Hydrol. Earth Syst. Sci. Discuss., 11, 13891–13929, 2014
www.hydrol-earth-syst-sci-discuss.net/11/13891/2014/
doi:10.5194/hessd-11-13891-2014
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Hydrology and Earth System Sciences
Open Access
Discussions

This discussion paper is/has been under review for the journal Hydrology and Earth System Sciences (HESS). Please refer to the corresponding final paper in HESS if available.

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

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Received: 2 October 2014 – Accepted: 14 November 2014 – Published: 23 December 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

This study investigated how reservoir performance varied across different hydrogeologic settings and under plausible future climate scenarios. The study was 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 applied 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 was 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 suggested 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 highlighted how hydrologic uncertainty is likely to complicate planning for climate change in basins with substantial groundwater interactions.

1 Introduction

In addition to long-standing uncertainties related to variable inflows and the market price of power, reservoir operators face a number of new uncertainties related to hydrologic nonstationarity, changing environmental regulations, and increasing water and energy demands. Anticipated air temperature increases in the Pacific Northwest (PNW) region are projected to generate changes in the timing and quantity of streamflow associated with more precipitation falling as rain rather than snow, shorter winter runoff periods, earlier spring runoff, and longer and drier summers (Chang and Jung, 2010;

Tague and Grant, 2009). Longer periods of drought during the summer and shorter wet seasons as a result of climate change may impact the ability of reservoirs to meet water storage needs, environmental flows, and water supply obligations (Payne et al., 2004). The earlier runoff associated with transition from spring snowmelt to winter rainfall may make it necessary to refill reservoirs earlier in the season to ensure adequate releases will be available for summer water supply, potentially increasing flood risk if adequate flood storage is not available in the reservoir when a spring flood arrives.

Climate change is likely to affect basins and reservoir operations differently based on an individual basin's hydrogeology and elevation. Changes in precipitation and temperature patterns for the Mediterranean climate of the PNW 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) (Nolin and Daly, 2006; Safeeq et al., 2013). On the other hand, mixed SW-GW systems with rain-snow transitions and GW systems that depend on snow accumulation for sustaining base flow 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). In the Cascade range of the Pacific Northwest, basins located at the rain and snow transitional elevations, are likely the most sensitive to warming climate due to large projected changes in snow accumulation (Jefferson et al., 2008; Tague et al., 2008) compared to areas at higher elevations characterized by snow precipitation. Such differences in hydrogeology and elevation may impact differently a water resource system's reliability, defined as the probability of failure to achieve some target demand or level of flood protection (Watkins and McKinney, 1995).

In this study, we investigated the impact and importance of climate-related uncertainties and hydrologic variability on reliability and sensitivity of reservoir operations for meeting water resources objectives, given current operating procedures, across basins with two different hydrogeologic settings in the Santiam River Basin (SRB), Oregon. We assessed whether changes in the timing and quantity of water resources could affect the reliability of reservoir systems located in 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. More specifically, we evaluated: (1) how the current reservoir operation performance for flood management, hydropower production, water supply, and environmental flows changes under future 2.5, 50 and 97.5 percentile streamflow projections for the two hydrologic regimes; (2) which operating system (NSB or SSB reservoirs) is more sensitive to hydrologic variability, and; (3) the sensitivity of different elements of reservoir operations to climate variability. We evaluated and compared hydrosystem reliability for: (a) Simulated Historical (SH) time period (1960–2000), (b) Near Future (NF) time period (2030–2060), and Far Future (FF) time period (2070–2100). This analysis of the reliability, sensitivity, and uncertainty of two hydrologic regime systems under a changing climate was undertaken to provide water managers information about plausible future water resource system capacities and limitations when developing adaptive and responsive water management and water allocations.

2 Methods

2.1 Study area

The Santiam River Basin (SRB) encompasses approximately 4700 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 to 1200 m, and snow at elevations higher than 1200 m (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 hydrologic systems within

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the SRB: Detroit and Big Cliff located in the North Santiam Basin dominated by the High Cascade geology, and Green Peter and Foster located in the South Santiam Basin 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 2000 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). Over 50 % of the watershed is in public ownership and is administered primarily as the Willamette National Forest by the US Forest Service (ODEQ, Oregon Department of Environmental Quality, 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. 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. 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 generates 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

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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, Oregon Department of Environmental Quality, 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, 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 % 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) 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.

2.2 Study approach

We applied streamflow projections (Hamlet et al., 2010; Surfleet and Tullos, 2013Estimates of future water supply) as inputs to a reservoir operation model (HEC-ResSim) to analyze reservoir system reliability under future climate (Fig. 2). 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

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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.

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. Inflows for the SRB were obtained from GSFLOW, a coupled groundwater-surface water flow model. Inflows for the other reservoirs in the WRB were obtained from Variable Infiltration Capacity (VIC), a spatial-distributed surface water model (Liang, 1994). Climate change projections for the basin were simulated within GSFLOW (Surfleet and Tullos, 2013) for the SRB and within VIC (Hamlet et al., 2010) for the WRB using the same eight GCMs, GHG emission (A1B and B1), and downscaling method (Delta-Hybrid method). We applied GSFLOW simulations for the SRB because these simulations, available only for the SRB, include a groundwater component and distributions of streamflows to represent the uncertainty attributed to hydrologic modeling parameters in GSFLOW simulations. The groundwater model 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 flow is stored in deep storage and did not appreciably contribute to streamflow in the Western Cascades. Across the three hydrogeologic settings of the SRB, posterior distributions of hydrologic model parameters were developed for both dry summer and wet winter seasons using a formal Bayesian parameter approach, the Differential Evolution Adaptive Metropolis (DREAM). Five hundred of the parameter combinations with

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the best fit for each GCM and GHG emission scenario were used to obtain the 2.5, 50 and 97.5 % daily values. Please see Surfleet and Tullos (2013) for further details on GSFLOW modeling and DREAM analysis. The ensemble mean of all the GCMs, as the lower, median and upper confidence interval from 1960 to 2100, are used as inflows in HEC-ResSim for the SRB. For the rest of the WRB we used the median ensemble mean of all the GCMs from VIC projections. The scenarios evaluated include A1B and B1 GHG emission scenarios for Simulated Historic (SH) time period (1960–2000), Near Future (NF) time period (2030–2060), and Far Future (FF) time period (2070–2100).

2.2.2 Reservoir operation modeling description

We applied the same rule curves implemented in the US Army Corps of Engineers' (USACE) 2010 Willamette Basin HEC – ResSim model, which includes Biological Opinion (NMFS, 2008) operations for spring and summer flow releases for the seasonal life histories for Chinook and Steelhead, in addition to winter flood control operations from the Water Control Manuals (WCMs) for each project. The reservoirs are operated by a set of operation objectives or rule curves (Fig. 3) originally designed (USACE, 1953, 1968a, b) 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.

A reservoirs' storage and release schedule varies for each reservoir (Fig. 3). Detroit reservoir starts releasing water in September to create storage capacity for flood

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control, dropping the reservoir elevation from 477 to 442 m by December (USACE, 1953). As flood risk decreases across the winter season, the reservoir is allowed to refill, beginning 31 January to reach maximum Conservation pool at 477 m by 4 May at a rate of 5 $\mathrm{Mm^3\,day^{-1}}$ during February and 3 $\mathrm{Mm^3\,day^{-1}}$ 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 9 May (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 28 March. The reservoir is then is lowered back to 187 m by 15 April. For the period of 15 April to 15 May, 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 30 May (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

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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. Reservoir performance measures were chosen based on reservoir primary functions, including flood risk, hydropower production, environmental flows and probability of refill. The uncertainty related with streamflow projections, and thus with each metric, is represented by the error bars as the range between the 2.5 and 97.5 percentile output. The 2.5, 50, and 97.5 percentile values for each metric were 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.

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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 (1 yr), 2-year (2 yr), 5-year (5 yr), 25-year (25 yr), 50-year (50 yr), 100-year (100 yr), and 200-year (200 yr) recurrence interval (R_I). We performed a flood frequency analysis using Log-Pearson Type III (LP3) distribution to obtain the flow (Q) associated with each R_I, as outlined in the federal Guidelines for Determining Flood Flow Frequency (i.e. Bulletin #17B) (US Department of the Interior, 21982), for each GCM separately. We then calculated the mean flow from the eight GCMs for each R_I to obtain the Flood–Storage (S_t) ratio (Eq. 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 R_I (Q_RI) to the maximum reservoir storage (R_st) (Eq. 1).

$$S_\mathrm{t} = \frac{Q_\mathrm{RI}}{R_\mathrm{st}} \tag{1}$$

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 R_I, assuming no previous floods were being stored in the reservoir. When above one, a higher ratio reflected a larger inadequacy for storing a given R_I event.

To evaluate the frequency of flooding at downstream control points, we evaluated the time reliability of flood control (F_C; Eq. 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.

$$F_\mathrm{C} = \frac{N_\mathrm{FC}}{N} \tag{2}$$

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: 4 May for Detroit; 9 May for Green Peter, and 30 May for Foster (Eq. 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.

$$R = \frac{S}{R_\mathrm{C}} \cdot 100 \tag{3}$$

where, R is the reservoir refill (%); S is reservoir storage 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; Eq. 4) and summer (S_UM; Eq. 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.

$$S_{\mathrm{PR}} = \frac{N_{\mathrm{t}}}{N} \tag{4}$$

$$S_{\mathrm{UM}} = \frac{N_{\mathrm{t}}}{N} \tag{5}$$

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 (Eq. 6) at each reservoir, where power generated is estimated from the head and discharge at each time step (Eq. 7).

$$P_{\mathrm{e}} = \frac{P}{P_{\mathrm{C}}} \tag{6}$$

$$P = \rho \eta Q g h \tag{7}$$

where, P is hydropower production (MW); ρ is the water density (kg m^{-3}); η is turbine efficiency (assumed 90 %); Q is water discharge (cms); g is acceleration of gravity (m s^{-2}); h is the falling height (m), and; P_{C} 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.

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 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.

The change in the magnitude of floods draining into the reservoirs (Fig. 5) was projected to vary with R_I and between basins. The percent change from simulated historic for floods of a particular R_I was projected to be higher for smaller floods (i.e., 1 yr) compared to larger floods (i.e., 100 yr). While inflows of 5 yr or lower R_I were projected to increase into the future for all three reservoirs, the response of larger magnitude floods, such as the 100 yr or 200 yr R_I, was to not change or to decrease, with variability across the reservoirs. Results thus 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. While the general trends were similar, projected changes in inflows to Detroit reservoir were higher than pro-

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jected changes in inflows to Green Peter and Foster reservoirs. Flood events up to the 25 yr R_I were projected to be higher than historical at Detroit when uncertainty was considered, while flows up to only the 5 yr R_I at Foster and Green Peter reservoirs were projected to increase over historical. For the larger events, projected changes were small. The largest, 100 yr flood events were not projected to change at Detroit and Green Peter when uncertainties were considered, and the arrival of 100 yr events to Foster were projected to decrease only by 2 % for the lower confidence interval under both NF and FF time periods. For the 200 yr 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 Detroit and Green Peter 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 only projected 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 R_I s.

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

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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. While Detroit reservoir in the NSB may never refill during a dry water year (e.g. 1996 for the simulated historical time period) (Fig. 9a), reaching only ~ 94 % of maximum Conservation pool under the lower confidence interval, it may refill ~ 10 days after the 4 May 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 ±4 feet 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 9 May 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 30 May 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

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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 FFB1 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.

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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 impacts to reservoir operations in the Santiam River were limited. To review, projections indicated that summer baseflow could decrease while winter runoff could increase (Fig. 4). This modified hydrology resulted in projected future increases in the magnitude and frequency of small floods (i.e. 1 yr) and small decreases in large floods (i.e. 100 yr) relative to the simulated historical time period (Fig. 5). These changes in floods appeared to be greater for the NSB reservoir system compared to the SSB reservoir system. However, these 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 and only in the surface water basin, 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. Regarding sensitivity to summer low flow, only the ability to meet summer environmental flow targets appeared to decline in the future (Fig. 11) and only for the SSB. 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. 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. Finally, the uncertainty in streamflows for the NSB has implications for waters managers seeking to evaluate the reliability of the water resources of the basin. Relationships between climate projection uncertainty, system reliability and system sensitivity to climate variability suggests that reservoir systems located in basins with groundwater interactions are more unpredictable than reservoir systems located in surface water basins. Higher uncertainty for groundwater basins compared to surface water basins is likely a result uncertainty associated with transfer of model parameters in the groundwater model (Rosero et al., 2010; Surfleet and Tullos, 2013). Thus, it is likely that the large uncertainty for other basins with substantial groundwater interactions and snow cover will be similarly challenged by high uncertainty in model projections.

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. Key factors that may have impacted our results included modeling uncertainties around groundwater recharge and discharge. As described and justified in the Methods, groundwater was only modeled within GSFLOW where substantial groundwater interactions occur (High Cascades) and subsurface flows were not transferred as surface water flow to lower sections in the basin. 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. In addition, we acknowledge that our analytical 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 significantly impacted our key findings.

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; and (3) 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.

Author contributions. The study was conceived and designed by Cristina Mateus, with substantial input from Desiree Tullos, and all modeling and data processing analysis was conducted by Cristina Mateus. Both authors contributed equally to interpreting results and writing the manuscript.

Acknowledgements. This material is based upon work supported by the National Science Foundation under Grant No. 0846360. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. The research was supported in part by the National Science Foundation through TeraGrid resources provided by Purdue University under grant number TG-ECS100006. Funding was also provided by Secretaria Nacional de Educación Superior, Ciencia, Tecnología e Innovación SENESCYT, ECUADOR.

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References

Buccola, N. L., Rounds, S. A., Sullivan, A. B., and Risley, J. C.: Simulating Potential Structural and Operational Changes for Detroit Dam on the North Santiam River, Oregon, for Downstream Temperature Management, http://pubs.usgs.gov/sir/2012/5231/ (last access: 23 July 2014), 2012.

Chang, H. and Jung, I. W.: Spatial and Temporal Changes in Runoff Caused by Climate Change in a Complex Large River Basin in Oregon, J. Hydrol., 388, 186–207, 2010.

Hamlet, A. F., Salathé, E. P., and Carrasco, P.: Statistical Downscaling Techniques for Global Climate Model Simulations of Temperature and Precipitation with Application to Water Resources Planning Studies The Columbia Basin Climate Change Scenarios Project (CBCCSP) Report, http://www.hydro.washington.edu/pub/itohver/HB2860/CBCCSP_chap4_gcm_final.pdf (last access: 29 July 2014), 2010.

Hashimoto, T.: Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation, Water Resour. Res., 18, 14–20, 1982.

Jefferson, A., Nolin., A., Lewis, S., and Tague, C.: Hydrogeologic controls on streamflow sensitivity to climate variation, Hydrol. Process., 22, 4371–4385, 2008.

Liang, X.: A Two-Layer Variable Infiltration Capacity Land Surface Representation for General Circulation Models Thesis (Phd. thesis), University of Washington, source: Dissertation Abstracts International, 55, Section: B, p. 3788, University of Washington, 1994.

McMahon, T. A., Adeloye, A. J., and Zhou, S. L.: Understanding Performance Measures of Reservoirs, J. Hydrol., 324, 359–382, 2006.

Milutin, D. and Bogardi, J.: Evolution of Release Allocation Patterns within a Multiple-Reservoir Water Supply System Operation Water Management, Department of Water Resources, Wageningen Agricultre University, the Netherlands, 179–186, 1997.

NMFS: National Marine Fisheries Service, Endangered Species Act Sect. 7(a) (2) Consultation Biological Opinion and Magnuson-Stevens Fishery Conservation and Management Act Essential Fish Habitat Consultation: seattle, Washington, NOAA National Marine Fisheries Log Number FINWR12000/02117, various Pagination, http://www.nwr.noaa.gov/Salmon-Hydropower/Willamette-basin/Willamette-BO.cfm (last access: 16 Januar 2014), 2008.

Nolin, A. W.: Perspectives on climate change, mountain hydrology, and water resources in the oregon cascades, USA, Mt. Res. Dev., 32, 35–46, 2012.

Nolin, A. W. and Daly, C.: Mapping “at risk” snow in the pacific northwest, J. Hydrometeorol., 7, 1164–1171, 2006.

Obeysekera, J and Salas, J. D.: Quantifying the uncertainty of design floods under non-stationary conditions, J. Hydrol. Eng., 19, 1438–1446, 2014.

ODEQ, Oregon Department of Environmental Quality, 2006a Willamette Basin TMDL: north Santiam SubBasin, http://www.deq.state.or.us/wq/tmdls/docs/willamettebasin/willamette/chpt8nsantiam.pdf (last access: 28 July 2014), 2006a.

ODEQ, Oregon Department of Environmental Quality, Willamette Basin TMDL: south Santiam Subbasin http://www.deq.state.or.us/wq/tmdls/docs/willamettebasin/willamette/chpt9ssantiam.pdf (last access: 28 July 2014), 2006b.

Payne, J. T., Wood, A. W., Hamlet, A. F., Palmer, R. N., and Lettenmaier, D. P.: Mitigating the effects of climate change on the water resources of the Columbia River Basin, Climatic Change, 62, 233–256, 2004.

Risley, J., Wallick, J., Mangano, J., and Jones, K.: An Environmental Streamflow Assessment for the Santiam River Basin, Oregon, Open-File Report, US Geological Survey, Reston, Virginia, 66 p., 2012.

Rosero, E., Yang, Z. L., Wagener, T., Gulden, L. E., Yatheendradas, S., and Niu, G. Y.: Quantifying parameter sensitivity, interaction, and transferability in hydrologically enhanced versions of the Noah Land surface model over transition zones during the warm season, J. Geophys. Res., 115, D03106, doi:10.1029/2009JD012035, 2010.

Safeeq, M., Grant, G. E., Lewis, S. L., and Tague, C. L.: Coupling snowpack and groundwater dynamics to interpret historical streamflow trends in the Western United States, Hydrol. Process., 27, 655–668, 2013.

Schaefli, B., Hingray, B., and Musy, A.: Climate change and hydropower production in the Swiss Alps: quantification of potential impacts and related modelling uncertainties, Hydrol. Earth Syst. Sci., 11, 1191–1205, doi:10.5194/hess-11-1191-2007, 2007.

Sullivan, A. and Rounds, S.: Modeling Streamflow and Water Temperature in the North Santiam and Santiam Rivers Scientific Investigations Report, US Geological Survey Scientific Investigations Report, Portland, Oregon, 35 p., 2004.

Surfleet, C. G. and Tullos, D.: Uncertainty in hydrologic modelling for estimating hydrologic response due to climate change (Santiam River, Oregon), Hydrol. Process., 27, 3560–3576, 2013.

Tague, C. and Grant, G.: A Geologic Framework for Interpreting the Low-Flow Regimes of Cascade Streams, Willamette River Basin, Oregon, Water Resour. Res., 40, W04303, doi:10.1029/2003WR002629, 2004.

Tague, C. and Grant, G. E.: Groundwater Dynamics Mediate Low-Flow Response to Global Warming in Snow-Dominated Alpine Regions Water Resour. Res., 45, W07421, doi:10.1029/2008WR007179, 2009.

Tague, C., Grant, G., Farrell, M., Choate, J., and Jefferson, A.: Deep groundwater mediates streamflow response to climate warming in the Oregon Cascades, Climatic Change, 86, 189–210, 2008.

USACE, US Army Corps of Engineers: Water Control Manual for Green Peter Lake, Oregon: Portland District Report, 5 September 1968, 1968a.

USACE, US Army Corps of Engineers: Water Control Manual for Foster Lake, Oregon: Portland District Report, 26 December 1968, 1968b.

USACE, US Army Corps of Engineers: Water Control Manual for Detroit and Big Cliff Lakes, Oregon: Portland District Report, 18 December 1953, 1953.

USACE, US Army Corps of Engineers: Willamette Basin Guide: Standard Operating Procedures (SOP) for Reservoir Control Center, available at: http://www.nwp.usace.army.mil/Locations/WillametteValley.aspx, last access: 1 November 2011.

USACE, US Army Corps of Engineers: HEC-ResSim Reservoir System Simulation Version 31, User's Manual, http://www.hec.usace.army.mil/software/hec-ressim/documentation/HEC-ResSim_31_UsersManual.pdf (last access: 1 June 2014), 2013.

US Department of the Interior, U.: Bulletin 17-B: Guidelines for determining flood frequency frequently asked questions, http://acwi.gov/hydrology/Frequency/B17bFAQ.html (last access: 4 April 2013), 1982.

Vonk, E., Xu, Y. P., Booij, M. J., Zhang, X., and Augustijn, D. C. M.: Adapting Multireservoir Operation to Shifting Patterns of Water Supply and Demand: a Case Study for the Xinanjiang–Fuchunjiang Reservoir Cascade, Water Resour. Manag., 28, 625–643, 2014.

Watkins, D. W. and McKinney, D. C.: Robust optimization for incorporating risk and uncertainty in sustainable water resources planning, IAHS Publications-Series of Proceedings and Reports-Intern Assoc. Hydrol. Sci., 231, 225–232, 1995.

Watts, R. J., Richter, B. D., Opperman, J. J., and Bowmer, K. H.: Dam reoperation in an era of climate change, Mar. Freshwater Res., 62, 321, 2011.

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Table 1. Reservoir characteristics.

	GREEN PETER	FOSTER	DETROIT	BIG CLIFF
Primary Function	Flood Control	Re-Regulating Flood Control	Flood Control	Re-Regulating
Project Purposes[a]	FN, 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	1279	1134	1171
Storage (m^3)	528 053 582	74 872 349	561 357 592	7955 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 s^{-1})	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	4814	2791	–
Total Capacity at Full Pool (cms)	283	5663	4127	5069
Total Capacity at Max Pool (cms)	283	5663	5427	5069
Number of Regulating Outlets	2	–	4	–
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	–

[a] F – Flood Control; N – Navigation; E – Environmental; HP – Hydropower; I – Irrigation; M – Municipal & Industrial; R – Recreation

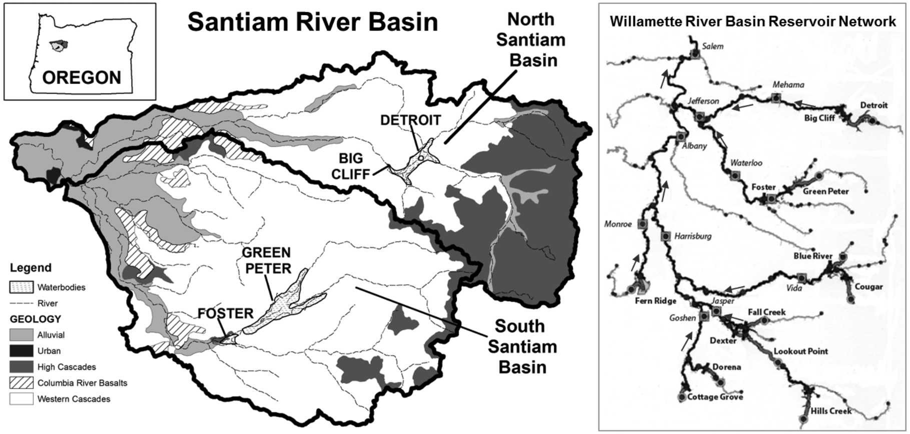

Figure 1. Left inset: santiam River Basin (SRB), reservoirs and geology. Right inset: willamette River Basin Reservoir Network. Thirteen multipurpose dams and reservoirs (in bold) work as a system to meet downstream flow targets at control points (in italic). The arrows indicate the direction of the 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.

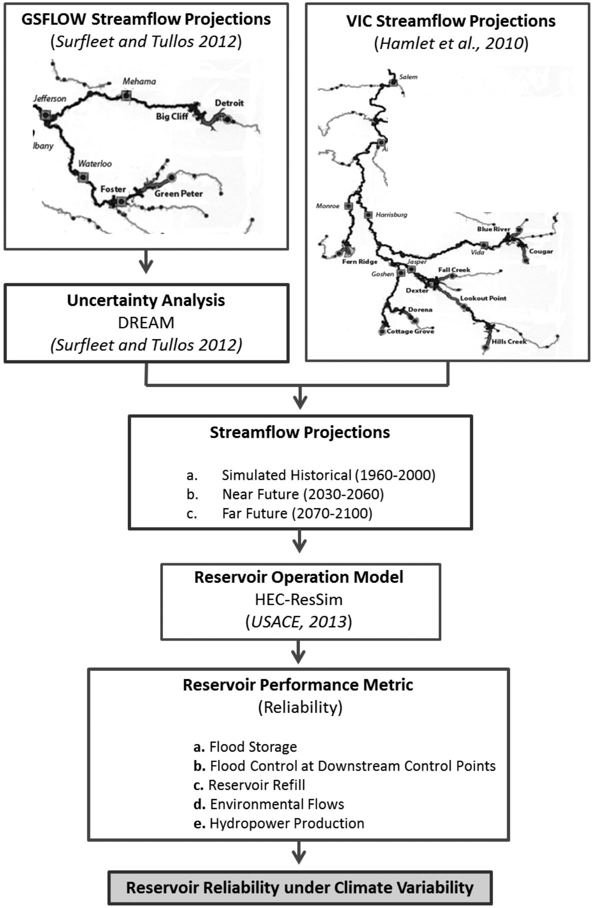

Figure 2. Study approach.

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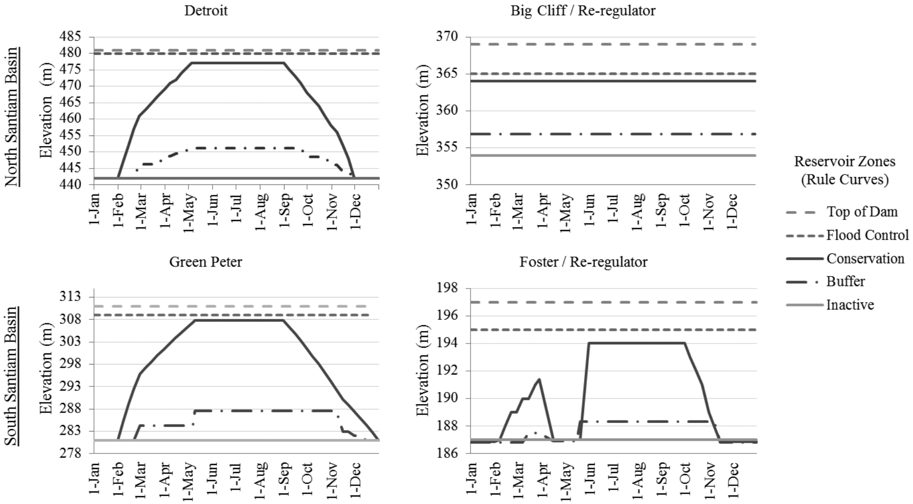

Figure 3. Santiam Basin reservoir rule curves.

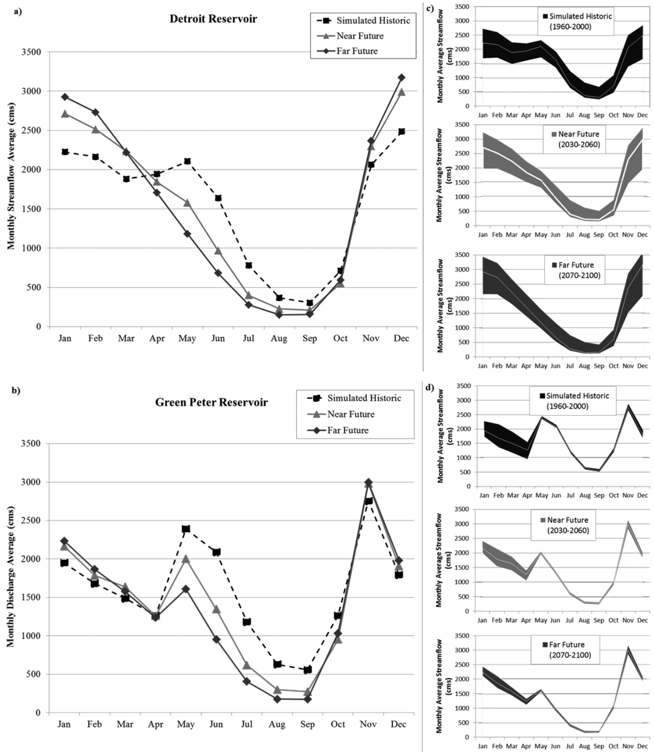

Figure 4. GSFLOW streamflow inputs at Detroit reservoir and Green Peter reservoir. Figures **(a)** and **(b)** shows the median confidence interval for the Simulated Historical (SH), Near Future (NF) and Far Future (FF) time periods, and figures **(c)** and **(d)** shows the median confidence interval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

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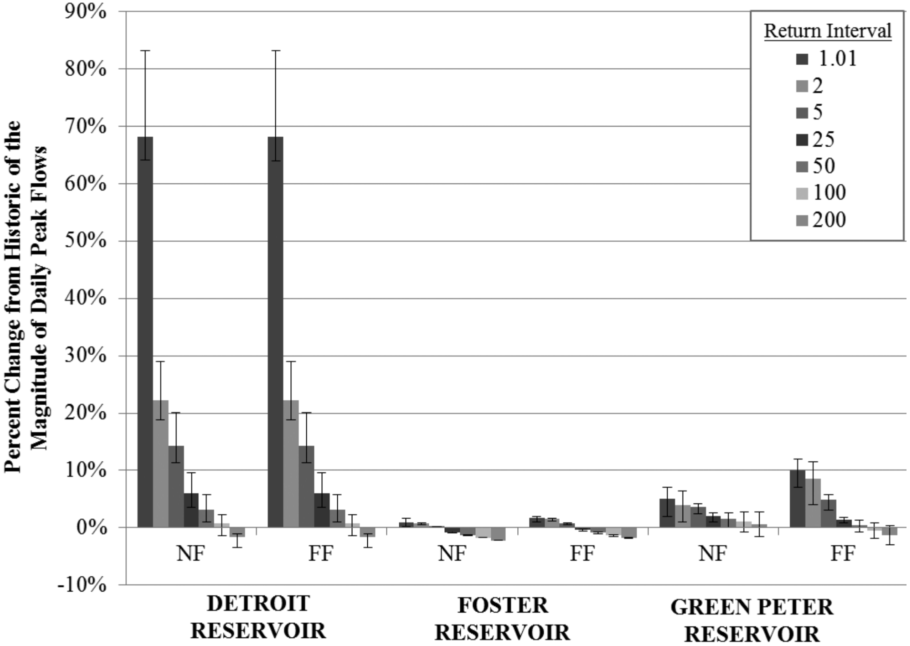

Figure 5. Percent change from historic in the size and frequency of peak daily inflows (median) of 1, 2, 5, 25, 50, 100 and 200 yr recurrence intervals (R_I). Error bars represent the upper and lower confidence interval. The likelihood of the various discharges as a function of recurrence interval is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

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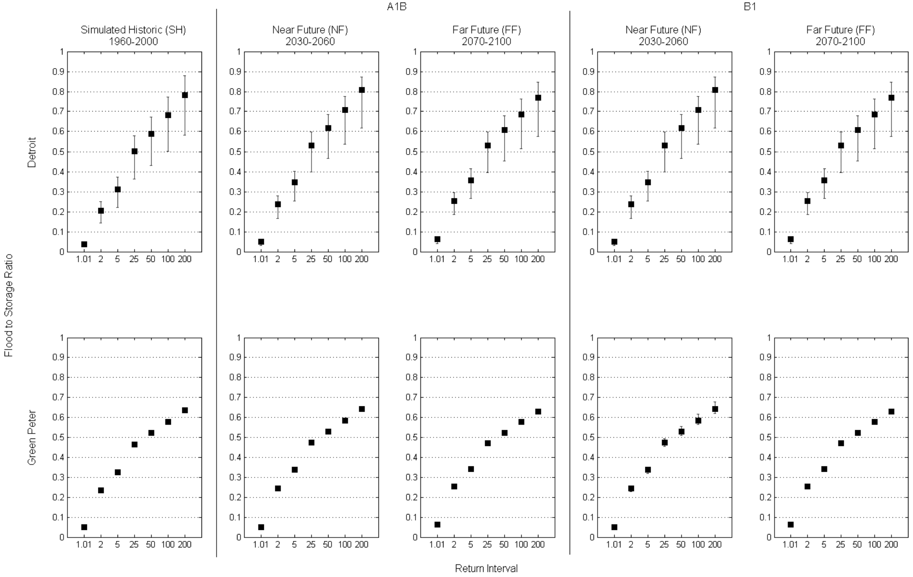

Figure 6. Flood to storage ratio represented as the ability of a reservoir, on any given day to store a three day event of a particular recurrence interval was calculated for Detroit, and Green Peter reservoirs for the Simulated Historical (SH), Near Future (NF), and Far Future (FF) time periods under A1B and B1 GHG emission scenarios. A higher ratio means a potentially larger failure to store high flood events.

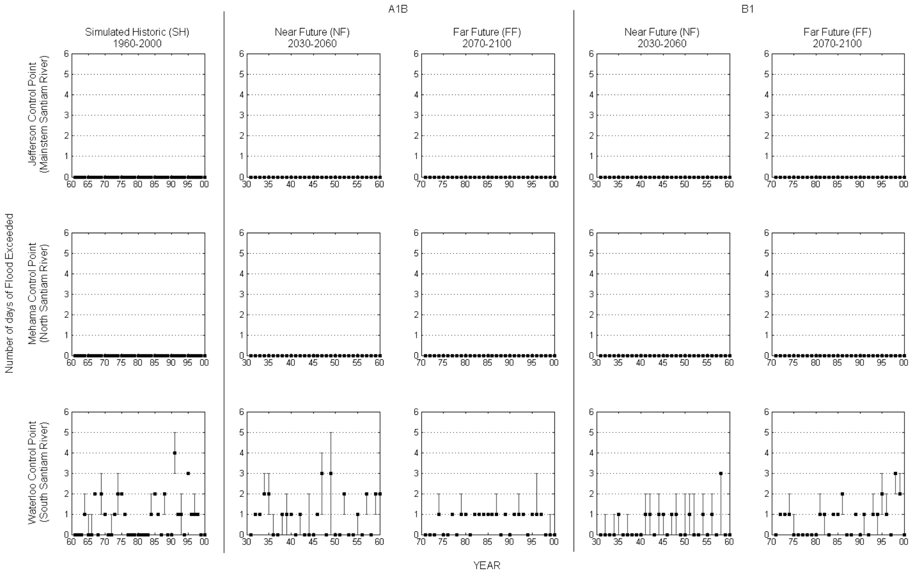

Figure 7. Time reliability of flood control at downstream control points represented as the number of days flood exceeded at Jefferson in the mainstem of the Santiam River, Mehama in the North Santiam River, and Waterloo in the South Santiam River for the Simulated Historical (SH), Near Future (NF), and Far Future (FF) time periods under A1B and B1 GHG emission scenarios. Error bars represent the upper and lower confidence interval.

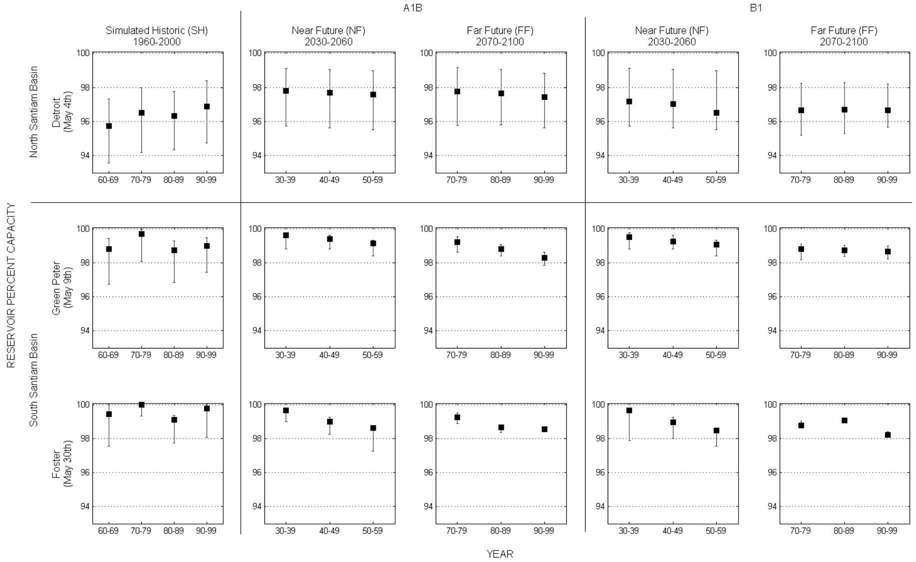

Figure 8. Reservoirs ability to refill by decade to maximum conservation pool showed as percentage of water stored by 4 May at Detroit, 9 May at Green Peter and 30 May at Foster during the Simulated Historical (SH), Near Future (NF), and Far Future (FF) time periods under A1B and B1 GHG emission scenarios. Error bars represent the upper and lower confidence interval.

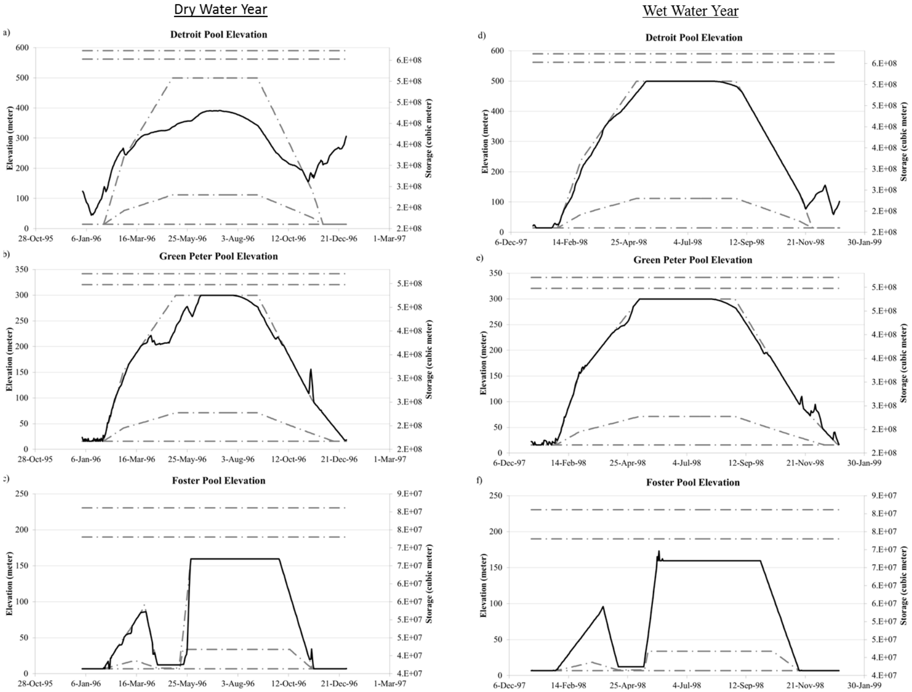

Figure 9. Reservoir (median) pool elevation and storage for a dry (left column) and wet (right column) water years during the Simulated Historical (SH) time period for Detroit, Green Peter, and Foster reservoirs.

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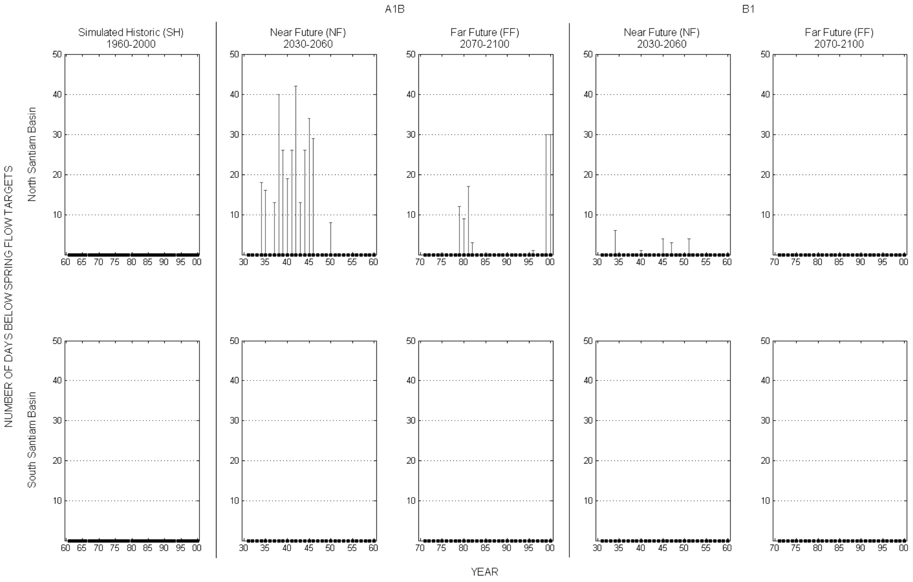

Figure 10. Spring flow target reliability. This figure shows the number of days (y axis) discharge is below spring minimum flow target per year at Mehama control point in the North Santiam basin and Waterloo control point in the South Santiam basin. Error bars represent the upper and lower confidence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

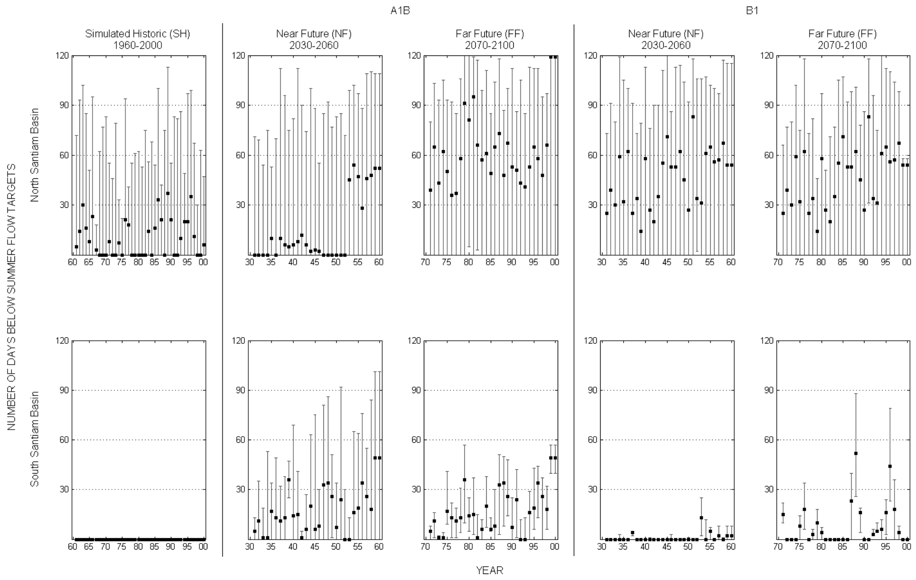

Figure 11. Summer flow target reliability at Mehama in the North Santiam basin and Waterloo in the South Santiam basin represented as the number of days (y axis) discharge is below summer minimum flow target per year. Error bars represent the upper and lower confidence interval.

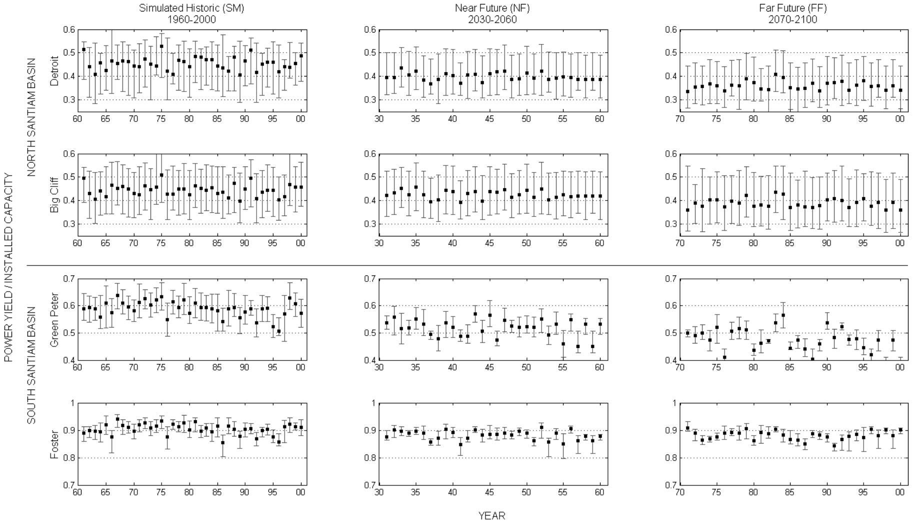

Figure 12. Hydropower production represented as reservoirs' ability to produce the total power capability in a given year under the A1B GHG emission scenario. Error bars represent the upper and lower confidence interval. Scale for the *y* axis is different for each reservoir.