Climatic Change
DOI 10.1007/s10584-012-0629-8

# Modeling the transport of nutrients and sediment loads into Lake Tahoe under projected climatic changes

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Received: 12 December 2011 / Accepted: 29 October 2012


**Abstract** The outputs from two General Circulation Models (GCMs) with two emissions scenarios were downscaled and bias-corrected to develop regional climate change projections for the Tahoe Basin. For one model—the Geophysical Fluid Dynamics Laboratory or GFDL model—the daily model results were used to drive a distributed hydrologic model. The watershed model used an energy balance approach for computing evapotranspiration and snowpack dynamics so that the processes remain a function of the climate change projections. For this study, all other aspects of the model (i.e. land use distribution, routing configuration, and parameterization) were held constant to isolate impacts of climate change projections. The results indicate that (1) precipitation falling as rain rather than snow will increase, starting at the current mean snowline, and moving towards higher elevations over time; (2) annual accumulated snowpack will be reduced;

**Electronic supplementary material** The online version of this article (doi:10.1007/s10584-012-0629-8) contains supplementary material, which is available to authorized users.

This article is part of a Special Issue on *Climate Change and Water Resources in the Sierra Nevada* edited by Robert Coats, Iris Stewart, and Constance Millar

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Published online: 15 November 2012

(3) snowpack accumulation will start later; and (4) snowmelt will start earlier in the year. Certain changes were masked (or counter-balanced) when summarized as basin-wide averages; however, spatial evaluation added notable resolution. While rainfall runoff increased at higher elevations, a drop in total precipitation volume decreased runoff and fine sediment load from the lower elevation meadow areas and also decreased baseflow and nitrogen loads basin-wide. This finding also highlights the important role that the meadow areas could play as high-flow buffers under climatic change. Because the watershed model accounts for elevation change and variable meteorological patterns, it provided a robust platform for evaluating the impacts of projected climate change on hydrology and water quality.

## 1 Introduction

We used a combined hydrology and water quality model to project the impacts of climate change on Lake Tahoe and its contributory watersheds. Lake clarity is influenced by the supply of fine sediment (<63 μm), nitrogen (N) and phosphorus (P) from incoming hydrologic flows. These flows are dominated by snowmelt, and exhibit marked inter-annual variability. In this paper we describe model development and use in simulating the Lake's watershed hydrology and water quality responses to 21st Century climate projections. The hydrologic response is characterized by changes in annual variables, such as peak snowpack depth and duration, and mean timing of the snowmelt hydrograph, as well as changes in the frequency and severity of extremes, including floods, low flows, and droughts, which play crucial roles in substance transport and inputs to the lake.

Pursuant to the Clean Water Act, the Lahontan Regional Water Quality Control Board developed a Total Maximum Daily Load (TMDL) program for the Tahoe basin using historical stream monitoring data and locally observed stormwater runoff data (Roberts and Reuter 2007; Smith and Kuschnicki 2009). The Lake Tahoe Watershed Model was a major component of this effort (Tetra Tech 2007) and was developed using the Loading Simulation Program C++ (LSPC) framework (Shen et al. 2005). The Lake Tahoe Interagency Monitoring Program (LTIMP) provided the water quality data sets required for model calibration and validation. This data set extends from 1980 to the present, and includes daily discharge and frequent measurements (30–130 samples/year) of sediment, N and P concentrations at 10 tributary mouths (that account for about 70% of the basin-wide streamflow), and 8–10 intermediate upstream stations (Rowe et al. 2002).

The coupling of the projected and downscaled climate data from General Circulation Models (GCMs) with distributed hydrologic models has become an increasingly important approach for projecting the impacts of climate change, such as large-scale regional modeling of snow water equivalent (e.g. Elsner et al. 2010), snowmelt timing (Stewart et al. 2004), daily flood frequency (Dettinger et al. 2004), monthly streamflow changes (Maurer and Duffy 2005), and flood forecasting (Anderson et al. 2002). Das et al. (2011) used output from three GCMs and two emissions scenarios with the VIC model to project future changes in the maximum 3-day flood in large river basins in the Sierra Nevada.

The present study is unique in the Sierra Nevada in its simulation of water quality (suspended sediment, N and P) coupled with hydrology in fine detail in time (hourly) and space (about 5–10 km$^2$). The results, which served as the inputs to the Tahoe Lake Clarity

Model reported in Sahoo et al. (2012, this special issue) and the hydrologic analysis of streamflow and drought statistics presented in Coats et al. (2012, this special issue), provide new considerations for researchers, stakeholders and policy makers concerned with the future water quality and surface level of Lake Tahoe.

## 2 Methods

### 2.1 Downscaled 21st century climate projections

Due to differences in the mathematical representation of physical processes in different GCMs, their projections for any given scenario of future greenhouse emissions can differ considerably. Inclusion of a suite of GCMs provides an uncertainty range for process representation (e.g., Mote et al. 2011). Pierce et al. (2009) argue for including about six GCMs in climate impact studies. Other major uncertainty sources (see e.g., Hawkins and Sutton 2009) concern future emissions of greenhouse gases, and the adequate capture of regional and local manifestations of global climate, particularly over complex topography, given GCMs' coarse scales.

The fine spatial (about 5–10 km$^2$) and temporal (hourly) resolution and large number of environmental variables required by our model application preclude the consideration of output from most of the available GCMs, such as those of the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 (CMIP3, Meehl et al. 2007), because many variables are only archived at monthly time scales, or for discontinuous daily series. In addition to precipitation and temperature, the variables required by our model include surface wind speed, humidities, and surface radiative fluxes, which bear directly on overturning and mixing of deep waters and on biological activity in the lake, influencing lake clarity and ecology (Abbott et al. 1984; Jassby et al. 2003).

Our study is made possible by the availability of such variables at the daily time step for GFDL (Delworth et al. 2006). We use GFDL projections for two contrasting scenarios of future greenhouse gas emissions, A2 and B1 (Nakicenovic et al. 2000), described in On-line Resource 1, which respectively lead to 830 and 550 ppmv of $CO_2$ by year 2100. Figure 2 in Costa-Cabral et al. (2012), this issue shows the projected changes in temperature and precipitation for the 16 CMIP3 GCMs. GFDL's temperature projections are somewhat above the average of the GCMs in CMIP3 for either emission scenario, with the exception of the end-of-century period under scenario B1 where they are about average. GFDL's precipitation projections for B1 are for drier conditions than average among GCMs (indicating a small decline by 10 to 20%), excepting the end-of-century period under scenario B1 where its projected precipitation decline is less than 5%.

GFDL outputs for daily maximum and minimum temperature ($T_{min}$ and $T_{max}$), precipitation, daily wind, downward radiation, and dewpoint temperature were subjected to two consecutive downscaling techniques. First, they were downscaled (to 1/8°, i.e., about 12× 12 km$^2$) using the method of constructed analogues (Hidalgo et al. 2008) as described in Dettinger (2012, this special issue). They were then further downscaled to the local scale (5 to 10 km$^2$) using the BCSD (Bias Correction Statistical Downscaling) technique developed by Wood et al. (2002, 2004) with modifications as described in Coats et al. (2012, this special issue), and in more detail in Coats et al. (2010, Appendix 2).

In the constructed analogues (CA) procedure, a set of days is identified (for each season) having the same coarse-scaled climate pattern ("weather map") as the modeled historical record. Then the linear combination of weather maps that best fit the model pattern is determined by linear regression, and the regression equations are applied to high resolution maps of the explanatory variables. The CA downscaling procedure also incorporated a high-resolution regional climate reanalysis (called CARD10) of the meteorology over California and Nevada (Dettinger 2012, this special issue). In the subsequent BCSD procedure, daily values were obtained for the fine scale grid based on the record of daily observations at the nearest meteorological station. First, the quantile corresponding to each daily value in the 1/8° CA-downscaled time series (for the given month) was determined. Then, the value was replaced by the meteorological station value having the same quantile for the given month. This "quantile mapping" is similar to that of Wood et al. (2002, 2004) except that it uses daily values rather than monthly. This is possible because our input time series, produced by the CA downscaling, already has daily resolution.

The resulting downscaled time series represents well the 1-day maxima distribution for the historical time series. The highest values of 3-day annual maxima are mildly under-represented, and this is tentatively attributed to a lower degree of temporal correlation in the simulated time series during heavy storms, as compared to observations (Coats et al. 2012, this special issue). Because intense, long-duration storms, and 3-day storms in particular, are capable of generating high runoff rates and play an important role in sediment and pollutant transport, the lowered frequency of 3-day annual maxima may lead to under-estimation of peak runoff and transport rates and contributes to uncertainty of results.

To disaggregate the downscaled daily precipitation to hourly, the hourly records for 1996–2003 from 12 Snowpack Telemetry (SNOTEL) stations located in the Lake Tahoe basin were used (http://www.wcc.nrcs.usda.gov/snow), as described in Online Resource 2. For each day and each of the 12 model grid cells, the month of the year and percentile (for the month) of the daily precipitation were used to randomly select an hourly precipitation array from the closest SNOTEL station for the same month of the year having a similar daily total.

Wind was disaggregated to hourly by applying a similar procedure as used for precipitation, using the observational record from South Lake Tahoe airport (1989–98). For temperature, $T_{min}$ and $T_{max}$ were disaggregated using average monthly observed diurnal distributions at South Lake Tahoe Airport (1989–98). Twelve diurnal distributions—one for each month—were computed using averages of each hour for the entire period of record by month. For each day, the respective (1 of 12 depending on the month) distribution was scaled between the projected minimum and maximum from the downscaled record.

In order to disaggregate downward short-wave and long-wave radiation, total daylight hours for each day were calculated using the latitude of each grid cell and rotation/revolution of the earth. A sine function was used to disaggregate the total daily radiation to hourly over the daylight hours, with the peak value occurring at the middle hour between sunrise and sunset. The effect of clouds on radiation was included in the down-scaling of the daily GFDL output. We recognize that this approach may fail to account for local orographic effects on cloud formation.

Daily pan evaporation was computed using the Penman (1948) energy balance approach and the downscaled values for daily $T_{min}$ and $T_{max}$, dewpoint temperature, solar radiation, and wind speed time series. Daily values were then disaggregated to hourly using a sine curve across the daylight hours, calculated as a function of gage latitude and the rotation/revolution of the Earth. A factor of 0.875 was used to calculate potential evapotranspiration (PET) from pan evaporation, following the relationship identified by Riverson et al. (2005) for the region.

## 2.2 Lake Tahoe watershed model

The Lake Tahoe Watershed Model was developed using the LSPC (Loading Simulation Program C++) modeling platform, which evolved from the Stanford Watershed Model (Crawford and Linsley 1966). LSPC is a U.S. Environmental Protection Agency-approved modeling system that includes the HSPF (Hydrologic Simulation Program – FORTRAN) simulation model for watershed hydrology, erosion, in-stream transport and water quality processes, coded in an object-oriented C++ environment. LSPC is designed to facilitate large-scale, data-intensive watershed modeling applications, with no inherent limitations on modeling size or operations. A relational Microsoft Access database serves as the framework for managing watershed data. A detailed discussion of simulated processes and model parameters is available as part of the HSPF User's Manual (Bicknell, Imhoff et al. 1997).

In the Lake Tahoe Watershed Model, the Lake's watershed is divided into 184 subwatersheds and their respective channel networks. Because land use affects hydrologic fluxes and the supply of pollutants to streams that carry them to the Lake, each subwatershed is further subdivided into land use segments. For urban developed areas, the land use segments are categorized into pervious and impervious. During a simulation run, the model links the surface runoff and groundwater flow contributions from each of the land segments and subwatersheds and routes each contribution through the network of channel reaches as water moves toward the Lake. Each stream segment also considers precipitation and evaporation from water surfaces, as well as flow contributions from the watershed, tributaries, and upstream reaches (see Figure 4 in Online Resource 3).

The pollutants of concern for the Lake Tahoe TMDL that affect lake clarity are fine sediment (particles $<63$ μm), nitrogen (N), and phosphorus (P). Loads for Suspended Sediment Concentration (SSC), total N and total P were estimated by linear regression with the streamflow components of baseflow and surface flow, which were derived from the USGS discharge records by hydrograph separation (Slotto and Crouse 1996; see On-Line Resource 3). Fine sediment particle loads (number of particles) were first estimated using the urban and rural land use distribution by subwatershed, together with the particle count converters used in the TMDL analysis (LRWCB and NDEP 2010). These were then normalized to the baseline period average for comparison.

Model calibration was an iterative procedure that involved comparing simulated and observed values of interest, both spatially and temporally at different locations across the basin. Calibration of the Lake Tahoe Watershed Model for the basin followed a sequential, hierarchical process that began with snow and hydrology calibration, and was followed by calibration of water quality (see Online Resource 3). The Lake Tahoe Watershed Model hydrology was calibrated using both historical LTIMP stream monitoring data and locally observed stormwater runoff monitoring data (Heyvaert et al. 2007). Ten U.S. Geological Survey (USGS) stream flow gages and 11 LTIMP water quality gages around the perimeter of Lake Tahoe were used for model calibration. The calibrated parameter set produced good agreement between simulated and observed streamflow values over the calibration and validation periods. Table 2 in Online Resource 3 presents calibration statistics at the 10 stream flow gages (modeled vs. measured daily flow) for the 8-year period between 10/1/1996 and 9/30/2004.

For each of the 184 designated subwatersheds in the Tahoe basin, hourly discharge and output of SSC, fine sediment, total N and total P were calculated and routed downstream to the lake. The annual totals were examined at the subwatershed level, and also aggregated for the entire basin. We normalized the basin-wide average annual outputs of water, sediment and nutrients for the water year periods 2002–2033, 2034–2066, and 2067–2099 by dividing by the corresponding modeled average for the baseline period of 1967–1999. We then calculated confidence limits (at $\alpha$=0.05), and tested for significance of differences between the baseline means and the corresponding future third-century means (Zou and Donner 2008) for the A2 and B1 scenarios.

Though a few of the basin-wide averaged values showed significant changes, a closer look revealed that spatial averaging masked some important trends. The same significance test used for basin-wide averages was also applied to outputs from each subwatershed. Outputs tested included precipitation, rainfall/snowfall, surface runoff, total actual evapotranspiration, total sediment load, fine sediment load, and nutrients loads. For both the basin-wide averaged and subwatershed-based significance tests we compared the three temporally averaged 33-yr periods of the 21st century against the historical baseline period (1967–1999) for both the A2 and B1 scenarios. This paper focuses on those that tested significant at $\alpha$= 0.05, henceforth referred to as "significant."

In order to examine trends by region and elevation, the subwatersheds were aggregated into three regions (west, south and east) and two elevation zones, (low and high), with subwatersheds having an average elevation less than 2,000 m categorized as "low." For each zone, third-century averages of annual variables for climate, hydrology and water quality were compared with baseline values, and the differences tested for significance.

Changes in timing of runoff and yields of nutrients and sediment may be as important as changes in annual totals. We examined historical and projected changes in seasonality of streamflow, and inputs of total suspended sediment (TSS), total nitrogen (TN) and total phosphorus (TP) using the simple metric of "half timing date" (or "half date"), defined as the day of the water year (which starts October 1) when half of the water-year's streamflow, TSS, TN or TP, has been reached. The half timing date was computed for each of those variables for the historical and future projection simulations, for three contrasting LTIMP watersheds, and for the entire Tahoe basin.

## 3 Results and discussion

With the model developed, calibrated, and validated for hydrology and water quality using observed historical data, the database file was reconfigured to interface with the downscaled and disaggregated hourly GFDL historical and 21st century meteorological time series. Before running the future projections, the model results generated using the GFDL 1967–1999 historical baseline were compared against all observed historical data (as available over the same period of time) using the original model calibration sites. Although the year-to-year GFDL-generated outputs were not expected to match observed data, similarity in long-term total volumes and aggregated seasonal streamflow variation was considered adequate. This served as further validation that the downscaled GFDL historical meteorological time series produced watershed model results that were statistically-comparable to observed data. After validating the GFDL historical baseline, the downscaled and disaggregated hourly GFDL 21st century time series were used to drive the watershed model for future projections.

For the first set of tests we looked at basin-wide averaged results. Figure 1 displays the changes to each future period relative to the simulated baseline period for climatic metrics and resulting hydrologic and water quality impacts for scenarios A2 and B1. As a result of the projected warming trend, our model indicates a significant shift in the mean fraction of precipitation falling as rain, from the 0.4 average in 1967–1999 to about 0.5 in 2067–2099 for both scenarios B1 and A2 (see snowfall dashed lines in Figure 1, and Online Resource 4),

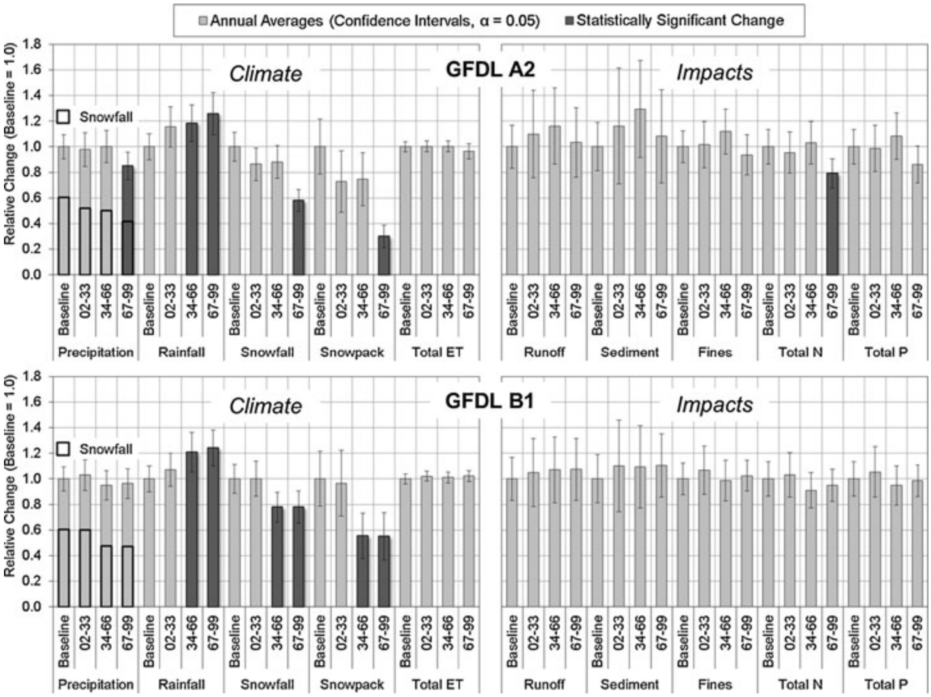



**Fig. 1** Modeled basin-wide average annual climate metrics (precipitation, rainfall, snowfall, snowpack, and Total ET) for GLFD A2 and B1 scenarios and corresponding runoff, total sediment, fine sediment, total N and total P loads, for 2002–2033, 2034–2066 and 2067–2099, relative to the corresponding modeled values of the baseline period, 1967–1999. For total precipitation, the snowfall portion is also shown as a dotted line. Those with statistically significant change are highlighted

resulting in significantly declining snowpack, expressed as snow water equivalent (SWE), throughout the basin (Figs. 1, and Figure 1 in Online Resource 4). In general, spatially averaged precipitation totals were not significantly different, except for the last third century under scenario A2, where there is a significant drop in the southern and western portions of the basin.

Total actual sublimation-evapotranspiration (henceforth referred simply as evapotranspiration, ET) was the least sensitive (least change) of all constituents tested, as shown in Online Resource 5. It is possible that this is an artifact of the model not having a plant growth model where species densities might change as climate changes. Nevertheless, there is a justifiable rationale for this finding. The plants generally find the water they need to survive. In wet years, where there is an abundance of water, ET reaches capacity and the land yields the excess water to streamflow. In dry years, plant roots go deeper to satisfy demand, which depletes baseflow. This balancing act results in year-to-year fluctuations in ET that are not statistically significant; however, significant fluctuations in precipitation and temperature forcing variables are readily manifested in metrics such as snowpack, rainfall/snowfall, precipitation, and streamflow. On average, runoff is relatively unchanged or slightly lower than baseline in the flatter meadow regions near South Lake Tahoe, but increases at a few higher elevation subwatersheds where the rain/snow shift is more pronounced.

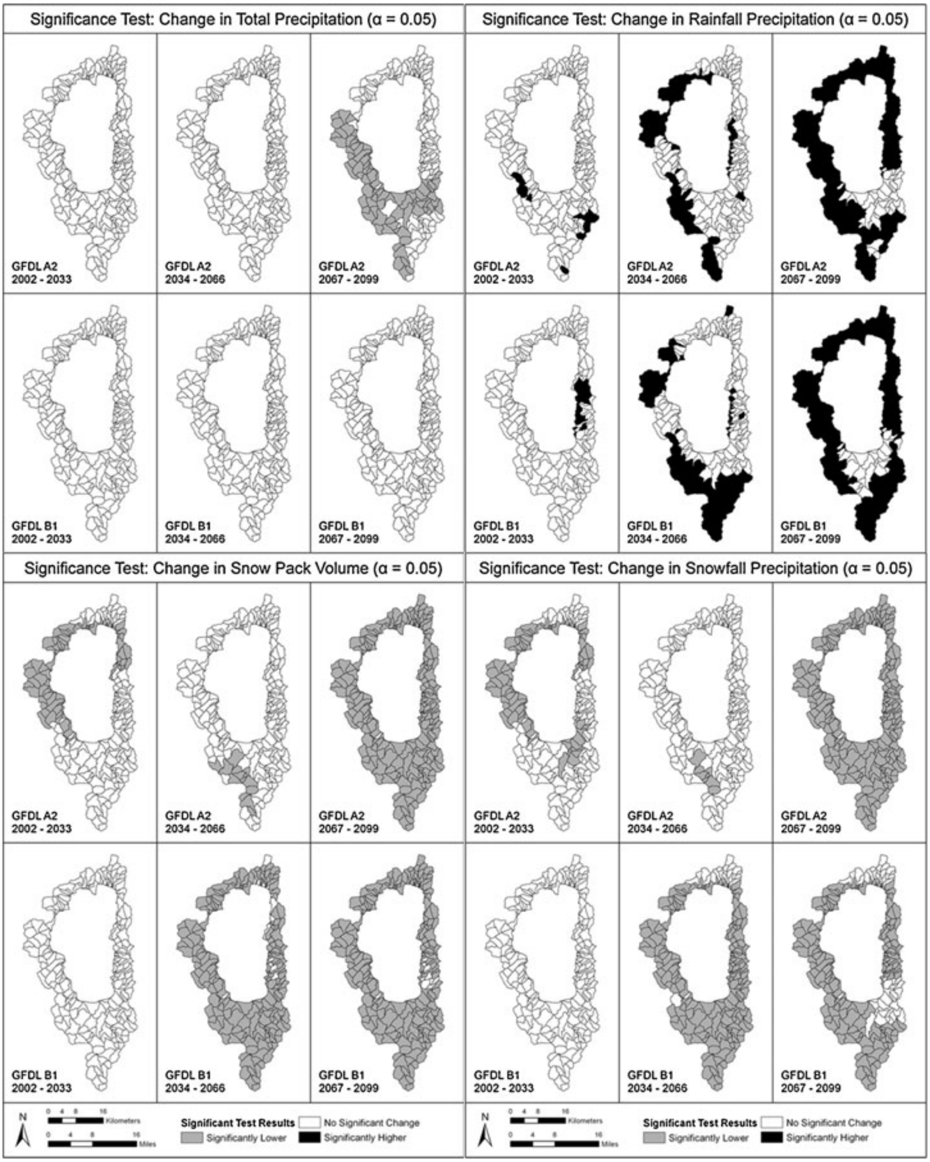



**Fig. 2** Spatial map of significance test results at $\alpha$=0.05 for selected climate change metrics (total precipitation, rainfall, snowfall, and snowpack) for the GFDL A2 and B1

The projected impact of snowpack water equivalent changes spatially during the course of the climate change scenarios, with the east side of the Lake being more strongly affected relative to the west side in the latter third of the century under scenario A2 (Fig. 2). However, under scenario B1, the east side is less affected relative to the west side. This corroborates the changes in the Palmer Drought Severity Index reported in Coats et al. (this special issue). Figure 2 in Online Resource 4 shows the projected shortening of snowpack duration. Between scenarios

A2 and B1, there are notable projected impacts on the snowpack duration (-1 to -30%) and magnitude (-3 to -60%), relative to baseline conditions. Table 1 in Online Resource 4 presents synoptic summary statistics for projected average snowpack start, peak, end, duration and associated percent change (relative to baseline), and peak depth and associated percent change (relative to baseline). Projected declining water yields to the Lake affect lake surface levels and water quality, as reported by Sahoo et al. (this special issue).

Comparison of basin-wide water, sediment yield and nutrient loads by third-century periods with baseline (1967–1999) showed little significant change (Fig. 1). For the A2 scenario, only average annual basin-wide Total N yield was significantly lower by the end of the century (2067–2099, $\alpha=0.05$). For Total N, the trends suggest that the decrease in loading is associated with the decrease in water yield to the lake. In the model, sediment load is driven primarily by runoff, while nutrients (especially nitrogen) are mostly conveyed with baseflow. The fact that Total N load tests significantly lower for A2 (Fig. 1) is explained by the reduction in baseflow. We note that the projected sediment loads do not take into account the potential impact to channel erosion that may result from the projected upward shift in the flood frequency-magnitude relationships—especially for the B1 scenario in the middle third of the century (see Simon et al. 2003 and Coats et al. 2012, this special issue). An upward shift in the flood magnitude-frequency relationships could cause upward shifts in the sediment load-discharge relationship, and such shifts are not modeled.

In examining trends in hydrology and water quality by individual subwatersheds (Figs. 2 and 3), however, we found that local trends are masked by taking basin-wide averages. For example, projected future sediment loads do not show a significant departure from baseline loads when aggregated basin-wide; however, spatial analysis shows variability among individual subwatersheds. Runoff and fine sediment loads that increase in some of the higher elevations are counterbalanced by decreasing runoff and pollutant loads in the flatter meadow regions (Fig. 3). The shift from snow to rain is also most pronounced in areas that historically received more snowfall under baseline conditions. Shifting from snow to rain results in increased urban runoff, which tends to increase fine sediment yield; however, the largest urbanized region in the southeastern part of the watershed generally shows a decrease in fine sediment load relative to baseline levels. Recall that those areas are also projected to experience a significant decrease in total precipitation volume for the last third century under A2 (Fig. 2). Lower precipitation volume and warmer temperatures—with no other significant changes in ET or rainfall/snowfall distribution—yield lower runoff volumes and fine sediment loads. On average, the slight increase in some of the wetter and higher elevation subwatersheds is counterbalanced by the decrease in the dryer and lower elevation subwatersheds. Nevertheless, this does not necessarily signal no-net-impact on lake clarity because other factors such as water temperature and streamflow timing influence insertion depth of streamflow and pollutant loads to the lake (see Sahoo et. al, this special issue).

Figure 4 shows the results of comparing third-century climate, hydrology and water quality averages with base-line values, by regional and elevation zones. The regional summaries show the drop in snowpack beginning in the west and progressing eastward, while elevation summaries show the rainfall increase progressing from lower to higher elevations over the projected century. For the zones evaluated, there is no significant change in total sediment load; however, there is a projected drop in fine sediment yield and total P in the south (primarily from the meadow region) for the last third-century under A2, in tandem with the significant drop in precipitation. Total N significantly drops in the west and south, where baseflow represents a larger portion of streamflow.

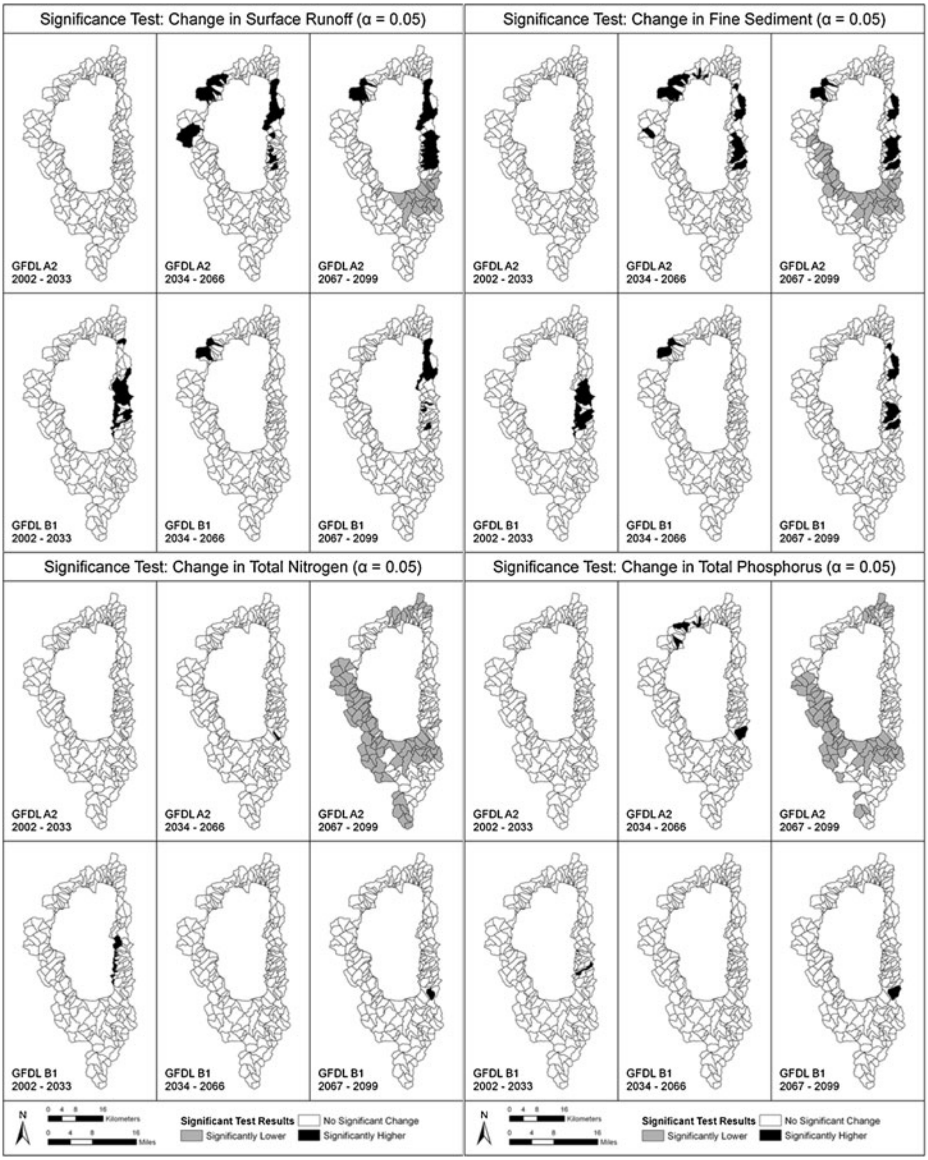
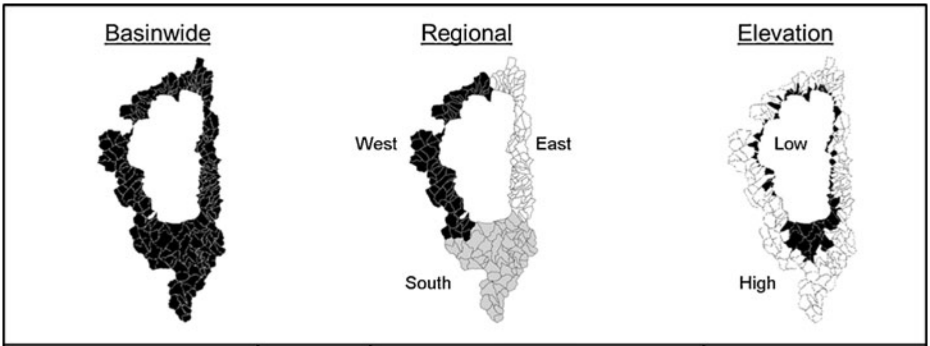



**Fig. 3** Spatial map of significance test results at $\alpha=0.05$ for selected modeled impacts (runoff, fine sediment, total nitrogen, and total phosphorus loads) for the GFDL A2 and B1

The relative magnitude of each variable and its average half-timing date for the historical (1967–1999) and 21st century periods is shown in Figs. 5 and 6 for the A2 and B1 scenarios, respectively. In addition to the basin-wide average summary, three tributaries around the lake are also summarized to illustrate spatial variability. Both the relative load magnitude and the rate of change for the half date are notably different for the subwatersheds depicted. Generally speaking, half-timing is consistently earlier in all tributaries for all outputs with climate change compared to historical.




Significance Test (α = 0.05)
More / Less
◖ A2 Only
◗ B1 Only
● A2 and B1

| | | Basinwide | | | Regional | | | | | | | | | Elevation (Low < 2,000 m) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 02-33 | | | 34-66 | | | 67-99 | | | 02-33 | | 34-66 | | 67-99 | |
| | | 02-33 | 34-66 | 67-99 | West | South | East | West | South | East | West | South | East | Low | High | Low | High | Low | High |
| Climate | Precipitation | · | · | ◖ | · | · | · | · | · | · | ◖ | ◖ | · | · | · | · | · | ◖ | ◖ |
| | Rainfall | · | ● | ● | · | · | · | ● | ◗ | · | ● | ● | ● | · | · | ● | · | ● | ● |
| | Snowfall | · | ◗ | ● | ◖ | · | · | ◗ | ◗ | ◗ | ● | ● | ● | · | · | ◗ | ◗ | ● | ● |
| Hydrology | Snowpack | · | ◗ | ● | ◖ | · | · | ◗ | ◗ | ◗ | ● | ● | ● | · | · | ◗ | ◗ | ● | ● |
| | Runoff | · | · | · | · | · | · | · | · | · | · | · | · | · | · | · | · | · | · |
| | Total ET | · | · | · | · | · | · | · | · | · | · | · | · | · | · | · | · | · | · |
| Water Quality | Total Sediment | · | · | · | · | · | · | · | · | · | · | · | · | · | · | · | · | · | · |
| | Fine Sediment | · | · | · | · | · | · | · | · | · | · | ◖ | · | · | · | · | · | · | · |
| | Total N | · | · | ◖ | · | · | · | · | · | · | ◖ | ◖ | · | · | · | · | · | ◖ | ◖ |
| | Total P | · | · | · | · | · | · | · | · | · | · | ◖ | · | · | · | · | · | · | · |

**Fig. 4** Summary of significance test results ($\alpha$=0.05) for climate, hydrology, and water quality model outputs for GFDL A2 and B1, resampled as basin-wide, regional, and elevation averaged categories

Projected timing shifts are large, reaching about 2 months for the Tahoe watershed as a whole (Fig. 5, panel a). Projected total streamflow for 2067–2099, representing approximately a 24% loss relative to historical (1967–1999) for the Tahoe watershed, will have a half timing date nearly 2 months earlier, similar to the timing shift tor TN and TP. The projected timing shift for TSS is even larger, surpassing 2.5 months for scenario A2. Timing shifts are somewhat less at eastern-side creeks, such as Logan House Creek (Fig. 6, panel b); however recall that runoff and sediment loads were significantly higher (Fig. 3) due to the significant shift of precipitation there from snow to rain (Fig. 2).

In this study we focused on the direct future hydrologic and water quality impacts of climate change in the Tahoe basin. We recognize that other future changes may also affect hydrology and water quality. For example land use distribution, stream morphology, urban runoff water quality, wildfire frequency and intensity, vegetation and biogeochemical cycling all may change in the future, but were held constant in this study. In addition, both theoretical and ecosystem carbon enhancement experiments indicate there may be an important feedback from increased $CO_2$ concentrations, which allow plants to increase stomatal closure, partially offsetting the effects of increased temperature on evapotranspiration (Betts et al. 2007; Leakey et al. 2009; Johnson et al. 2012). In fact, Johnson et al. (2012) used an ensemble approach that compared six North American Regional Climate Change Assessment Program (NARCCAP) downscaled scenarios in 20 watersheds across the contiguous US and Alaska using two different watershed models. For five of the watersheds,

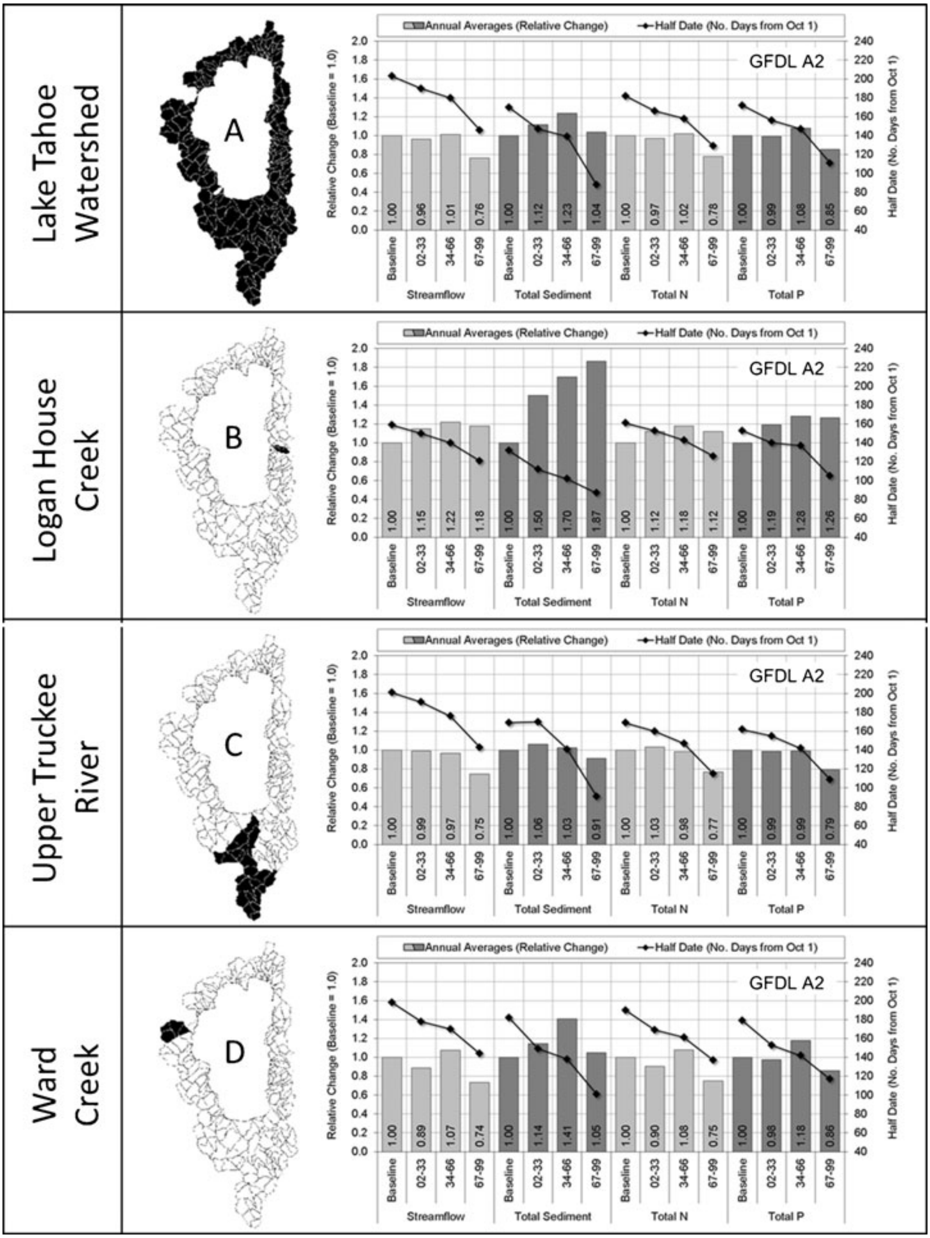



**Fig. 5** The four panels show projected changes under GFDL A2 for mean annual streamflow, and loads of total sediment, total nitrogen, and total phosphorus for the entire watershed (panel **a**) and three tributaries around Lake Tahoe (**b**–**d**). These differ both in terms of historical magnitude and timing of the four variables and future projected changes. The basin-wide summary includes outflow from all streams and intervening zones

HSPF was applied in addition to the Soil and Water Assessment Tool (SWAT). Under historical baseline conditions both HSPF and SWAT responded in a similar way. Under future projections, the SWAT configuration considered plant growth feedback on actual ET,

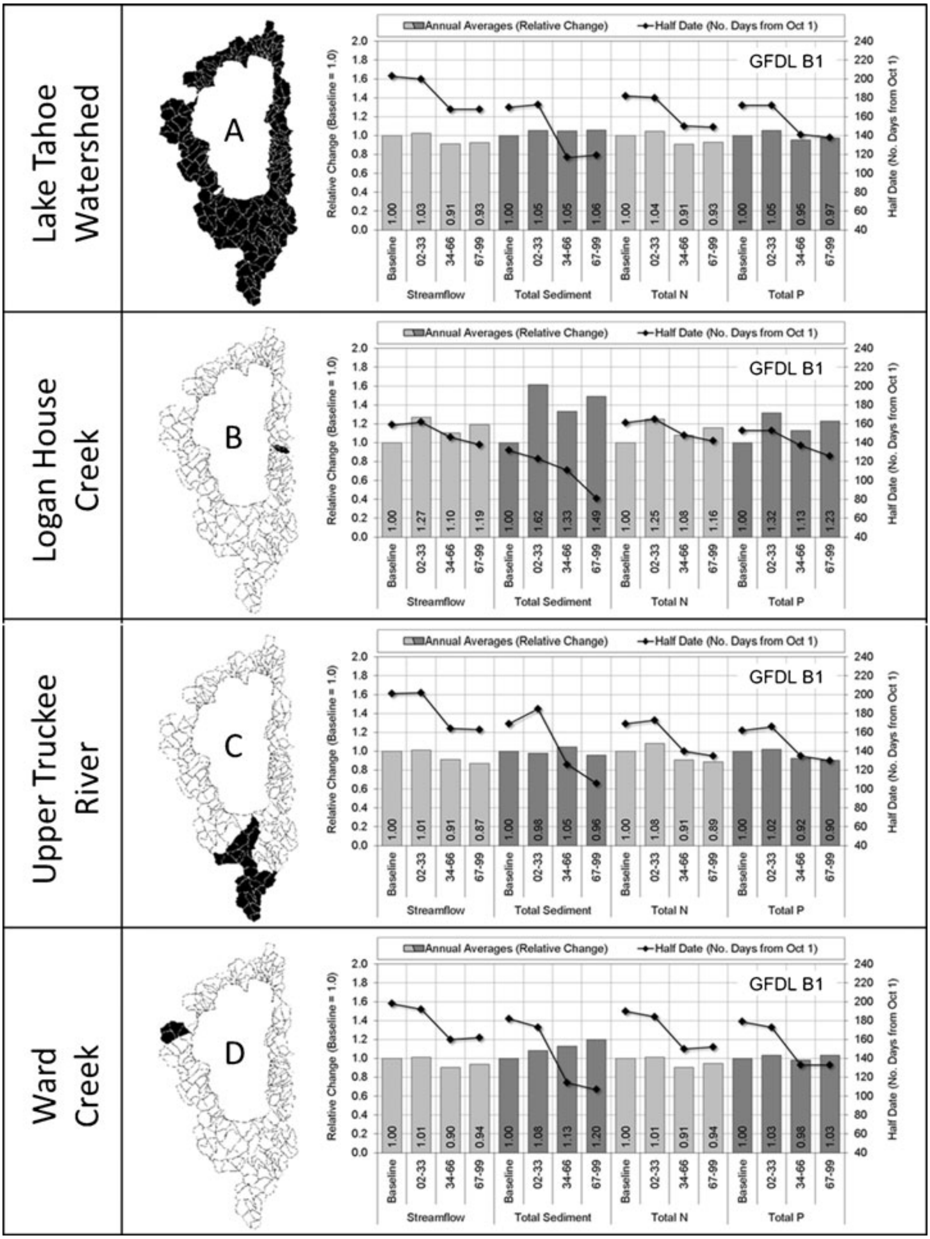



**Fig. 6** Same as Fig. 5, but for GFDL B1

but the HSPF model (upon which LSPC is based) assumed that the relationship between actual ET and potential ET was static. That study showed that on average, SWAT predicts about 10% higher water yield than HSPF. That is because in SWAT, higher $CO_2$ levels cause increased stomatal closure, which results in lower ET and higher water yield. Associated pollutant loads also increased with higher water yield. Had factors such as land use change, stream morphology, vegetation changes, and wildfire frequency and intensity been factored into this study, they probably would have resulted in more adverse hydrology and water quality impacts than we projected. While the neglect of those difficult-to-predict future land cover changes represents a source of uncertainty in the results, this study nevertheless provides information on the range of potential basin-wide and subwatershed scale impacts associated with climate change.

## 4 Conclusions

Two climate change projection scenarios were generated using the calibrated Lake Tahoe LSPC watershed model, which was developed as a study component of the Lake Tahoe TMDL. These scenarios were the statistically downscaled projections of the GFDL climate model under emissions scenario A2 (accelerating carbon emissions) and GFDL B1 (emissions leveling off). GFDL was selected due to its unique availability of output at a daily resolution. The GFDL climate projections indicate higher temperatures and drier conditions than most of the CMIP3 global climate models, especially under scenario A2 in the latter half of this century. The watershed model used an energy balance approach for computing both snowpack dynamics and evapotranspiration so that those processes would also be a function of the climate change projections. The model does not explicitly simulate physical changes in vegetative cover associated with climate change. It assumes a fixed land use distribution; therefore, any resulting impacts are only attributable to changes in the meteorological boundary condition. Because the LSPC watershed model accounts for elevation change and spatial variation of meteorological patterns, it is a robust platform for evaluating the regional impacts of climate change projections.

Certain climate change impacts were masked when tested using basin-wide averages; however, the most significant were those that tested significant at $\alpha=0.05$ in spite of averaging. In order of significance, as measured by the percent of the Tahoe basin showing a significant change ($\alpha=0.05$) for both A2 and B1 (see Online Resource 5), the most important changes were: (1) decreased snowpack, (2) decreased snowfall, and (3) increased rainfall. With regard to other modeled indicators such as streamflow, sediment, and nutrient loads, geophysical characteristics of the watershed are responsible for some of the spatial variability present in both the downscaled meteorological projections and the modeled watershed response. For example, spatial analyses showed a significant increasing trend over time for runoff and sediment load (under both A2 and B1) for certain higher elevation watersheds around the lake, and significantly lower sediment yield from the flatter meadows south of Lake Tahoe (A2 only). Consequently, the *net* impact of fine sediment load delivered to the lake appears less significant under climatic change than the change in the spatial distribution of the predominant fine sediment sources. From an erosion management perspective, this finding also highlights the important role that the lower elevation and meadow areas could play as a buffer against the projected increased flow and erosion from the higher elevations as snowfall shifts to rainfall. The projected climate changes also result in earlier delivery of streamflow and loading of total nitrogen, total phosphorus and sediment to the lake; our results suggest a timing shift of roughly 2 months earlier. This work demonstrates the importance of using spatially and temporally detailed process-based models when evaluating environmental impacts of climatic changes in heterogeneous environments.

**Acknowledgements** The Tahoe Climate Change Project was supported by grant #08-DG-11272170-101 from the USDA Forest Service Pacific Southwest Research Station using funds provided by the Bureau of Land Management through the sale of public lands as authorized by the Southern Nevada Public Land Management Act. We thank Jonathan Long for his patience and administrative help.

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