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Simulating future water temperatures in the North Santiam River, Oregon

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SUMMARY

A previously calibrated two-dimensional hydrodynamic and water-quality model (CE-QUAL-W2) of Detroit Lake in western Oregon was used in conjunction with inflows derived from Precipitation-Runoff Modeling System (PRMS) hydrologic models to examine in-lake and downstream water temperature effects under future climate conditions. Current and hypothetical operations and structures at Detroit Dam were imposed on boundary conditions derived from downscaled General Circulation Models in base (1990–1999) and future (2059–2068) periods. Compared with the base period, future air temperatures were about 2 °C warmer year-round. Higher air temperature and lower precipitation under the future period resulted in a 23% reduction in mean annual PRMS-simulated discharge and a 1 °C increase in mean annual estimated stream temperatures flowing into the lake compared to the base period. Simulations incorporating current operational rules and minimum release rates at Detroit Dam to support downstream habitat, irrigation, and water supply during key times of year resulted in lower future lake levels. That scenario results in a lake level that is above the dam's spillway crest only about half as many days in the future compared to historical frequencies. Managing temperature downstream of Detroit Dam depends on the ability to blend warmer water from the lake's surface with cooler water from deep in the lake, and the spillway is an important release point near the lake's surface. Annual average in-lake and release temperatures from Detroit Lake warmed 1.1 °C and 1.5 °C from base to future periods under present-day dam operational rules and fill schedules. Simulated dam operations such as beginning refill of the lake 30 days earlier or reducing minimum release rates (to keep more water in the lake to retain the use of the spillway) mitigated future warming to 0.4 and 0.9 °C below existing operational scenarios during the critical autumn spawning period for endangered salmonids. A hypothetical floating surface withdrawal at Detroit Dam improved temperature control in summer and autumn (0.6 °C warmer in summer, 0.6 °C cooler in autumn compared to existing structures) without altering release rates or lake level management rules.

1. Introduction

Detroit Dam has altered the natural thermal regime in the North Santiam River, Oregon, since construction in 1953. Beginning in 2007, the U.S. Army Corps of Engineers (USACE) has managed releases from Detroit Dam with the intent of managing downstream temperatures for threatened/endangered Upper Willamette River Chinook salmon (*Oncorhynchus tshawytscha*) and winter steelhead (*Oncorhynchus mykiss*). USACE finished construction of Detroit Dam (141.1 m [463 ft] tall) and the smaller, re-regulating Big Cliff Dam (58.2 m [191 ft] tall) in 1953. Initial purposes for the 9-mile long impoundment of Detroit Lake were to provide flood damage reduction, navigation, irrigation/water storage (560,000,000 m^3 [455,000 acre-feet] at full pool), hydropower (100 MW), and recreation (popular swimming, boating, and fishing destination). Following the 2008 Willamette Project Biological Opinion issued by the National Marine Fisheries Service (2008), interim operations at Detroit Dam have been incorporated to improve downstream flow and temperature conditions for fish passage, spawning, incubation and rearing of ESA-listed Upper Willamette River Spring Chinook salmon and Upper Willamette River Winter Steelhead until permanent solutions can be developed and completed. Since 2007, USACE has applied specific minimum release rates year-round and has managed release temperatures during summer full-pool and autumn low-pool seasons by blending releases from multiple dam outlets (U.S. Army

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Corps of Engineers, 2014). Previous work using a two-dimensional hydrodynamic temperature model (CE-QUAL-W2) of the lake has quantified the potential improvements to downstream temperatures of hypothetical operational and structural scenarios at Detroit Dam under cool/wet, normal, and hot/dry (historically based) conditions (Buccola et al., 2012, 2015).

The primary tributaries to Detroit Lake are the North Santiam and Breitenbush Rivers (Fig. 1), which have about 78% and 46% of their headwaters located in the High Cascades hydrogeologic unit. High Cascades streams are dominated by snowmelt runoff and strong groundwater baseflow (Tague and Grant, 2004). The groundwater baseflow provides a relatively steady, cool water source throughout the late summer dry season and is projected to be relatively resilient (less year-to-year variability) to climate change than lower elevation sub-basins in the vicinity (Mateus et al., 2014). Other research has shown that similar and nearby sub-basins with headwaters in the High Cascades (i.e., McKenzie and Deschutes River basins) could have an earlier peak in spring runoff and/or large reductions in snow-water storage available as runoff in the future (Sproles et al., 2013; Waibel et al., 2013).

The goal of this study was to provide insights into potential future water temperatures (years 2059–2068) in and downstream of Detroit Lake as a result of climate change and under a range of temperature management operations at Detroit Dam. To achieve this goal, General Circulation Models (GCMs) from the Coupled Model Intercomparison Project (CMIP3) (accessible at http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php) were used as the basis for future conditions that could be compared to base conditions to assess relative changes. By focusing on changes rather than absolute predictions, the uncertainty attributed to each step in the modeling process is minimized because base and future time frames embody the same assumptions. Although this study does not include the more recent CMIP5 data, the conceptual framework described here using GCM results, rainfall–runoff models, and lake models in sequence could be applied to the newest generation of GCMs, such as CMIP5. Throughout this article, historical measurements are provided when possible; however, caution should be exercised in comparing simulated dam release temperatures with historical measurements at a downstream location, as the simulations encompass a different set of assumptions (e.g., dam operations).

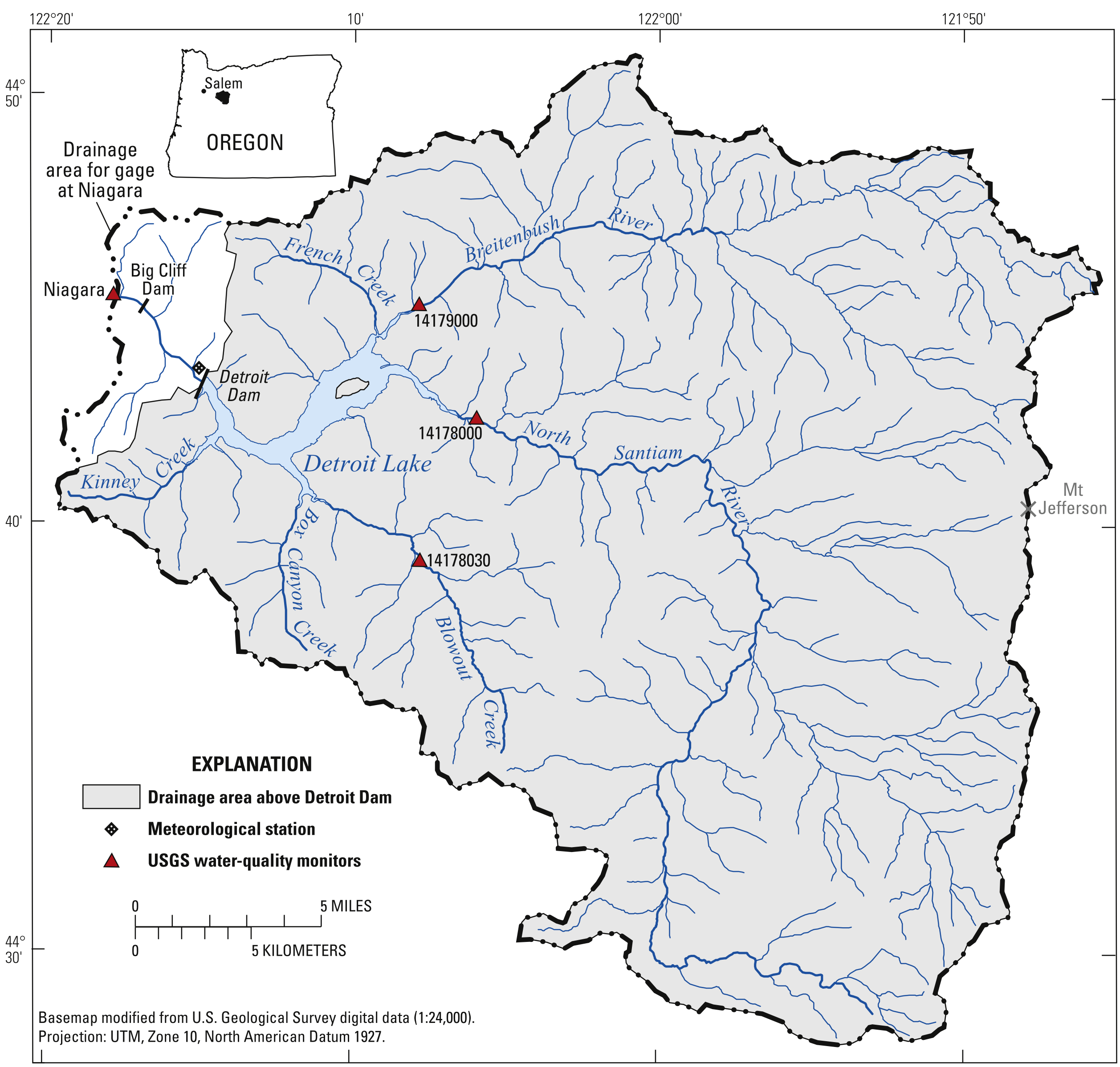

Fig. 1. Map of the upper North Santiam River Basin near Detroit Lake, Oregon.

2. Methods

Mechanistic models of lake circulation (CE-QUAL-W2) and streamflow response to precipitation (PRMS) were used to simulate water temperature. Those models were driven by spatially and temporally downscaled datasets from GCMs. The downscaled daily meteorological data were appropriate for capturing precipitation-runoff processes (e.g., peak flows) and estimating upstream temperature boundary conditions (capturing heat-wave effects) necessary to run lake model simulations at sub-hourly time steps for multiple years in a row (Fig. 2).

2.1. Downscaled data from General Circulation Models

Downscaled daily climate time series created by Hostetler et al. (2011) were used as input to Precipitation-Runoff Modeling System (PRMS) hydrologic models and the Detroit Lake CE-QUAL-W2 hydrodynamic and water-quality model. Hostetler et al. (2011) used simulated A2 emission scenarios from three GCMs provided by the World Climate Research Programme fourth assessment report (Intergovernmental Panel on Climate Change, 2007) as input to a regional climate model. The regional climate model, RegCM3 (Pal et al., 2007), was the third generation of a regional climate model originally created by the National Center for Atmospheric Research (Boulder, Colorado) and is currently maintained by the Abdus Salam International Centre for Theoretical Physics (ICTP) in Trieste, Italy. The three GCMs used with RegCM3 were GFDL CM 2.0 (*gfdl*), GENMOM (*gma2*), and MPI ECHAM5 (*ech5*), which have been widely applied and comprise similar date ranges. Two of these models, *ech5* and *gfdl* were part of the CMIP3 and were chosen because of their availability and relative ease of applying downscaled products already developed at the time of this study. As the newer generation of CMIP5 models have become available, comparison studies have shown that CMIP3 models predict lower air temperature and lower precipitation compared to CMIP5 scenarios, which generally show a stronger El Niño Southern Oscillation signal throughout the Pacific Northwest (Rupp et al., 2013).

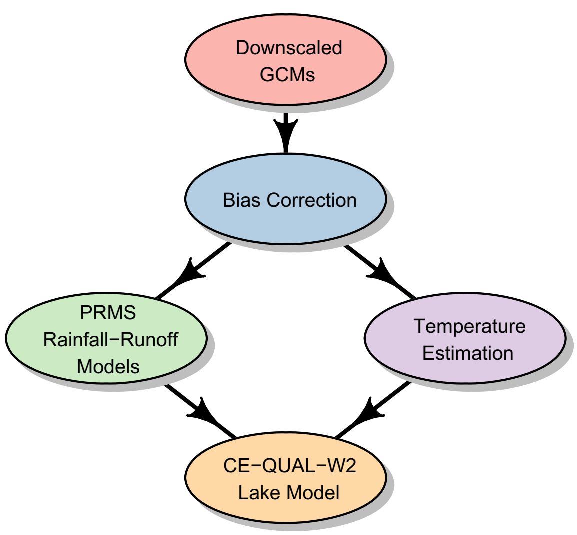

Fig. 2. Model linkages from General Circulation Models to hydrologic and lake models.

A suite of 49 surface level climate parameters were dynamically downscaled by Hostetler et al. (2011) using RegCM3 over western and eastern North America at a 15-km spatial resolution and a daily time step for base and future time periods. Of these parameters, precipitation (PRCP) and minimum/maximum air temperature (TMIN, TMAX) were used in both the PRMS and CE-QUAL-W2 models, while relative humidity, eastward and northward wind vectors (at 2 m), net solar radiation absorbed, and total cloud cover were additionally used in CE-QUAL-W2 simulations.

2.1.1. Bias adjustments for CE-QUAL-W2 model

Downscaling the coarse GCM data (gridded on the order of a few degrees latitude/longitude) to daily increments and 15-km grid size at the Detroit Lake sub-basin creates an inherent bias that warrants some correction. Air temperature from downscaled models of GCM data is commonly bias adjusted to better fit the current-period (measured) data (Hamlet et al., 2010; Hagemann et al., 2011). This bias correction can then be applied to the future (i.e., projected) time period and ideally lead to a better representation of air temperature at a finer resolution. Prior to application of downscaled RegCM3 air temperature data to the CE-QUAL-W2 model, a method of bias correction called "equidistant quantile matching" (EQF) was applied to RegCM3 air temperatures. EQF bias correction uses the difference between the cumulative distribution functions (CDFs) of the RegCM3 and observed air temperature data in the base period as a bias adjustment for air temperature values in the future period of each RegCM3 scenario (Li et al., 2010). For the base period, a CDF was created for the observations at Detroit Dam weather station (National Climatic Data Center site number 352292 [National Climatic Data Center, 2015]) during 1968–1999 ($F^{-1}{}_{o-b}$ *in* Eq. (1)). This CDF was used to match percentiles from the RegCM3 data (F_{m-b}) in the base period that correspond to unadjusted RegCM3-derived air temperature (x_{m-b}), leading to the adjusted RegCM3 air temperature ($xadj_{m-b}$):

$$xadj_{m-b} = F^{-1}_{o-b}(F_{m-b}(x_{m-b})) \tag{1}$$

In the future period, the EQF-bias-correction method consisted of using the CDFs of the observed data ($F^{-1}{}_{o-b}$) and RegCM3 data ($F^{-1}{}_{m-b}$) in the base period to predict two future period values from the future period CDF (F_{m-f}). The air temperature in the projected period ($xadj_{m-f}$) was then calculated from the unadjusted air temperature (x_{m-f}) as follows:

$$xadj_{m-f} = x_{m-f} + F^{-1}_{o-b}(F_{m-f}(x_{m-f})) - F^{-1}_{m-b}(F_{m-f}(x_{m-f})) \tag{2}$$

where the -1 superscript represents the quantile of the given CDF.

Aside from the *gma2* GCM scenario, EQF-bias-corrected air temperatures were generally lower in the base period and higher in the future period relative to historical measurements (Table 1). The relatively small amount of seasonal and long-term (decadal scale) variation from base to future period air temperature displayed in gma2 may be attributed to the relatively low grid resolution compared with the other GCMs (~3.75° compared with ~2.5° and ~1.9° for gfdl and ech5, respectively) (Hostetler et al., 2011).

Table 1
Mean difference between EQF-bias-corrected air temperature under RegCM3 scenarios and measured air temperature at Detroit Dam (1990–1999), in degrees Celsius.

Model	1990–1999				2059–2068			
	ech5	gfdl	gma2	Multi-model Mean	ech5	gfdl	gma2	Multi-model Mean
Min	−0.35	−0.43	1.90	0.43	2.62	3.01	1.61	2.41
Max	−0.55	−0.13	1.97	0.37	2.31	2.53	1.96	2.27

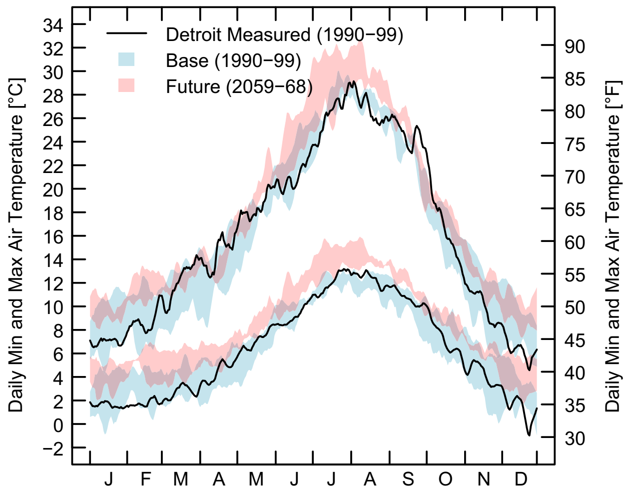

Fig. 3. Minimum and maximum EQF-bias-corrected air temperature measurements at Detroit Dam (1990–1999) compared to bias-corrected GCM base (1990–1999) and future (2059–2068) time frames.

Examining all three RegCM3 scenarios, EQF-bias-corrected air temperatures in the base period were within or greater than mean daily historical measurements at Detroit Dam while future air temperatures were above both the historical record and base period for most of the year (Fig. 3). The multi-model mean of EQF-bias-corrected TMAX and TMIN in all three RegCM3 scenarios increased by about 2 °C from the base to future time frame. Throughout this article, a multi-model mean of the three RegCM3 scenario results is regularly used to more easily compare base and future time frames.

2.1.2. Bias adjustments for PRMS models

A separate method of bias correction, different from the EQF-bias-correction approach (Section 2.1.1), was applied to the three downscaled future climate datasets prior to usage in the PRMS models. The need to adjust data from many locations to drive the PRMS models precluded the application of the EQF-bias-correction approach, so a simpler approach was applied. Adjustments were made by first identifying the 14 RegCM3 latitude and longitude coordinate locations spatially nearest to 14 climate measurement stations located within or near the upper North Santiam River basin. These stations covered a spatial extent that encompassed the varied terrain surrounding Detroit Lake. An algorithm within PRMS weighted the input from each station based on horizontal and elevation distance (Markstrom et al., 2015). For each of these 14 coordinate locations, mean annual values were computed for each climate variable (PRCP, TMAX, and TMIN) and for each downscaled GCM dataset during 1968–1999. These downscaled GCM PRCP, TMAX, and TMIN mean annual values were compared to the measured PRCP, TMAX, and TMIN mean annual values of the 14 climate stations during the same period (1968–1999). Optimal bias adjustments to the downscaled daily climate data were computed by minimizing the difference between the two sets of mean annual values. For the downscaled TMAX and TMIN datasets, the bias adjustments were uniformly added (or subtracted) to all daily values in each time series. However, this approach could not be used for the precipitation time series because it would force days with no precipitation to have a positive or negative precipitation value. For the downscaled precipitation datasets, a unique multiplier ratio was computed for each year in the time series.

$$MR_{year} = (TP_{year} + PBA)/TP_{year} \quad (3)$$

where MR_{year} is the multiplier ratio for the year, TP_{year} is total precipitation for the year, and PBA is the PRCP bias adjustment described above. Each daily value in the downscaled precipitation datasets was then multiplied by the multiplier ratio of that year to compute the daily bias-adjusted precipitation value.

This method of bias correction resulted in multi-model mean TMAX and TMIN increases of 1.6 °C from base (1990–1999) to future (2059–2068) time frames; similar to the 2 °C increases derived from the EQF-bias-corrected data in Section 2.1.1. Bias-corrected PRCP values generally decreased from base to future periods (ranging from 0.13 to 1.47 mm/yr in *gfdl* and *ech5* datasets, respectively) with a multi-model mean 0.80 mm (14%) decrease over the three RegCM3 datasets.

2.2. PRMS inflow discharge simulations

PRMS precipitation-runoff models were used to simulate daily streamflow in the two major rivers feeding Detroit Lake using three future climate condition scenarios. The river inputs were the North Santiam River below Boulder Creek (14178000) and Breitenbush River above French Creek near Detroit (14179000) (Table 2).

2.2.1. PRMS basin models

The two precipitation-runoff basin models were created using the Precipitation-Runoff Modeling System (PRMS) (Leavesley et al., 1983; Markstrom et al., 2008). PRMS simulates water and energy processes such as precipitation, snowmelt, evaporation, evapotranspiration, interception, and infiltration within the confines of a drainage basin. Land surface heterogeneity is accounted for by partitioning the basin into areas based on user-defined criteria such as elevation, slope, aspect, land use, soil type, geology, and precipitation. Areas with similar properties are assumed to respond in a hydrologically similar manner and are designated as a hydrologic-response unit (HRU). Required PRMS model input data include daily PRCP, TMAX, and TMIN. Using a daily time step, simulated PRMS output includes water flows within the basin and daily mean streamflow at the basin outlet.

For the PRMS model calibration process, PRCP, TMAX, and TMIN data measured at 14 climate stations located within or nearby the North Santiam River basin from 1951 to 2009 were used. These climate stations are operated by the U.S. National Weather Service Cooperative and U.S. Natural Resources Conservation Service Snow telemetry programs.

Daily values of PRCP, TMAX, and TMIN for each HRU were computed using a monthly multiple linear regression relation developed for each dependent variable (PRCP, TMAX, and TMIN) based on the independent location variables of the 14 climate stations.

Table 2
River basins upstream of Detroit Lake simulated with Precipitation-Runoff Modeling System (PRMS) models.

USGS station number	Streamflow station name	Drainage area (km^2)	Mean basin elevation (m)	Mean runoff (m^3/s)	Period of record, in water years
14178000	North Santiam River below Boulder Creek	559	1259	29	1929–2011
14179000	Breitenbush River above French Creek	280	1149	16	1933–1987; 1998–2011

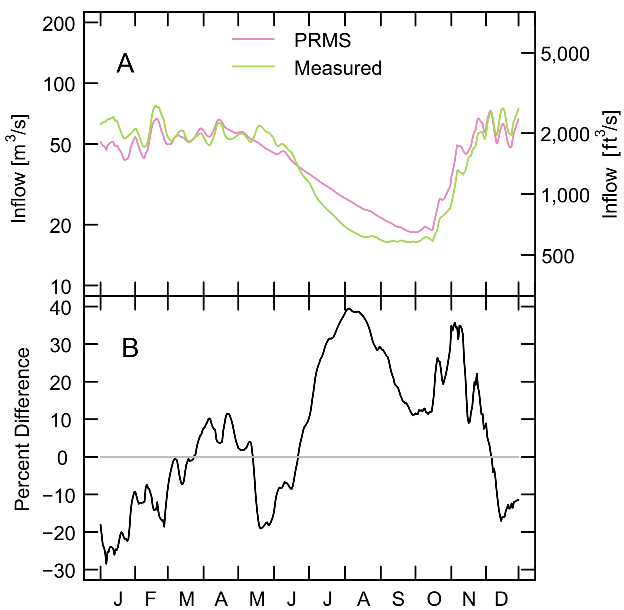

Fig. 4. PRMS-simulated and measured (A) long-term average inflows to Detroit Lake (total discharge of the North Santiam and Breitenbush Rivers) and (B) PRMS model percent difference during the periods 1978–1986 and 1998–2009.

Location variables are based on latitude (y), longitude (x), and elevation (z). Monthly multiple linear regression relations were calculated using measured climate data from the stations according to Markstrom et al. (2008) and Hay et al. (2000, 2002).

The initial calibration of the two PRMS models (North Santiam and Breitenbush River basins) evaluated the basin water balance. Simulated basin- and HRU-averaged precipitation and maximum and minimum air temperature were compared with measured data from the nearest climate station. Simulated basin- and HRU-averaged short-wave solar radiation and potential evapotranspiration were compared with interpolated spatial datasets from Hostetler et al. (2011) and Farnsworth et al. (1982) and measured data from the Detroit, Oregon (DTRO) AgriMet climate station (Bureau of Reclamation, 2013). Both PRMS models were able to simulate a reasonable approximation of their basin water balances. Major manual adjustments to the model parameter values were not needed at this stage. In the second phase of the calibration, a step-wise multiple objective calibration program called **L**et **U**s **CA**librate (LUCA) was used (Hay et al., 2006; Hay and Umemoto, 2006). LUCA used measured daily mean streamflow data to calibrate the annual water balance, peak flows, and low flows at the basin outlet. Measured monthly solar radiation data and estimated monthly potential evapotranspiration data also were used by LUCA to optimize PRMS solar radiation and evapotranspiration related parameters.

Each of the PRMS models was calibrated using measured daily climate data (PRCP, TMAX, and TMIN) and measured daily streamflow data for water years 1951–1980. A 9-month period from January 1, 1950 to September 30, 1950 was used as a model "spin up" period. Water years 1981–2009 were used as a model validation period. However, the Breitenbush River PRMS model validation period used water years 1981–1986 and 1999–2009 because measured streamflow data for water years 1987–1998 were unavailable. Mean errors for the predicted streamflows ranged from −0.8 to 0.4 m^3/s. The Nash–Sutcliffe statistic (Nash and Sutcliffe, 1970), which evaluates model error in relation to data variability, ranged from 0.64 to 0.77. A comparison of measured and simulated long-term average daily streamflow results for the North Santiam River and Breitenbush River PRMS models (Fig. 4A) showed that the PRMS-simulated streamflow typically was less than the measured streamflow in May and June, but greater than measured streamflow in July, August, and September (Fig. 4B). The hydrograph pattern mismatch in the falling limb of the hydrograph (May–September) can likely be attributed to an inability to capture local groundwater flow contributions in PRMS. PRMS algorithms were developed for shallow groundwater systems in Colorado, which are not like the headwaters of the North Santiam River basin located in the High Cascades, a high elevation area underlain by young relatively permeable material consisting of volcanic rocks and glacial deposits (Tague and Grant, 2004).

Despite this limitation of the PRMS model, the annual amount of streamflow simulated was largely correct, as some underprediction of streamflow in spring was balanced by overprediction during the drier July–September base-flow period. This may have led to some overestimation of simulated lake levels during summer months.

2.3. CE-QUAL-W2 model setup

CE-QUAL-W2 is a two-dimensional, laterally averaged hydrodynamic and water-quality model developed by the USACE and Portland State University that has been applied to hundreds of lakes, low-sloping rivers, and estuaries (Cole and Wells, 2011). The Detroit Lake model used in this study originally was developed using CE-QUAL-W2 version 3.12 (Sullivan et al., 2007) but a modified version 3.7 model was used in this study to allow enhanced blending of releases from different outlets at the dam to match a time series of downstream temperature targets (Rounds and Sullivan, 2006; Buccola et al., 2015; Rounds and Buccola, 2015). To create boundary conditions for the CE-QUAL-W2 model, this study applied methods or assumptions used in previous studies when possible, but new methods (Table 3) were necessary to develop base (1990–1999) and future (2059–2068) meteorological conditions (hourly estimates based on RegCM3 data), upstream tributary inflows (daily output from PRMS simulations), and water temperatures (daily estimates based on RegCM3 air temperatures). A test period (1999, used for *m2test* and *m1* boundary conditions in Table 3) also was simulated using combinations of both measured and estimated forcing conditions (derived from RegCM3 scenarios)

Table 3
Data sources for the CE-QUAL-W2 model of Detroit Lake, Oregon.

Boundary condition set	Meteorological data sources	Major tributary flow data sources	Major tributary temperature data sources
ech5	RegCM3 ECH5 data	PRMS	Mohseni regressions
gfdl	RegCM3 GFDL data	PRMS	Mohseni regressions
gma2	RegCM3 GMA2 data	PRMS	Mohseni regressions
m2test	TAIR from DET; TDEW, WIND, PHI from NCDC Salem, OR; SRO and CLOUD average from all RegCM3 scenarios	PRMS	Mohseni regressions
m1	TAIR from DET; TDEW, WIND, PHI from NCDC Salem, OR; SRO and CLOUD average from all RegCM3 scenarios	USGS monitors	USGS monitors

Abbreviations: DET, Detroit Dam weather station; TAIR, air temperature; TDEW, dew-point temperature; WIND, wind speed; PHI, wind direction; SRO, solar radiation; CLOUD, cloud cover; NCDC, National Climatic Data Center.

Table 4
Description of operational scenarios at Detroit Dam under potential future climate change conditions.

Scenario name	Minimum outflow used to keep lake elevations near minimum pool	Day in which refill began	Release structures
curmins	28.3 m^3/s (1000 ft^3/s)	January 31	Existing
curmins_fl	28.3 m^3/s (1000 ft^3/s)	January 31	Hypothetical floating structure 1 m below surface
curmins_rc30	28.3 m^3/s (1000 ft^3/s)	January 1	Existing
lowmins	16.4 m^3/s (580 ft^3/s)	January 31	Existing

and used to assess potential model bias under base and future periods where little to no measured data exist to compare with model output.

2.3.1. Minor inflow estimation

The North Santiam and Breitenbush Rivers account for the majority of the inflow to Detroit Lake. Inflows from the smaller tributaries of French, Box Canyon, Kinney, and Blowout Creeks were estimated based on scaling the discharge from the Breitenbush River (from historical discharge, otherwise from PRMS simulated discharge) by relative drainage area size (25.6, 27.7, 35.5, 67.3, and 290.1 square kilometers respectively). This estimation method was checked for reasonableness using Breitenbush River and Blowout Creek flow data in 2011 and resulted in a mean error of 0.43 m^3/s. An additional CE-QUAL-W2 tributary inflow, the "distributed tributary" (QDT), was used to approximate any other surface runoff and groundwater inflow to the lake under each RegCM3 scenario. The QDT was estimated based on a linear regression between the QDT used under three calendar-year scenarios to complete the water balance for the lake in a previous study (Buccola et al., 2012) and daily average total inflow under these same scenarios. This method resulted in a correlation coefficient of 0.80 and a regression equation as follows:

$$\mathrm{QDT} = -0.5743 + 0.1184 * \mathrm{QIN}_{\mathrm{total}} \tag{4}$$

where QDT is the distributed tributary inflow and $\mathrm{QIN}_{\mathrm{total}}$ is the total tributary inflow to Detroit Lake (sum of North Santiam and Breitenbush Rivers, and French, Box Canyon, Kinney, and Blowout Creeks).

Some changes to the methods used for the previously calibrated Detroit Lake temperature model (Sullivan et al., 2007) were applied in this study. Precipitation inputs (in units of m/s and multiplied by a constant area of 9.517×10^6 m^2 to achieve a flowrate in m^3/s) were added to the QDT defined in Eq. (4). Separate precipitation inputs were turned off in the CE-QUAL-W2 control file (PRE set to OFF), and internal model-calculated evaporative mass losses also were turned off (EVC set to OFF) to make iterative water balancing manageable. Heat losses associated with evaporation were still accounted for in the model. Final QDT values were 5–12% of the total inflow to Detroit Lake over all GCM scenarios with higher QDT values occurring during high-flow season.

2.3.2. Outflow calculations

Daily releases from Detroit Dam were estimated based on the total inflow (sum of all tributary inflows plus the QDT) into the lake and the specified lake surface elevation for each day as defined by the USACE "rule curve" for Detroit Lake. The rule curve is a guide for dam operators that specifies the lake elevation that should not be exceeded on any day of the year. Under ideal conditions, inflow to the lake should allow dam operators to finish filling the lake (refill) by May 31 and begin lowering lake level for flood management (drawdown) on or about September 1 each year. Furthermore, minimum flow requirements exist downstream of Detroit and Big Cliff Dams during the summer and autumn to maintain downstream spawning habitat for endangered salmon species. Due to lower inflows under the future RegCM3-based hydrology, three alternative outflow rules were developed to keep Detroit Lake near minimum pool through late-summer and autumn of drier years (Table 4). Two sets of operational scenarios were used to reduce the minimum outflow when lake levels fell below the rule curve; named *lowmins* and *curmins*, these scenarios decreased minimum flows to as low as 16.4 and 28.3 m^3/s (580 and 1000 ft^3/s) respectively when total inflows fell below the minimum specified for that time period. In an effort to achieve higher lake levels in summer, *curmins_rc30* operational scenarios were developed to begin reservoir refill 30 days earlier (starting January 1 rather than January 31) while incorporating *curmins* outflow reduction rules. A hypothetical floating outlet 1 m below the lake surface was incorporated with *curmins* outflow rules in scenario *curmins_fl* to examine the potential effects from such a hypothetical release structure at Detroit Dam.

2.3.3. Model blending algorithm controls

The newblend6 version of CE-QUAL-W2 v3.7 used in this study includes an input file (w2_selective.npt) that allows fine tuning of parameters in the algorithm used to blend releases from the dam (Rounds and Buccola, 2015). In this file, the MINFRAC value controls the minimum fraction of total outflow that the model will assign to any particular outlet structure. For all scenarios except *curmins_fl*, MINFRAC values for the power penstock outlet were set to 0.4 (spillway and upper regulating outlets (RO) were set to 0), indicating a minimum release of 40% of total outflow from the power outlet at all times. For *curmins_fl* scenarios, MINFRAC values were set to 0 for all outlets and an additional floating outlet was added to the model with a DEPTH value of 1.0, indicating that the floating outlet always was 1.0 m below the lake surface.

2.3.4. Meteorological data

The CE-QUAL-W2 model requires time series of six meteorological parameters: air temperature, dew-point temperature, wind speed, wind direction, cloud cover and solar radiation. Meteorological data for the future scenarios were based on downscaled RegCM3 data as follows.

Following EQF bias correction, the daily range and daily mean of the air temperature data were used to estimate hourly air temperatures using an adaptation of the equation used by Erbs (1984):

$$\begin{aligned} T_h = T_d + A_{td}(&0.4632\cos(a - 3.805) + 0.0984\cos(2a - 0.360) \\ &+ 0.0168\cos(3a - 0.822) + 0.0138\cos(4a - 3.513)) \end{aligned} \tag{5}$$

where $a = 2\pi(h-1)/24$, T_h = hourly air temperature, T_d = daily mean air temperature, A_{td} = daily range in air temperature, and h = hour of day.

Dew point temperature at Detroit Lake was estimated based on a non-linear Multivariate Adaptive Regressive Spline model of hourly air temperature at the Detroit Dam NCDC met station (Milborrow, 2014). Goodness-of-fit errors from this regression were relatively low (mean absolute error [MAE] = 1.5 °C, Nash–Sutcliffe coef. = 0.77). Hourly net solar radiation was estimated by scaling the theoretical cloudless-sky hourly solar radiation at Detroit Lake by the daily net solar data from each respective

RegCM3 scenario. Cloud cover (numeric values 0–10) was used as-is from each RegCM3 scenario. Northerly and easterly wind vector components (v, u) from RegCM3 data were converted to daily wind speed (WIND) and direction (PHI) using the following equations:

$$\mathrm{PHI} = (3\pi/2) - \tan^{-1}(v, u) \tag{6}$$

$$\mathrm{WIND} = \sqrt{v^2 + u^2} \tag{7}$$

For *m1* and *m2test* scenarios (Table 3) under the *test* time frame (1999), all meteorological inputs except air temperature, cloud cover and solar radiation came from the National Oceanic and Atmospheric Administration weather station at the Salem, Oregon, Airport. Air temperature was measured by USACE at Detroit Dam. No measured cloud cover or solar radiation data were available near Detroit for 1999, so a daily average of the cloud cover and solar radiation results from all three RegCM3 scenarios was used for both the *m1* and *m2test* boundary sets in the *test* time frame (Table 3).

2.3.5. Inflow temperature estimation

Methods of estimating stream temperature based on a non-linear relation with weekly air temperature have been applied by Mohseni et al. (1998) and Morrill et al. (2005) to a variety of basins throughout the U.S. For this study, the validity of the Mohseni approach (daily mean stream temperature as a non-linear function of 7-day moving average of the daily maximum air temperature) was compared to multiple linear regressions of daily mean stream temperature as a function of 7-day moving average of both minimum and maximum air temperature as well as streamflow for the three tributaries upstream of Detroit Lake that had sufficient water temperature data available: North Santiam River at Boulder Creek (14178000), Breitenbush River (14179000), and Blowout Creek (14180300). The non-linear Mohseni approach was found to be the most realistic (and conservative) method under warmer RegCM3-based air temperatures. The Mohseni approach uses the following type of logistic equation:

$$T_s = \frac{\propto}{1 + e^{\gamma(\beta - T_a)}} \tag{8}$$

where T_s = stream temperature estimate, T_a = 7-day mean of daily maximum air temperature, and values for the Mohseni fitting parameters α, γ, and β are listed in Table 5.

Although Morrill et al. (2005) warned that the non-linear logistic regression method originally developed by Mohseni et al. (1998) may underpredict or need new parameters to predict appropriate stream temperatures under future (warmer) air temperatures, it also is true that linear models may overestimate stream temperatures under warmer air temperature conditions. Further, the source water for the major tributaries to Detroit Lake is located in the High Cascades, where glacial and snowmelt-sourced groundwater provide a relatively steady and cool year-round baseflow (Tague and Grant, 2004). At the time of this study, it was unclear that melting of Cascade Range glaciers that provide source water to Detroit Lake would translate downstream into warmer stream temperatures by the late 21st century (the time frame of this study). The Mohseni-type models provided the best relative fit of the tested stream temperature estimation methods and were applied to three tributary inflows to Detroit Lake for this study, despite the potential for underestimation at higher air temperatures and overestimation at low air temperatures (Table 5, Fig. 5). Minor inflow temperatures to Detroit Lake—French, Kinney, and Box Canyon Creeks—were estimated by using the Blowout Creek temperature estimates.

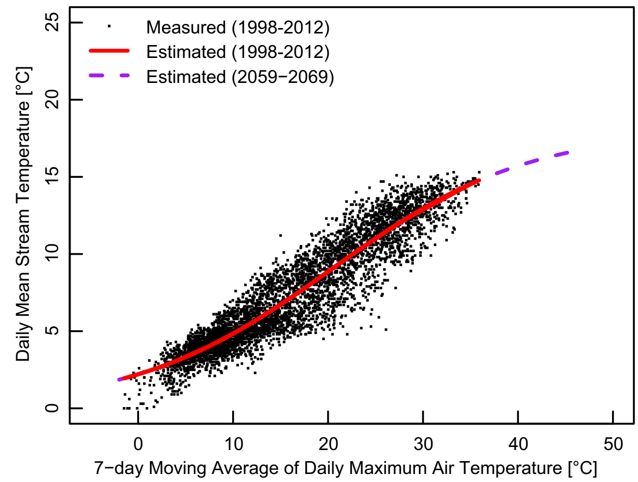

Fig. 5. Measured (black) and estimated (red) daily mean stream temperature as a function of the 7-day moving average of the daily maximum air temperature at North Santiam River near Boulder, Oregon (14178000). Note: NS = Nash–Sutcliffe coefficient, MAE = mean absolute error, meas = measured data, mod = model regression curve based on Mohseni et al. (1998) equation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.3.6. Temperature target

To provide realistic targets for dam operations, as well as context for the model simulations under base and future periods for each of the three RegCM3 scenarios, a without-dams water temperature at the Detroit dam site was estimated using the flow-weighted average of temperatures in the two major tributaries (North Santiam and Breitenbush Rivers) during 1977–2013, following methods documented by Rounds (2010). The CE-QUAL-W2 v3.7 temperature blending algorithm allows the user to specify a temperature target as a time series. The model uses that target as part of its algorithm for setting the relative release rates for the available outlets at the dam (Rounds and Buccola, 2015). A temperature target for Detroit Dam releases was developed based on a centered 30-day moving average of the maximum daily without-dams temperatures during water years 1998–2013 (Buccola et al., 2015). The time period chosen for this temperature target time-series encompassed the most recent continuous set of measured temperatures and provided a year-round goal that essentially directed the model to release as much warm water as

Table 5
Parameters and fit statistics for temperature estimation of Detroit Lake inflows using a Mohseni-type non-linear regression model.

Site name	USGS ID	Mohseni parameters			Goodness-of-fit statistics		
		Alpha	Gamma	Beta	MAE	ME	NS
North Santiam River at Boulder	14178000	18.08	0.10	20.42	1.00	0.00	0.84
Breitenbush River	14179000	19.50	0.08	22.67	1.00	0.00	0.84
Blowout Creek	14180300	23.97	0.10	24.23	1.30	0.00	0.86

Abbreviations: MAE, Mean Absolute Error; ME, Mean Error; NS, Nash–Sutcliffe Coefficient possible from the lake during the spring and early summer, while saving cooler, deeper water for release later in autumn.

3. Results and discussion

3.1. PRMS streamflow simulation results

As a consequence of changes to the water budget with increased air temperature, increased potential evapotranspiration, and decreased precipitation under the future period, the multi-model average of the RegCM3-based PRMS models simulated about a 23% decrease in annual streamflow from base (1990–1999) to future (2059–2068) periods (Fig. 6). On a seasonal basis some of the RegCM3 models, particularly *ech5*, simulated an increase in January, February, and December streamflows while *gfdl* and *gma2* simulated a decrease year round (Fig. 6b). Overall, warmer air temperatures led to more rainfall and less snow, decreased snowpack, and earlier spring snowmelt. Climate models can show substantial variability in the predicted future rate of precipitation. The downscaled GCM data used here predicted an overall drier future condition (a not uncommon result for this region), and that was a useful test for this study to determine how reservoir management strategies would be forced to react to drier future conditions.

3.2. Warming of upstream temperatures

Without-dams temperature estimates at Detroit Dam were created by applying methods documented by Rounds (2010) to the RegCM3-based stream-temperature estimates in the lake's tributaries, including an adjustment April–October to account for warming during transit through the reach where Detroit Lake exists. The resulting without-dams temperature estimates at Detroit Dam showed an overall annual warming from base to future periods, especially during winter (Fig. 7). Mean daily without-dams temperature estimates in the base time frame were within the historical range (1977–2013) for most of the calendar year aside from October–November, when they were cooler. Winter warming from the base to future period accounted for a majority of the calculated warming, and could represent the dependency of the stream temperature estimates on the Mohseni curve model at lower air temperatures (Fig. 5).

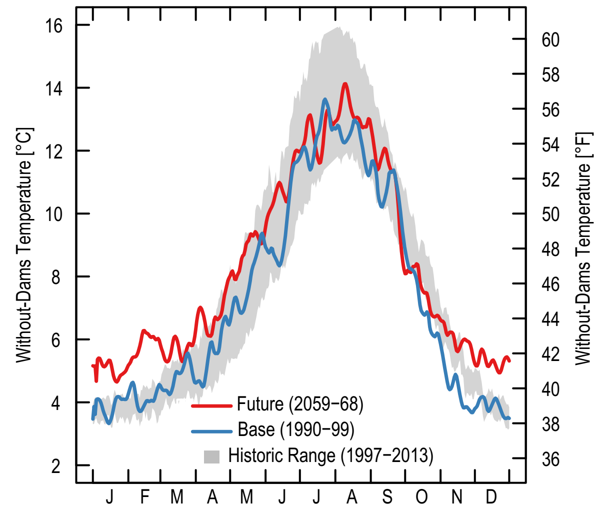

Fig. 7. Comparison of estimated mean daily without-dams temperatures at Detroit Dam under base (1990–1999) and future (2059–2068) scenarios derived from RegCM3 forcing, with the historical range (in gray, derived from 1997 to 2013 measurements).

3.3. CE-QUAL-W2 simulations

3.3.1. Test period

To assess the combined effects of PRMS modeling, inflow temperature estimations, and CE-QUAL-W2 parameter changes on simulated in-lake and release temperatures, a test period (1999) was used in which some measured inflows and temperatures were used as forcing conditions to the model. The *m2test* boundary conditions included PRMS-simulated inflows and Mohseni-type inflow temperature estimates, whereas the *m1* boundary conditions

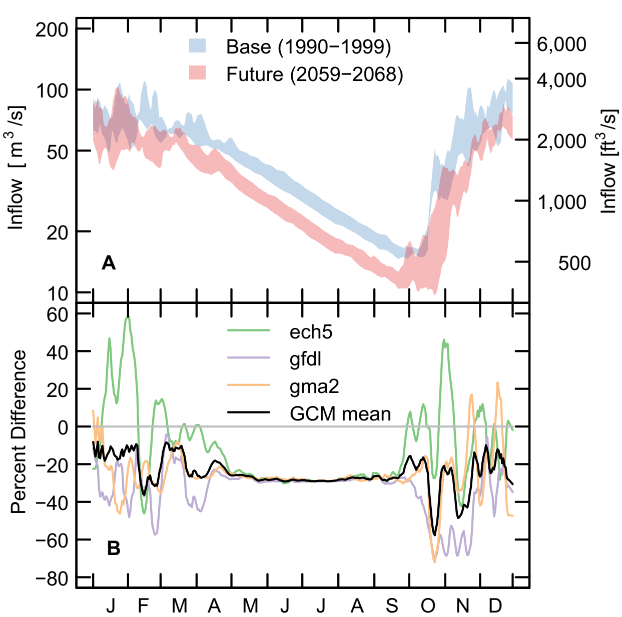

Fig. 6. PRMS-simulated inflow to Detroit Lake (total discharge of the North Santiam and Breitenbush Rivers) in RegCM3-averaged (A) future (2059–2068) and base (1990–1999) periods, and (B) percent difference in those inflows (future minus base) for each RegCM3 scenario and the RegCM3 GCM mean (black).

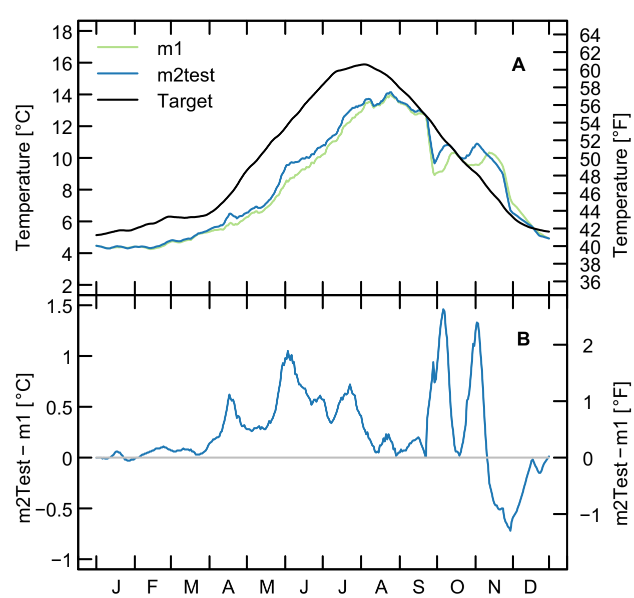

Fig. 8. Simulated release temperatures (A) and temperature differences (B) between scenarios with estimated (*m2test*) and measured (*m1*) inflow boundary conditions during 1999 at Detroit Dam, Oregon.

included measured streamflows and temperatures (Table 3). Using current dam-operating conditions, mean lake levels during autumn were 0.5 m lower under *m2test* compared to *m1* boundary conditions. This led to warmer lake temperatures under *m2test* boundary conditions, with a 0.2 °C increase in mean annual in-lake temperature, a 0.4 °C increase in summer release temperature (June–August) when the lake was above the spillway crest, and a 0.1 °C increase in autumn release temperature (September 20–December 1) (Fig. 8). Assuming that the goal was to have *m2test* results be as close as possible to results from *m1*, goodness-of-fit statistics were computed for release temperatures from Detroit Lake under *m2test* relative to *m1* boundary conditions, and resulted in an overall mean error of 0.26 °C, a mean absolute error of 0.34 °C, and a Nash–Sutcliffe coefficient of 0.98 during 1999. This comparison seemed acceptable, given the fact that a good fit for a temperature model to actual data results in a mean error less than a few tenths of a degree Celsius and a mean absolute error less than 1 °C or even approaching as low as 0.5 °C.

3.3.2. Base and future period comparisons

Relatively lower inflows under the future time frame led to decreased outflows from Detroit Dam (Fig. 9) and lower Detroit Lake levels (Fig. 10) compared to the base time frame. In particular, decreased inflows in the future combined with current release rules in the *curmins* operational scenario generally limited lake levels from meeting the maximum summer pool elevation (476.6 m [1563.5 feet]). In contrast, scenarios specifying lower minimum release rates or earlier refill dates (*lowmins* and *curmins_rc30* scenarios) generally led to higher lake elevations in summer (Fig. 10). All three operational scenarios in the future time frame resulted in outflows that were below the current minimum release flow rules at some time during the calendar year (Fig. 9b). Among the three future scenarios, *curmins_rc30* operations had the highest outflow during April–August, while *lowmins* operations had the lowest outflow (but generally the highest lake level) during those months. Compared to *curmins* operations in the base time frame, *curmins_rc30* scenarios minimized the percent change in outflow March–September in the future time frame, allowing more outflow for outmigrating juvenile fish during April–May when the lake was generally full or close to full. With greatly decreased releases in summer, the *lowmins* scenario was able to keep the lake level close to the fill curve in summer and throughout autumn. As a result, the *lowmins* scenario produced less of a change in outflows during September–October in the future time frame. Essentially, *lowmins* operational scenarios prioritized higher summer Detroit Lake levels and autumn outflows at the cost of lower spring and summer outflows.

Summer-maximum lake levels were lower under future *curmins* scenarios compared to the base period (from 475.0 to 470.7 m, Table 6), which led to more years (from 2 to 11) in which the lake level did not rise to the level of the spillway crest and fewer days per year in which the lake level was above the spillway crest (mean values from 147.6 to 75.0, Table 6, full distribution in Fig. 11). Fewer days of potential spillway use at Detroit Dam during future *curmins* scenarios resulted in limited ability to expel warmer surface water from the lake during summer. Not expelling warm surface water led to more heat stored in surface waters of the lake, compared to *curmins_rc30*, *lowmins*, and *curmins_fl* operations, and that heat was released later through the lower outlets (power penstocks and upper RO) in autumn (October–December) as the lake was drawn down (Fig. 12). As the warmer surface water reached the elevation of the power outlet each autumn (beginning mid-October), there was generally an exceedance of the temperature target (based on long-term without-dams temperatures) in all operational scenarios with existing structures in place (*curmins*, *curmins_rc30*, *lowmins*). The autumn peak also was present in the measured temperatures for 2007–2013 (*curmins* in Fig. 12A), but USACE was managing for a slightly different temperature target during those years. Compared with *curmins* base period scenarios, the autumn peak in release temperatures was more pronounced in the future time frame (Fig. 12). Only the *curmins_fl* scenario, which included the ability to release warm surface water through a hypothetical floating outlet during summer, resulted in year-round releases that matched the target temperatures relatively well year-round.

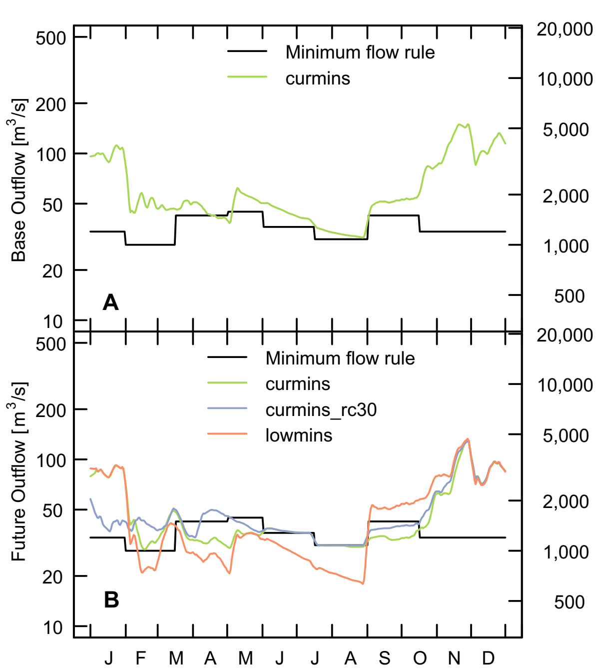

Fig. 9. Simulated dam outflows under operational scenarios in (A) base (1990–1999) and (B) future (2059–2068) time frames at Detroit Dam, Oregon [scenarios are defined in Table 4].

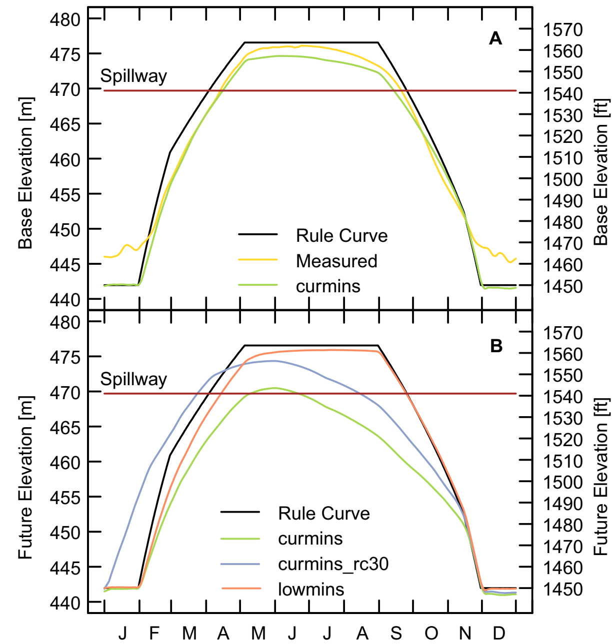

Fig. 10. Lake levels as measured (1970–2013) and simulated under three operational scenarios in (A) base (1990–1999) and (B) future (2059–2068) time frames at Detroit Dam, Oregon [scenarios are defined in Table 4].

Table 6
Summary metrics for Detroit Lake CE-QUAL-W2 scenarios.

Operational scenario	Measured	Base		Future			
	Niagara[a]	curmins	curmins_fl	curmins	curmins_fl	curmins_rc30	lowmins
Timeframe	2007–2013	1990–1999	1990–1999	2059–2068	2059–2068	2059–2068	2059–2068
Number of scenario years	7	30	30	30	30	30	30
Number of scenario years in which the lake level did not rise to spillway crest	0	2	3	11	13	4	1
Mean release rate (Sep 20-Dec 1) [m^3/s]	87.8	88.1	88.2	59.2	59.2	65.1	76.2
Mean outflow temperature when lake is above spillway crest [°C]	9.8	9.7	11.3	10.5	11.9	9.7	10.8
Mean outflow temperature Sep 20 – Dec 31 [°C]	8.9	7.4	7.2	8.9	8.3	8.5	8.0
Mean emergence day [day of year]	382.0	420.8	427.1	379.5	392.4	386.8	394.9
Maximum annual lake level [m]	476.9	475.0	474.5	470.7	470.4	474.7	76.1
Number of days lake level is above spillway	165.3	147.6	140.6	75.0	72.2	146.6	160.5
Mean annual lake temperature [°C]	NA	6.0	5.6	7.1	6.4	6.8	6.6

[a] Measurements at Niagara (USGS station 14181500) represent historical dam operations not equivalent to simulations; NA = not applicable.

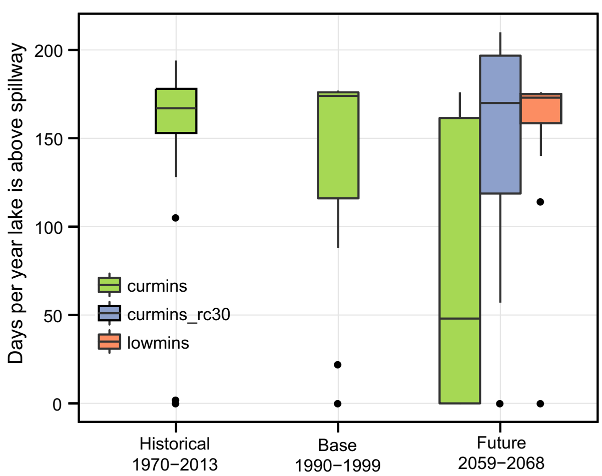

Fig. 11. Number of days per year that lake level was above the spillway crest historically (1970–2013) and in operational scenario simulations over base (1990–1999) and future (2059–2068) time frames at Detroit Dam, Oregon [scenarios are defined in Table 4].

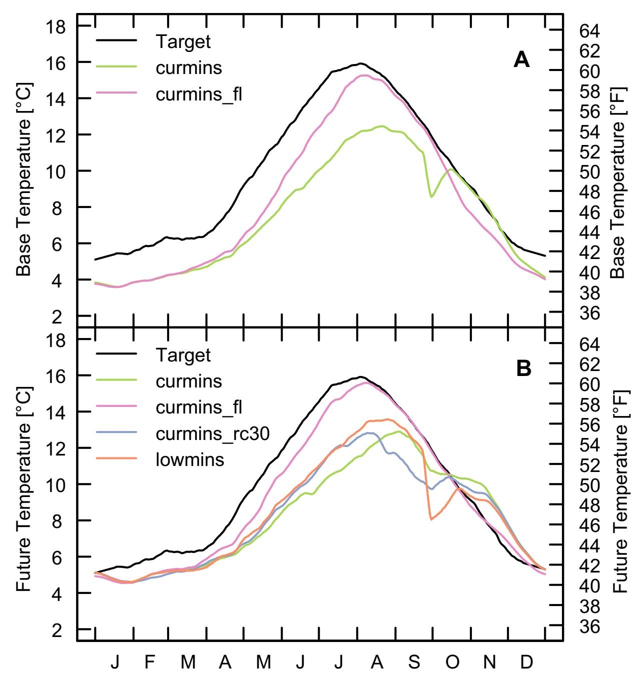

Fig. 12. Release temperature simulated under four different operational/structural scenarios in (A) base (1990–1999) and (B) future (2059–2068) time frames at Detroit Dam, Oregon [Scenarios are defined in Table 4].

When lake level was above the spillway crest, only a slight warming in the future release temperatures occurred under *curmins* operations (0.8 °C; statistically significant with $p < 0.05$ as determined by unpaired Wilcoxon test in R [R Core Team, 2013]), indicating that operations similar to the current rules may not be affected greatly by future climate while the lake level is above the spillway crest (Fig. 13). Lower lake levels and decreased ability to release warmer surface water during summer with existing structures resulted in warmer future release temperatures while the lake was below the spillway crest compared to the base period (1.5 °C increase, Table 6, Fig. 13B; statistical significance). Similarly, mean annual lake temperatures under *curmins* operations increased by 1.1 °C in the future compared to base simulations (Table 6, Fig. 14; statistical significance). While alternative operational and structural scenarios (*curmins_rc30*, *lowmins*, and *curmins_fl)* resulted in higher future mean annual in-lake temperatures and mean autumn release temperatures (when lake level was below the spillway crest) than *base curmins* operations, these hypothetical operations resulted in lower values compared to *future curmins* results (Table 6). This demonstrates the potential of alternative operations or hypothetical structures to mitigate at least some part of future climatic effects on water temperatures in and immediately downstream of Detroit Lake when compared to unchanged operations.

Hypothetical operations (*curmins_rc30* and *lowmins*) in the future period resulted in progressively lower in-lake temperatures and autumn release temperatures compared to *curmins* operations. These results indicate that operations incorporating decreased summer minimum release rates (*lowmins*) and/or earlier refill of the lake (*curmins_rc30*), resulting in lake levels that are higher late into the summer, may provide some potential mitigation of a warmer future climate by allowing temperature management through the summer and autumn under low flow years. However, the decreased release rates in these scenarios (Table 4; Fig. 9) may be a concern relative to fish habitat downstream. Temperature results using a hypothetical floating release structure (*curmins_fl*) were similar to results using decreased releases (*lowmins*) while maintaining existing minimum release rates intended to support in-stream habitat for fish downstream of the dams during the low-flow season in late summer and early autumn. The *curmins_fl* structural scenario also resulted in the greatest future mitigation of in-lake temperature (0.7 °C cooler than future *curmins*; only 0.4 °C warmer than base *curmins* scenarios in Table 6). Historical measurements in the North Santiam River at Niagara (USGS station 14181500, 9.2 km [5.7 miles] downstream of Detroit Dam) are

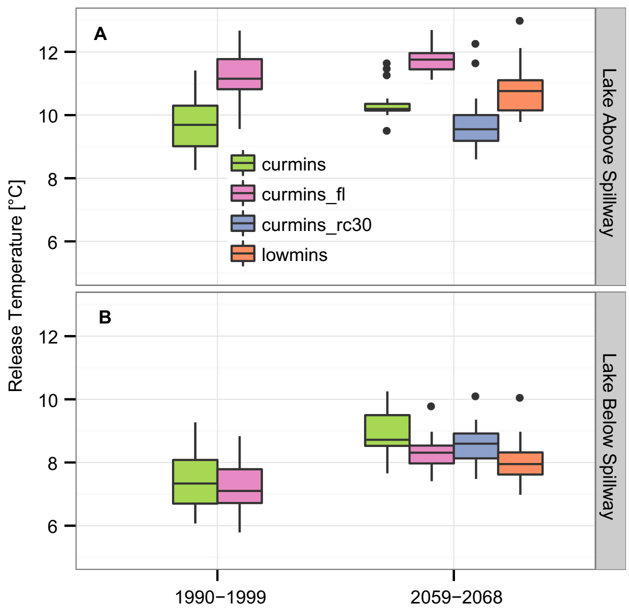

Fig. 13. Distributions of simulated release temperatures when lake level was (A) above or (B) below the spillway crest under base (1990–1999) and future (2059–2068) operational/structural scenarios at Detroit Dam, Oregon [Scenarios are defined in Table 4].

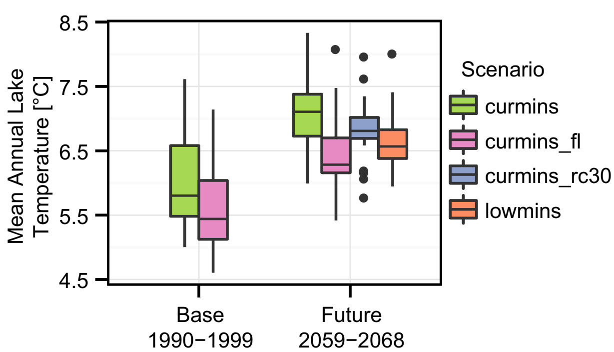

Fig. 14. Distributions of simulated whole-lake annual average temperatures under base (1990–1999) and future (2059–2068) operational/structural scenarios at Detroit Dam, Oregon [scenarios are defined in Table 4].

provided in Table 6 for reference, but a measured comparison to the model results is not possible, due to the variations in dam operations during 2007–2013. Usage rules for the spillway, power, and RO outlets were not exactly the same as the modeled conditions, and the temperature targets also were slightly different.

3.3.3. Estimated emergence day

The estimated emergence day is the theoretical day of the year in which salmon fry may emerge from eggs (U.S. Army Corps of Engineers, 2012). Emergence days were calculated as the day of year in which the cumulative sum of daily mean temperature above 32°F (starting on day 263 or September 20, the typical peak in spring Chinook spawning) of each scenario reached 1750 accumulated thermal units (°F – day). The emergence day is a metric that accounts for water temperatures that occur during the entire salmon spawning and egg incubation season in autumn. An earlier estimated emergence day is associated with warmer autumn and early winter water temperatures. The average emergence day under *curmins* operations was about 41 days earlier in future scenarios compared with the base period (Table 6). Alternative

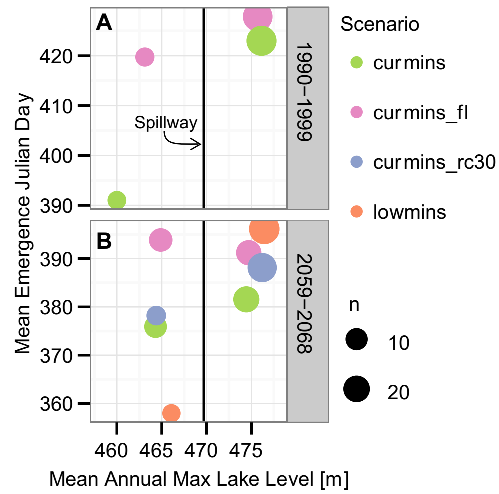

Fig. 15. Multi-model mean estimated emergence day of year (day 1 = January 1) as a function of multi-model mean annual maximum lake level in base (1990–1999) and future (2059–2068) operational/structural scenarios at Detroit Dam, Oregon, for scenario years in which the lake level did not rise to the elevation of the spillway crest (results to the left) and scenario years when the lake level was above the spillway (results to the right). [n = number of years in each group; Scenarios are defined in Table 4].

operations (*curmins_rc30*, *lowmins*) and hypothetical structural scenarios (*curmins_fl*) resulted in some mitigation (delay) of the emergence day compared to *curmins* future period scenarios. For all scenarios except *curmins_fl*, estimated emergence days were generally earlier for years in which the level of Detroit Lake did not meet the spillway crest elevation compared to years in which the lake level was above the spillway (Fig. 15). The hypothetical floating release structure (*curmins_fl*) allowed warm surface water to be expelled from the lake in low-water years and provide better year-round temperature control at Detroit Dam compared to scenarios with strictly operational changes and lake-surface releases existing only when the lake was above the spillway crest.

4. Uncertainty discussion

Through the application of multiple models in this research, model bias and error estimates have been highlighted and quantified as it was possible, within the scope of this work. A qualitative evaluation of uncertainty associated with each step of this project is shown in Table 7. While the accuracy of the CE-QUAL-W2 model is within 0.5–1.0 °C, uncertainties in boundary conditions to the model are likely, at certain times of the year to be as large or larger. Most notable of these perceived biases are related to streamflow boundary conditions and the resulting simulated lake volume, since the existing structures (the spillways) at Detroit Dam depend greatly on lake level for temperature management. Underestimated PRMS-simulated inflows (based on historical comparisons) may have resulted in exaggerated difficulty in filling the lake during the winter. While PRMS simulated streamflow during the summer exceeded historical values, the Jensen-Haise method of calculating potential evaporation used in PRMS for this study has been documented by Milly and Dunne (2011) as potentially leading to underestimates in future climate. While Hay et al. (2011) recognized that PRMS simulated AET trends over the 20th century are comparable to measured changes in the literature, these two potential biases from PRMS may cancel each-other out. The non-inclusion of evaporative water losses in the CE-QUAL-W2 lake model settings may have compensated for potentially low inflows and lake levels during winter and spring. During September and

Table 7
Qualitative uncertainty.

Model or estimation method	Perceived bias	Potential result
Downscaled CMIP3 GCMs	• Lower precip and air temp than CMIP5	• Underestimated lake levels • Underestimated stream temperature
Bias correction	• High multi-model mean air temperature	• Overestimated stream temperature
PRMS rainfall–runoff model	• Underestimated winter streamflow • Overestimated summer streamflow (historic conditions) • Underestimated summer streamflow (future conditions)	• Underestimated winter lake levels • Overestimated summer lake levels (historical conditions) • Underestimated summer lake levels (future conditions)
Stream temperature estimates	• Underestimates in autumn	• Underestimated autumn water temperatures
CE-QUAL-W2 lake model	• Evaporative losses not accounted for	• Overestimated summer lake levels

October, potential underestimates of inflow-temperatures may have led to underestimated in-lake and release temperatures during early autumn. Future modeling efforts similar to this study may benefit from using multiple seasonal models (e.g., winter-spring and summer-fall) for estimating inflow water temperature.

5. Summary

A two-dimensional hydrodynamic and water quality model (CE-QUAL-W2) of Detroit Lake in western Oregon, USA was used in conjunction with Precipitation-Runoff Modeling System (PRMS) hydrologic models to examine in-lake and downstream water temperature effects under base (1990–1999) and future (2059–2068) climatic periods driven by data from downscaled General Circulation Models. Simulated A2 emission climate data from three GCMs (GFDL CM 2.0 (gfdl), GENMOM (gma2), and MPI ECHAM5 (ech5)) provided by the CMIP3 were used as input to a regional climate model, and the downscaled results were used to drive the PRMS and CE-QUAL-W2 models. A positive bias of PRMS simulated streamflow during the summer led to higher summer lake levels than may be expected if the GCMs are accurate. Compared with the base period, the future period had about a 2 °C warming in air temperature and 14% lower precipitation, which led to a 23% reduction in annual average PRMS-simulated discharge and 1 °C increase in mean annual estimated stream temperatures flowing into the lake.

Current and hypothetical operations and structures at Detroit Dam were imposed on the CE-QUAL-W2 model to evaluate the effects of decreased and warmer inflows to the lake in the future. Simulations incorporating current operational rules and minimum release rates at Detroit Dam to support downstream habitat, irrigation, and water supply during key times of year resulted in lower future lake levels and about half as many days with the lake level above the spillway crest relative to historical conditions. The ability to manage temperature downstream of the dam is primarily limited by the ability to blend warmer surface water with cooler deep water year-round, and the spillway is the only currently available outlet structure for releasing warmer water near the surface of the lake in summer. Annual average in-lake and release temperatures from Detroit Lake warmed 1.1 °C and 1.5 °C, respectively, from base to future periods under present-day dam operational rules and fill schedules. Future warming of release temperatures during autumn resulted in earlier estimated emergence dates for salmon fry, which could lead to higher mortality rates for spring Chinook salmon. Scenarios including alternative dam operations and/or hypothetical outlet structures at Detroit Dam resulted in warmer summer and cooler autumn releases compared to scenarios with current operational rules and structures, temperatures that are closer to likely target release temperatures. For example, scenarios in the future timeframe that allowed Detroit Lake to begin refilling 30 days earlier in winter or that reduced minimum release rates during summer allowed more surface heat to be expelled while the lake was above the spillway crest elevation, leading to release temperatures 0.4 and 0.9 °C below existing operational scenarios during the autumn spawning period for endangered salmonids. A hypothetical floating surface-withdrawal structure at the dam resulted in better year-round temperature management (0.6 °C warmer in summer and 0.6 °C cooler in autumn compared to existing structures) under warmer future climatic conditions at Detroit Lake without altering release rates or lake level management rules.

Acknowledgement

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