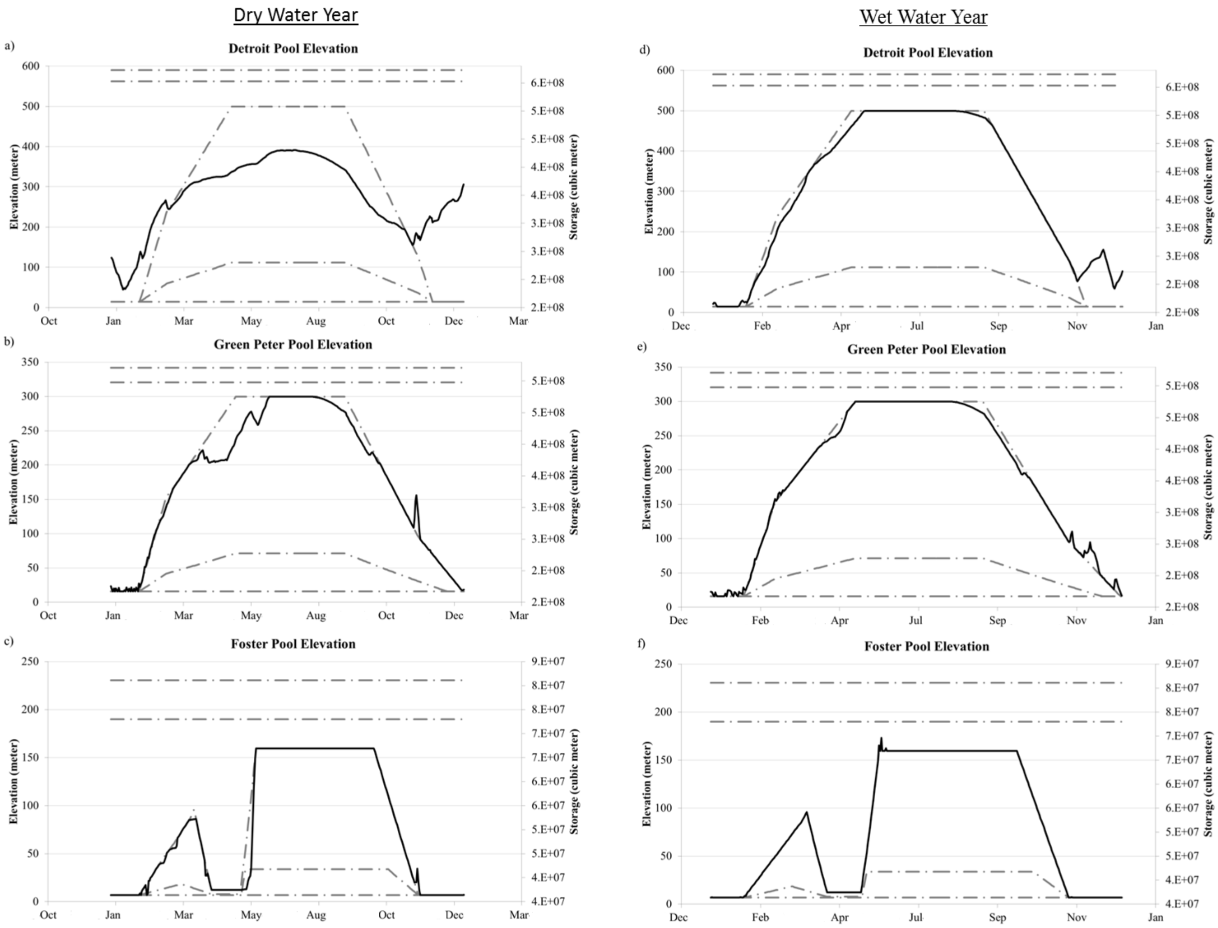


Fig. 9 Reservoir (median) pool elevation and storage for a dry (left column) and wet (right column) water years during the Simulated Historical (SH) time period for Detroit, Green Peter, and Foster reservoirs. The solid lines represent reservoir pool elevation and the dotted lines represent reservoir zones (from top to bottom): Top of Dam, Flood Control, Conservation, Buffer, and Inactive.

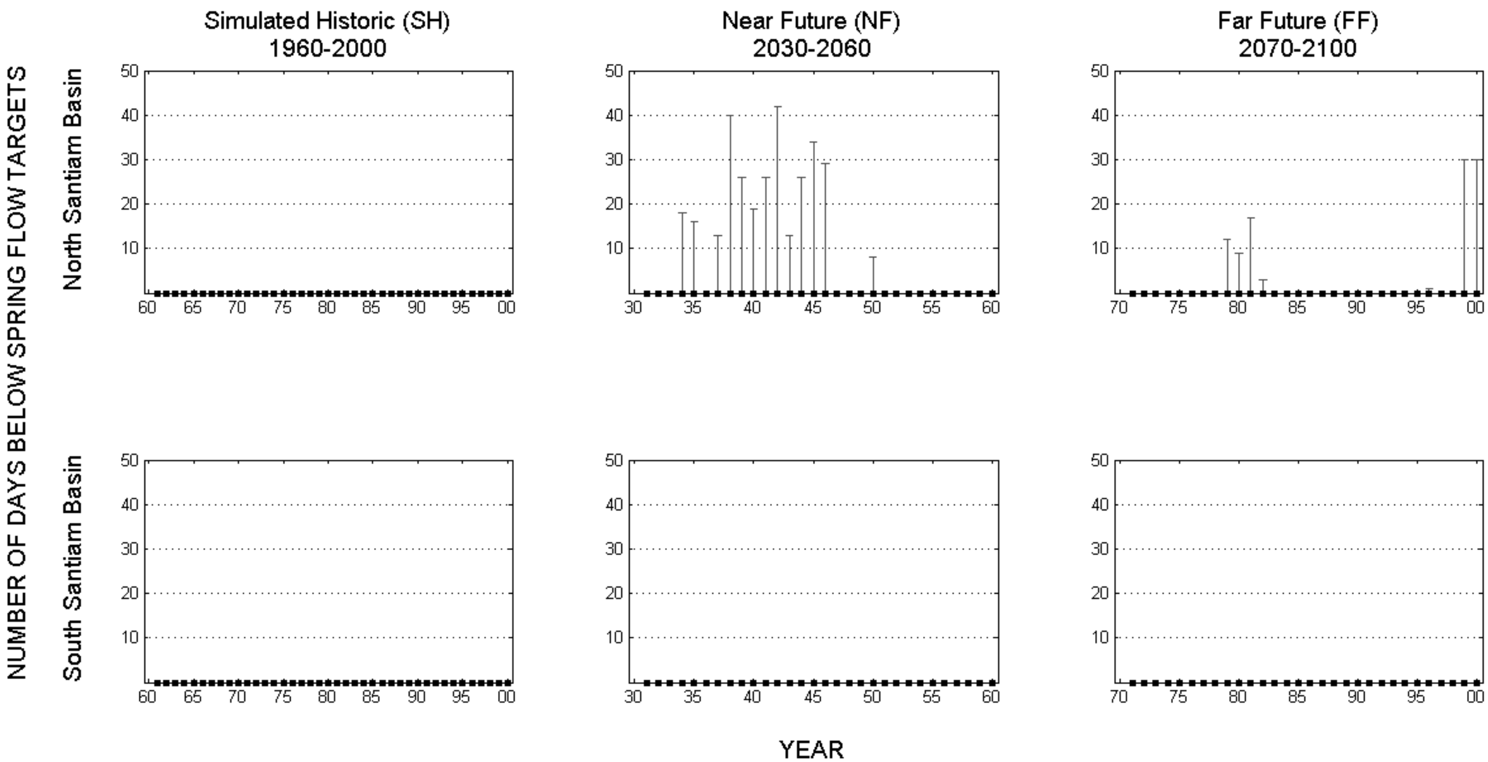


Fig. 10 Spring flow target reliability. This figure shows the number of days (y axis) discharge is below spring minimum flow target per year under A1B GHG emission scenario at Mehama control point in the North Santiam basin and Waterloo control point in the South Santiam basin. Error bars represent the upper and lower confidence interval

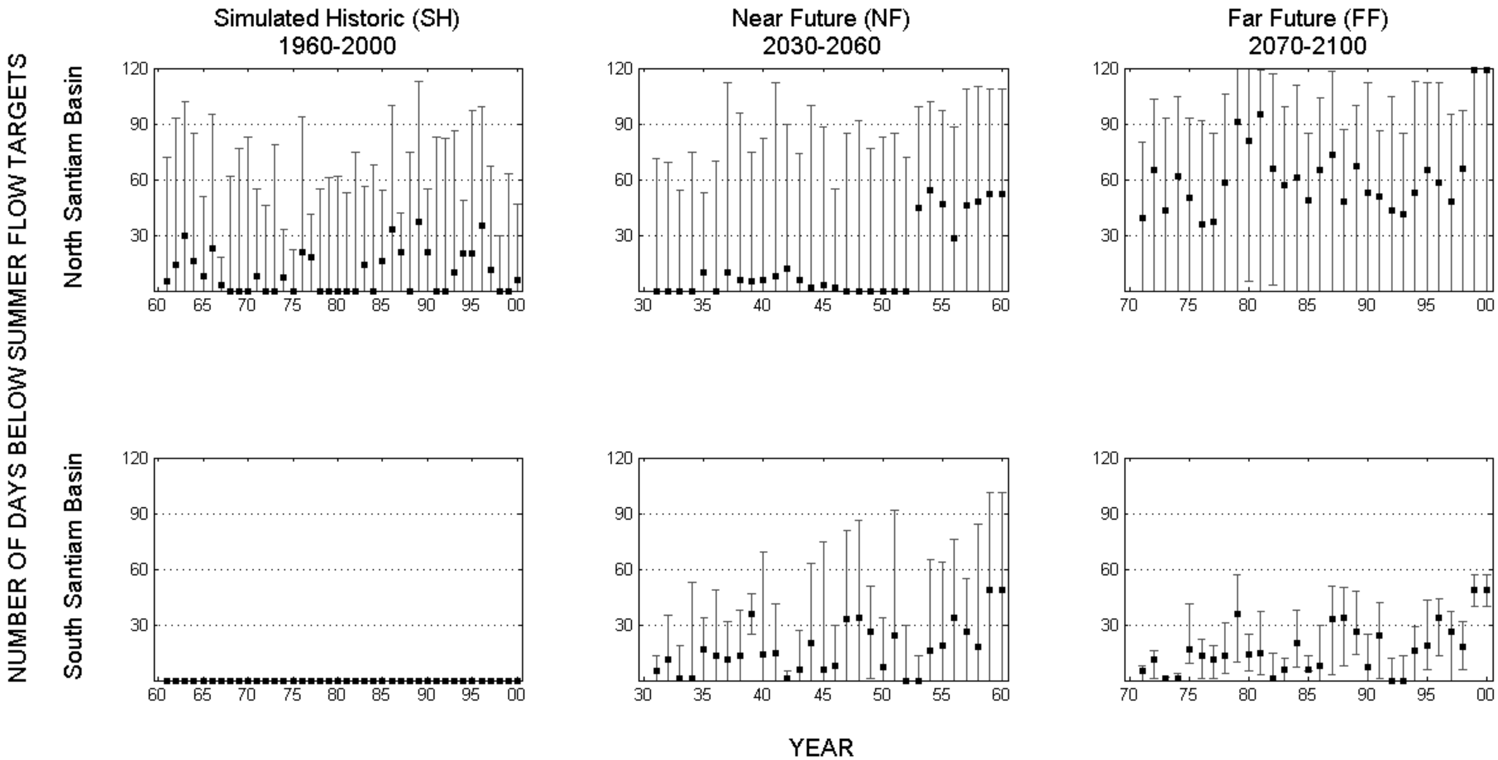


Fig. 11 Summer flow target reliability at Mehama control point in the North Santiam basin and Waterloo control point in the South Santiam basin under A1B GHG emission scenario represented as the number of days (y axis) discharge is below summer minimum flow target per year. Error bars represent the upper and lower confidence interval.

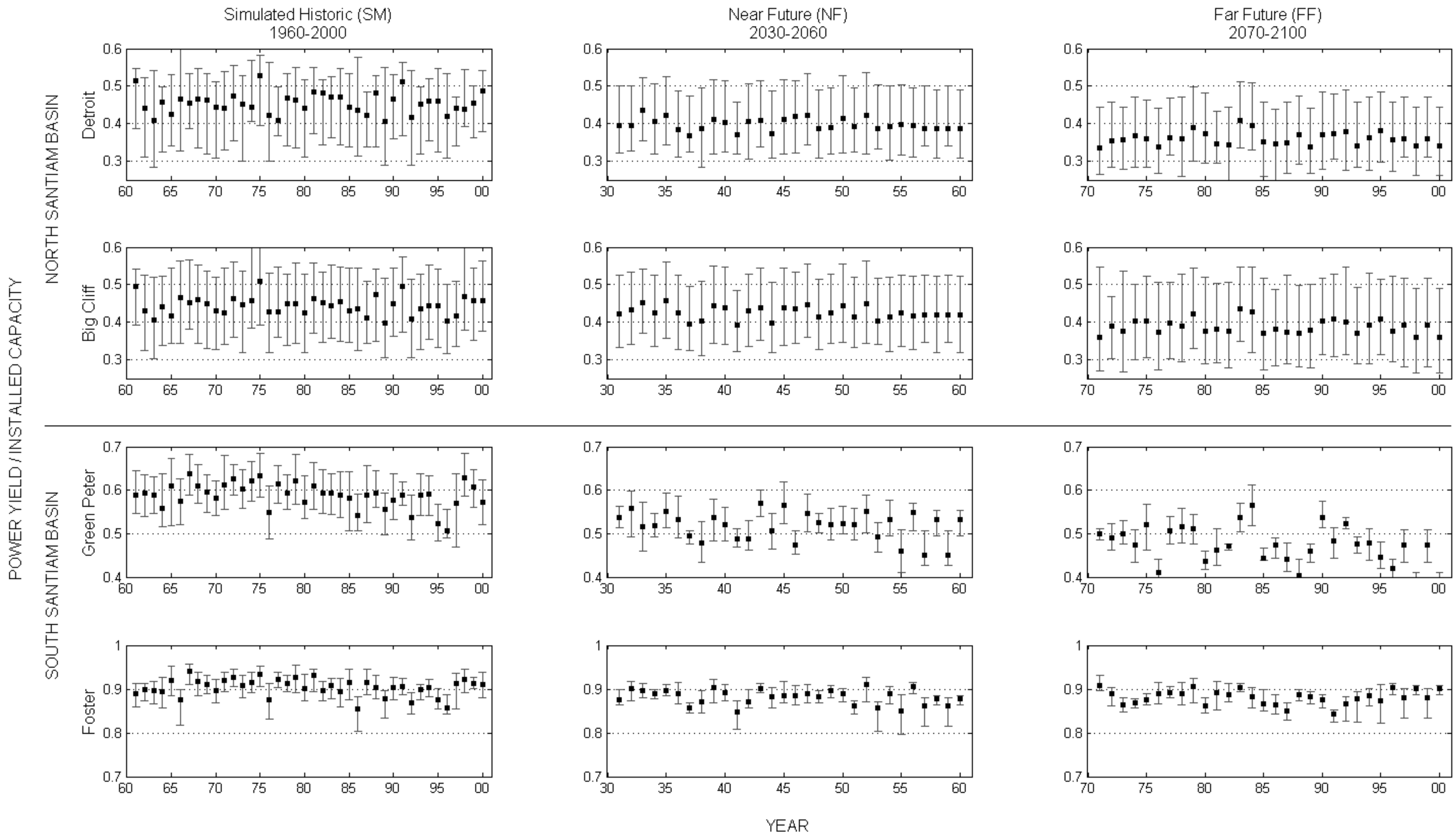


Fig. 12 Hydropower production represented as reservoirs' ability to produce the total power capability in a given year under the A1B GHG emission scenario. Error bars represent the upper and lower confidence interval. Scale for the y-axis is different for each reservoir.

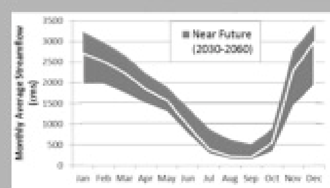
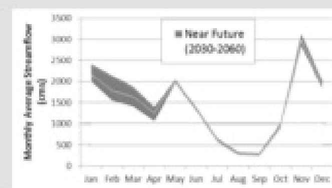
Reservoir Network	**North Santiam (Detroit-Big Cliff reservoir system)**	**South Santiam (Green Peter-Foster reservoir system)**
Hydrogeology	High permeability, deep aquifers and springs (90% High Cascades, 5% Western Cascades, 5% Alluvium)	Low permeability, low connectivity to aquifer (95% Western Cascades, 3% Basalt, 2% High Cascades)
Dominant Water Source	Substantial groundwater recharge Sustained baseflows	Shallow subsurface and surface flow Rapid runoff response
Precipitation Pattern	Rain and Snow precipitation at Detroit reservoir (477 m) 25% of the basin (507 km^2) located in the snow precipitation area (>1,200 m)	Rain precipitation at Green Peter (310 m) and Foster (165 m) reservoirs. 6.5% of the basin (176 km^2) located in the snow precipitation area (>1,200m)
Sensitivity to Climate Change Response relative to historical Across basins	Winter: Increases, Higher Summer: Decreases, Lower	Winter: Increases, Lower Summer: Decreases, Higher
Uncertainty across basins	Higher winter and summer uncertainty 	Lower winter and summer uncertainty 
Impacts on Reservoir Reliability across basins	Higher uncertainty in meeting summer flow targets	Higher frequency of failures in meeting summer flow targets.

Fig. 13 Hydrogeologic sensitivity, modeling uncertainty and impacts to reservoir operations between two different hydrogeologic settings.