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# MODELING STREAMFLOW AND WATER QUALITY SENSITIVITY TO CLIMATE CHANGE AND URBAN DEVELOPMENT IN 20 U.S. WATERSHEDS[1]

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ABSTRACT: Watershed modeling in 20 large, United States (U.S.) watersheds addresses gaps in our knowledge of streamflow, nutrient (nitrogen and phosphorus), and sediment loading sensitivity to mid-21st Century climate change and urban/residential development scenarios. Use of a consistent methodology facilitates regional scale comparisons across the study watersheds. Simulations use the Soil and Water Assessment Tool. Climate change scenarios are from the North American Regional Climate Change Assessment Program dynamically downscaled climate model output. Urban and residential development scenarios are from U.S. Environmental Protection Agency's Integrated Climate and Land Use Scenarios project. Simulations provide a plausible set of streamflow and water quality responses to mid-21st Century climate change across the U.S. Simulated changes show a general pattern of decreasing streamflow volume in the central Rockies and Southwest, and increases on the East Coast and Northern Plains. Changes in pollutant loads follow a similar pattern but with increased variability. Ensemble mean results suggest that by the mid-21st Century, statistically significant changes in streamflow and total suspended solids loads (relative to baseline conditions) are possible in roughly 30-40% of study watersheds. These proportions increase to around 60% for total phosphorus and total nitrogen loads. Projected urban/residential development, and watershed responses to development, are small at the large spatial scale of modeling in this study.

(KEY TERMS: climate change; urban and residential development; streamflow; water quality; sensitivity; assessment; Soil and Water Assessment Tool.)

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## INTRODUCTION

Climate change is expected to have widespread, but regionally varied effects on the quantity and quality of United States (U.S.) water resources. Throughout the U.S., air temperatures could increase on the order of 1-5°C by 2100, depending on the future trajectory of greenhouse gas emissions (IPCC, 2013). Warming-induced intensification of the hydrologic cycle will likely increase the amount and intensity of precipitation on the global scale, although large uncertainties remain concerning precipitation changes at the local to regional scales important to water management (Emori and Brown, 2005; Groisman *et al.*, 2012; Kharin *et al.*, 2013; IPCC, 2014; Melillo *et al.*, 2014).

Anticipated hydrologic changes include increased runoff at higher latitudes and in wet tropical areas, and decreased runoff at mid-latitudes and in dry and semiarid regions due to changes in both precipitation and evapotranspiration (IPCC, 2014; Melillo *et al.*, 2014). In northern and mountainous areas, a shift is anticipated toward more rain-dominated systems with less snowpack storage, resulting in greater winter and early spring runoff. Climate change will also have diverse and cascading effects on water quality. A few previous studies have illustrated the climate sensitivity of stream nutrient loads, sediment loads, and ecologically relevant attributes of streamflow (e.g., Poff *et al.*, 1996; Williams *et al.*, 1996; Monteith *et al.*, 2000; Murdoch *et al.*, 2000; Chang *et al.*, 2001; Bouraoui *et al.*, 2002; SWCS, 2003; Marshall and Randhir, 2008; Tong *et al.*, 2011; Wilson and Weng, 2011). Beyond this work, however, much is still uncertain about the potential effects of climate change on water quality (Whitehead *et al.*, 2009).

Climate change effects on water resources will vary across the U.S. due to regional differences in climate change, together with local to regional differences in watershed physiography, land use, water management, and other factors. For example, many watersheds are currently stressed by stormwater runoff from roads, rooftops, and other impervious surfaces associated with urban and residential development (Paul and Meyer, 2001; Walsh *et al.*, 2005). Climate change will interact with these and other stressors, potentially exacerbating or ameliorating effects on water quantity and quality. Successful adaptation strategies will need to encompass practices to reduce vulnerabilities across a range of future conditions. Meeting this goal requires an understanding of how watersheds in different regions of the U.S. could be affected.

Watershed models are effective tools for linking climate forcing (e.g., precipitation, temperature) and watershed response (e.g., local-scale interactions between land use and soils, plant growth, evapotranspiration, and runoff). Scenario analysis using simulation models is a useful approach for assessing system response to a range of plausible but uncertain conditions and events (Sarewitz *et al.*, 2000; Lempert *et al.*, 2006; Volkery and Ribeiro, 2009). Results can provide an improved understanding of system behavior, help to identify vulnerabilities, and guide strategies for risk management (Sarewitz *et al.*, 2000; Lempert *et al.*, 2006; Johnson and Weaver, 2009).

Scenario-based studies have been conducted at the large basin, continental, or global scale using gridded land surface models (e.g., Roads *et al.*, 1994; Döll and Zhang, 2010; Brekke *et al.*, 2013; van Vliet *et al.*, 2013). These studies provide a foundation for understanding broad scale changes in water and energy budgets, but their use in supporting water management is limited by their coarse spatial resolution and inability to simulate changes in water quality. Conversely, a number of studies have evaluated streamflow and water quality responses to combined land use and climate change at the small watershed scale (e.g., Tu, 2009; Wilson and Weng, 2011; Riverson *et al.*, 2012). These provide detailed simulations in modeled watersheds, but different studies typically use different methods, models, and scenarios making it difficult to extrapolate and compare results across regions. Hay *et al.* (2011) modeled hydrologic responses in multiple small U.S. watersheds using a consistent modeling approach, but did not evaluate water quality responses or simulate large-scale basin results.

Here, we present the results of watershed modeling in 20 large (15,000-70,000 $km^2$), U.S. basins to address gaps in our knowledge of streamflow and water quality (nitrogen, phosphorus, and suspended solids) sensitivity to a range of mid-21st Century climate futures. Potential interaction of climate change with urban and residential development is also assessed. We use a scenario-based approach with a consistent set of watershed models and scenarios in each location. Watershed simulations were conducted using the Soil and Water Assessment Tool (SWAT) (Neitsch *et al.*, 2005). SWAT has been used widely for hydrologic and water quality applications, including previous studies of watershed response to climate change (e.g., Marshall and Randhir, 2008; Ficklin *et al.*, 2009; Wilson and Weng, 2011; Luo *et al.*, 2013). Simulations were conducted to assess the watershed response to climate change scenarios, to urban/residential development scenarios, and to the combined effects of mid-21st Century climate change and development scenarios. The results presented in this paper include analyses and more detailed discussion of simulation results described in U.S. EPA (2013).

## METHODS

### *Study Areas*

The 20 study areas range in size from about 15,000-70,000 km$^2$, and were selected to represent a range of hydroclimatic, physiographic, and land-use conditions throughout the contiguous U.S. and Alaska (Figure 1). Site selection also considered the availability of data necessary to calibrate and validate SWAT, and opportunities to leverage preexisting SWAT models. Study areas are large relative to many modeling studies. Each study area is comprised of 7-19 hydrologic unit code (HUC) 8-digit watersheds (Seaber *et al.*, 1987; USGS, 2013). Most study areas are composed of a single, contiguous watershed draining to a single outlet. Several, however, are composed of multiple, adjacent but noncontiguous watersheds (e.g., draining to multiple locations, typically along the coast). The statistical analysis described here is based on results for a single location within each study area, hereafter referred to as study watersheds. In study areas that have a single, common outlet, study watersheds were defined from a downstream location to reflect changes across the entire study area. In study areas that do not share a common outlet (e.g., coastal sites), study watersheds were selected as a physically representative, and in most locations, the largest contiguous drainage within the study area.

Figure 1 outlines the locations of the 20 study areas with study watersheds shown in black. Study watersheds range in elevation from sea level to over 4,300 m. Average annual temperatures range from 2 to 19°C, and average annual precipitation from 37 to 167 cm. Urban lands range from near zero to about 61%, and agricultural land from near zero to 78% of the watershed areas. Table 1 provides a summary of study watershed attributes.

### *SWAT Setup and Calibration*

Watershed simulations were conducted using SWAT, version 2005 (the most recent, stable version available at the time this study was initiated), as distributed with ArcSWAT 2.1 (Neitsch *et al.*, 2005). As implemented in this study, SWAT employs a curve number approach (SCS, 1972) to estimate surface runoff, and completes the water balance through simulation of subsurface flows, evapotranspiration, soil storages, and deep seepage losses. Subbasin boundaries and hydrography for each study area

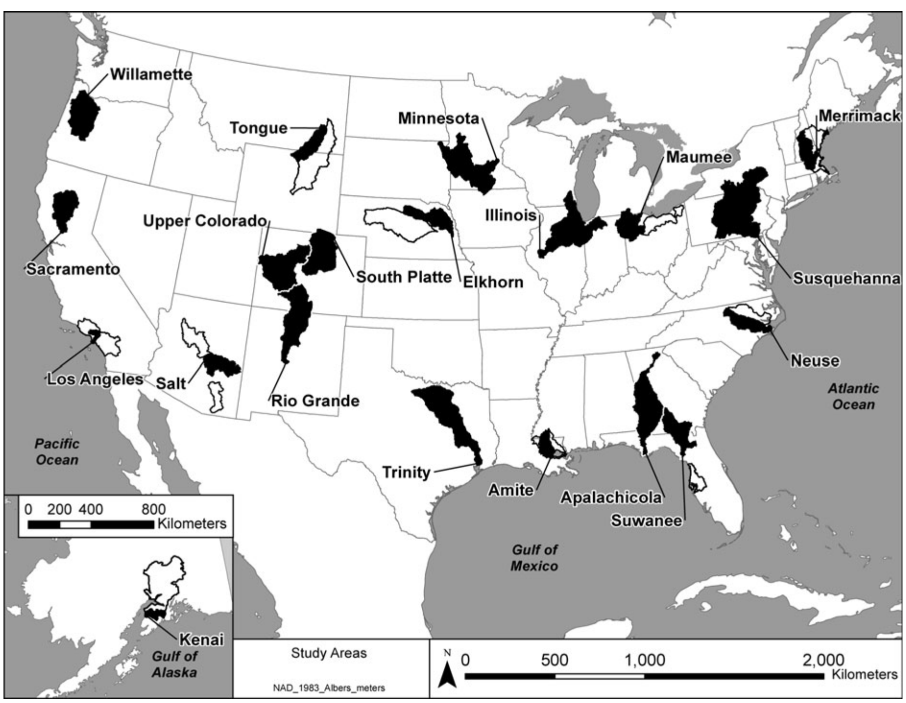


FIGURE 1. Location of the 20 Study Areas with Study Watersheds Shown in Black.

TABLE 1. Summary of the 20 Study Watersheds.

| Study Watershed | Study Area ID | Total Area ($km^2$) | Elevation Range (m MSL) | Urban/Res. (%) | Agric. (%) | Forest (%) | Avg. Precip. (cm/yr) | Avg. Temp. (°C) |
|---|---|---|---|---|---|---|---|---|
| Amite River | LPont | 8,606 | 0-153 | 11.00 | 15.10 | 19.70 | 167 | 19 |
| Apalachicola River | ACF | 49,943 | 0-1,325 | 9.30 | 21.60 | 47.90 | 138 | 17 |
| Elkhorn River | Neb | 18,133 | 349-825 | 4.20 | 57.10 | 1.30 | 68 | 9 |
| Illinois River at Beardstown | Illin | 44,040 | 111-361 | 18.10 | 66.10 | 10.30 | 97 | 9 |
| Kenai River | Cook | 5,937 | 0-1,969 | 1.50 | 0.10 | 36.90 | 80 | 2 |
| Los Angeles River | SoCal | 2,172 | 0-2,166 | 61.50 | 0.03 | 5.20 | 51 | 17 |
| Maumee River | LErie | 17,207 | 176-425 | 11.20 | 77.60 | 6.70 | 91 | 10 |
| Merrimack River | NewEng | 12,965 | 0-1,596 | 14.80 | 5.60 | 67.60 | 113 | 8 |
| Minnesota River | Minn | 44,002 | 208-650 | 6.60 | 78.00 | 2.90 | 72 | 7 |
| Neuse River | TarNeu | 25,828 | 0-260 | 9.40 | 28.40 | 33.50 | 127 | 16 |
| Rio Grande at Albuquerque | RioGra | 49,104 | 1,440-4,320 | 2.30 | 4.80 | 35.30 | 39 | 7 |
| Sacramento River | Sac | 21,537 | 5-3,177 | 4.30 | 21.90 | 22.40 | 95 | 14 |
| Salt River at Roosevelt | Ariz | 15,025 | 584-3,848 | 0.60 | 0.02 | 61.10 | 56 | 13 |
| South Platte River at Henderson | SoPlat | 37,991 | 1,308-4,347 | 7.10 | 18.00 | 23.70 | 43 | 6 |
| Susquehanna River | Susq | 71,236 | 0-957 | 7.40 | 27.00 | 61.10 | 105 | 9 |
| Suwanee River | GaFla | 25,765 | 0-90 | 9.70 | 18.10 | 33.50 | 126 | 19 |
| Tongue River | PowTon | 14,004 | 712-3,579 | 0.70 | 2.20 | 18.90 | 37 | 6 |
| Trinity River | Trin | 46,488 | 0-655 | 13.60 | 27.60 | 16.40 | 103 | 18 |
| Upper Colorado River | UppCol | 46,271 | 1,318-4,360 | 1.40 | 4.30 | 53.90 | 42 | 5 |
| Willamette River | Willa | 29,032 | 0-3,185 | 7.20 | 20.70 | 56.20 | 148 | 11 |

Note: Study area IDs are provided for reference to the discussion in the Supporting Information.

were defined from National Hydrography Dataset Plus (McKay *et al.*, 2012) catchments aggregated to approximately the HUC 10-digit spatial scale. SWAT models use land use data derived from the 2001 National Land Cover Database (NLCD) (Homer *et al.*, 2007). Simulations in each study area were run at a daily time step for a duration of 30-31 water years, with the first year dropped from the analysis to account for model initialization.

The large scope of modeling in this study required that model development be simplified and standardized for efficiency. Water management and operational features were represented only if they resulted in a modification of streamflow at downstream gages on the order of 10% or more. Use of surface water for irrigation was simulated only in those basins where it is estimated to be a significant factor in the overall water balance. Models include point source discharges from major permitted facilities (discharge greater than 1 mgd) listed in U.S. Environmental Protection Agency's (U.S. EPA's) Permit Compliance System database. A detailed description of SWAT setup in each study area is provided in U.S. EPA (2013).

Historical meteorological time series (daily precipitation, maximum and minimum temperature, solar radiation, relative humidity, and wind speed) at 20-40 stations within each study area were obtained from the 2006 BASINS 4 Meteorological Database (U.S. EPA, 2008). Potential evapotranspiration (PET) was estimated within SWAT using the full Penman-Monteith method (Allen *et al.*, 2005), including feedback on aerodynamic resistance from plant/crop height as simulated by the plant growth model. All models used observed time series for precipitation and temperature. Solar radiation, wind, cloud cover, and relative humidity were simulated with the SWAT weather generator using monthly statistics derived from the BASINS meteorological database.

All SWAT models were calibrated beginning with a representative HUC 8-digit subbasin within each study area. Model parameters were adjusted to achieve error statistics recommended by Lumb *et al.* (1994) and Moriasi *et al.* (2007) for total flow volume, seasonal flows, and high and low flows, while also seeking to maximize the Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970). Model calibration parameters were then extended to other subwatersheds within each study area, and additional adjustments were made to improve fit across scales. Water quality calibration focused on replicating loads for total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP). Calibration attempted to reduce the relative absolute deviation between simulated and estimated monthly loads to below 25% if possible. Water quality calibration also attempted to minimize bias in observed and simulated concentrations relative to flow regime and time of year. Validation tests were conducted at multiple locations including at the most downstream locations at each study area. A detailed discussion of model calibration and validation is provided in U.S. EPA (2013, Appendices D-W).

### *Climate Change, Urban/Residential Development, and Atmospheric $CO_2$ Scenarios*

Climate change scenarios are from the North American Regional Climate Change Assessment Program (NARCCAP). NARCCAP scenarios were developed by driving a number of different regional climate models (RCMs) with results from four global climate models from Phase 3 of the Coupled Model Intercomparison Project (CMIP3) (Mearns *et al.*, 2007, 2009, 2013) (Table 2). Two time periods were simulated, 1971-2000 and 2041-2070, at a spatial resolution of 50 km throughout most of North America. In addition, two global atmospheric model time slices were developed at the same spatial resolution with two of the global models. All scenarios assume the relatively high, Special Report on Emissions Scenarios (SRES) A2 greenhouse gas emissions trajectory (Nakicenovic *et al.*, 2000). Differences among SRES emissions scenarios, however, are not substantial for the future time period considered here. The NARCCAP scenarios were used because they provide higher resolution, credible climate change information for the entire contiguous U.S. and part of Alaska. The full set of variables needed for driving SWAT were also available, which is not the case for, for example, empirically downscaled climate information from CMIP3. In all study watersheds except the Kenai River in Alaska, baseline climate plus six climate change scenarios were evaluated. At Kenai, only the three NARCCAP scenarios available for southern Alaska were evaluated.

TABLE 2. NARCCAP GCM/RCM Model Combinations Used to Develop Climate Change Scenarios.

| Scenario | Global Climate Model | Regional Climate Model |
|---|---|---|
| 1 | CGCM3 | CRCM |
| 2 | HadCM3 | HRM3 |
| 3 | GFDL | RCM3 |
| 4 | GFDL | GFDL hi res |
| 5 | CGCM3 | RCM3 |
| 6 | CCSM | WRFG |

Note: NARCCAP, North American Regional Climate Change Assessment Program; CGCM3, Third Generation Coupled Global Climate Model (http://www.ec.gc.ca/ccmac-cccma/default.asp?lang=En&n=4A642EDE-1); HadCM3, Hadley Centre Coupled Model, version 3 (http://www-pcmdi.llnl.gov/ipcc/model_documentation/HadCM3.htm); GFDL, Geophysical Fluid Dynamics Laboratory GCM (http://www-pcmdi.llnl.gov/ipcc/model_documentation/GFDL-cm2.htm); CCSM, Community Climate System Model (http://www-pcmdi.llnl.gov/ipcc/model_documentation/CCSM3.htm); CRCM, Canadian Regional Climate Model (http://www.ec.gc.ca/ccmac-cccma/default.asp?lang=En&n=4A642EDE-1); RCM3, Regional Climate Model, version 3 (http://users.ictp.it/~pubregcm/RegCM3/); HRM3, Hadley Regional Model 3 (http://precis.metoffice.com/); WRFG, Weather Research and Forecasting Model, using the Grell convection scheme (http://www.wrf-model.org/index.php); GFDL hi res, Geophysical Fluid Dynamics Laboratory 50-km global atmospheric time slice (http://www-pcmdi.llnl.gov/ipcc/model_documentation/GFDL-cm2.htm).

Climate change scenarios were implemented in SWAT using a change factor approach (Anandhi *et al.*, 2011). NARCCAP climate model output were interpolated to each weather station used by the 20 SWAT models. Projected monthly change statistics (change factors) at each weather station were then calculated for total precipitation (%), precipitation above/below 70th percentile (%), air temperature (°C), relative humidity (°C), surface downwelling shortwave radiation (%), and wind speed (%). Change factors were calculated as changes in NARCCAP model simulations for mid-21st Century (2041-2070) relative to baseline (1971-2000). Monthly change factors were then used to adjust 30 years of daily historical observations (approximately 1971-2000) at each location. Temperature and precipitation adjustments were made by applying monthly change factors to historical daily values. Changes in event intensity can affect the partitioning between surface and subsurface flows and associated generation of pollutant loads. Projected changes in the proportion of precipitation volume occurring in larger events (i.e., event intensity) were represented by applying different change factors to events above and below the 70th percentile (based on daily depth). The remaining weather inputs were adjusted by modifying the monthly statistics used by the SWAT weather generator. Use of the change factor approach results in 30 years of daily weather data representing mid-21st Century conditions.

Urban and residential development scenarios (hereafter referred to as development scenarios) are based on projected mid-21st Century changes in housing density from U.S. EPA's Integrated Climate and Land Use Scenarios (ICLUS) dataset. ICLUS provides spatially explicit, decadal projected changes in housing density and impervious cover consistent with key assumptions underlying the IPCC greenhouse gas emissions storylines (U.S. EPA, 2009). A single scenario based on the ICLUS A2 projection for 2050 is used to be consistent with NARCCAP climate change scenarios. ICLUS projections were implemented in SWAT by adjusting the proportion of developed land classes in each of the 20 models to reflect projected changes in housing density. NLCD developed land categories data in each study watershed were reclassified into housing density ranges by cross-tabulating 2001 ICLUS housing density grids with 2001 NLCD data. These relationships were then used to estimate changes in NLCD developed land cover categories consistent with projected mid-21st Century changes in housing density. ICLUS projections are not available for Alaska, and thus were not evaluated in the Kenai River study watershed.

SWAT simulations in this study also represent the direct effects of increasing atmospheric $CO_2$ on plant physiology. In many plant species, increasing atmospheric $CO_2$ can result in decreased stomatal conductance, as plants require less time with open stomata to support the inward diffusion of $CO_2$ needed for growth, thus reducing leaf loss of water (Easterling *et al.*, 1992; Ainsworth and Rogers, 2007; Bernacchi *et al.*, 2007). Increasing atmospheric $CO_2$ can also increase plant growth rates and biomass via increased radiation use efficiency (Stockle *et al.*, 1992). To account for these effects, SWAT was implemented with a future atmospheric $CO_2$ concentration of 527 ppmv, the median of ISAM and Bern-CC reference concentrations for 2050 under both the A2 and A1B emissions scenarios of CMIP3 (Nakicenovic *et al.*, 2000), consistent with the mid-21st Century A2 emissions trajectory used by NARCCAP.

### *Data Aggregation and Analysis*

SWAT simulations in each study watershed resulted in 29-30 years of daily output for each scenario evaluated, except for the Elkhorn River, where data limitations resulted in only 20 years of output. For analysis, daily output was first aggregated to time series of annual and seasonal averages. Aggregated values within each study watershed were then normalized by the mean and standard deviation of their baseline climate and development scenario. This converts each time series to a set of deviations from mean baseline conditions that share a common scale of projected change across watersheds. The endpoints we consider are total streamflow, annual seven-day minimum streamflow, annual one-day maximum streamflow, the date of streamflow centroid (Julian date at which half the annual streamflow volume has occurred), TN load, TP load, and TSS load.

We used a three factor, generalized least squares model (GLS) (Pinheiro and Bates, 2000; Zuur *et al.*, 2009) to assess the significance of simulated annual and seasonal mean changes in response to climate change and urban/residential development scenarios for each endpoint and study watershed. Factors included in the model are study watershed (19 levels, excluding the Kenai River), climate scenario (7 levels, including simulated baseline climate), and the presence or absence of the urban/residential development scenario. All interaction terms among factors were included in the model. Results for the Kenai study watershed were assessed separately using a single factor GLS that only considered difference among climate scenarios.

GLS was used rather than a traditional ANOVA to account for heterogeneity of variances across study watersheds and climate scenarios. Residuals were assumed to be normally distributed with mean zero, but to have unique variances for each study watershed and climate scenario combination. Because the study watershed and climate scenario interaction was significant in all models, *post hoc* tests were used to determine which individual scenarios, and ensemble means of scenarios differed significantly from baseline by study area. Main effects were considered significant if $p < 0.05$ and *post hoc* tests if $p < 0.007$ (using a Bonferroni correction for multiple comparisons). Models were fit using restricted maximum likelihood, and were implemented using the "nlme" and "lsmeans" packages in R (Lenth and Hervé, 2015; Pinheiro *et al.*, 2015; R Core Team, 2015).

## RESULTS AND DISCUSSION

The SWAT simulations across the 20 study watersheds allow comparison of the sensitivity to climate change and urban/residential development in different regions of the U.S.

### *Model Calibration and Validation*

A summary of calibration and validation results for the representative HUC 8-digit subbasin gage in each study watershed is shown in Table S1 in the Supporting Information. All models performed credibly for hydrology with total volume errors at downstream stations for each study area within ±20% (median −2.1%) and NSE values for monthly streamflow ranging from −0.10 to 0.95 (median 0.82). Among these stations, NSE was less than 0.6 only for the Rio Grande at Albuquerque where the model did not represent seasonal patterns likely driven by water management. Confidence limits (95%) on mean monthly flows derived from validation tests at downstream gages ranged from ±3% to ±34% of the baseline mean, with 16 out of 20 study watersheds having confidence limits within ±15% of the mean (see Table S2 in the Supporting Information).

Water quality simulation focused on matching simulated loads to monthly loads estimated from observations. The estimated loads often have high uncertainty due to limited availability of sampling data at many sites and differences between model output and estimated loads can be large for individual site-parameter combinations. In most cases, however, the pollutant load simulations from SWAT models generally appear to be reasonable (median difference of 4.4% and median absolute difference of

23.8% relative to loads estimated from monitoring data for downstream monitoring sites in each study area). To minimize the effects of model bias and error, all analyses in this study are based on simulation results expressed as mid-21st Century changes relative to historical baseline conditions. For reference, Table 3 shows simulated annual streamflow and water quality endpoint values under baseline conditions. Table S3 in the Supporting Information shows seasonal endpoint values under baseline conditions. More detailed discussion of model setup and calibration is provided in U.S. EPA (2013, Appendices D-W).

### *Climate Change and Urban/Residential Development Scenarios*

Projected mid-21st Century changes in annual average air temperature range from approximately 2 to 3°C across the 20 study watersheds (Figure 2). Within study watersheds, variability among the six NARCCAP scenarios is from 0.5 to 1°C, with systematic differences between the scenarios. For example, the NARCCAP scenario using the GFDL model downscaled with RCM3 typically is among the coolest scenarios. Projected changes in annual average precipitation range from approximately ±20% of historical baseline values across the 20 study watersheds (Figure 3). In each study watershed, the ensemble includes at least two scenarios based on different climate models that differ in the direction of change relative to baseline, i.e., one showing increases and the other decreases in precipitation volume. For the Kenai River, results are shown only for the three NARCCAP scenarios available in this part of Alaska.

Climate change scenarios in this study also represent changes in the fraction of precipitation volume occurring in larger magnitude events (i.e., event intensity). Among the six NARCCAP scenarios, the average fraction of total precipitation volume occurring in events above the 70th percentile under baseline conditions ranges from a low of 62% (Willamette River) to a high of 94% (Los Angeles River). Projected mid-21st Century changes in this fraction (based on 70th percentile of the baseline distribution) range from about −3 to +8% with an average increase of 1.2% across all NARCCAP scenarios and study areas.

Baseline (2001) impervious cover ranges from near zero to about 6% of watershed area in all study watersheds except the Los Angeles River, which was 30% impervious (Table 4). Projected mid-21st Century changes in impervious cover were relatively small. In 15 of the 20 study watersheds, projected increases were on the order of 1% or less. The

TABLE 3. Simulated Streamflow and Water Quality Endpoint Values under Baseline Climate (1970-2000).

| **Study Watershed** | **Baseline Mean Streamflow ($m^3$/s)** | **Baseline Average Annual Seven-Day Low Streamflow ($m^3$/s)** | **Baseline Average Annual Daily Max Streamflow ($m^3$/s)** | **Baseline Mean TSS (kg × $10^3$/day)** | **Baseline Mean TP (kg × $10^3$/day)** | **Baseline Mean TN (kg × $10^3$/day)** |
|---|---|---|---|---|---|---|
| Amite River | 96.1 | 16.1 | 1,015 | 581 | 1.5 | 8.9 |
| Apalachicola River | 742 | 407.7 | 1,245 | 48 | 4.5 | 45.8 |
| Elkhorn River | 53.9 | 16.8 | 281 | 8,731 | 2.8 | 17.1 |
| Illinois River at Beardstown | 535.3 | 268.6 | 1,062 | 4,542 | 4.8 | 57.4 |
| Kenai River | 135.5 | 10.4 | 632 | 402 | 0.1 | 2.9 |
| Los Angeles River | 1.8 | 0.2 | 49 | 104 | 0.2 | 0.5 |
| Maumee River | 169.1 | 8.7 | 1,404 | 3,372 | 5.4 | 87.1 |
| Merrimack River | 245.1 | 40.3 | 1,013 | 63 | 1.9 | 20.9 |
| Minnesota River | 221.7 | 24.4 | 1,187 | 4,960 | 8.2 | 86.9 |
| Neuse River | 193.5 | 26.6 | 924 | 1,915 | 2.1 | 23.9 |
| Rio Grande at Albuquerque | 44.8 | 23.7 | 70 | 185 | 0.3 | 2.1 |
| Sacramento River | 332 | 173.4 | 3,031 | 5,315 | 5.9 | 28.9 |
| Salt River at Roosevelt | 25.4 | 3 | 670 | 6,602 | 0.5 | 1.8 |
| South Platte River at Henderson | 21.6 | 5.2 | 133 | 220 | 1 | 12.7 |
| Susquehanna River | 966.3 | 185.5 | 5,581 | 17,665 | 11.6 | 173.6 |
| Suwanee River | 254.2 | 122.8 | 622 | 96 | 3.6 | 25 |
| Tongue River | 10.4 | 1.4 | 63 | 1,082 | 0.3 | 1.2 |
| Trinity River | 289.7 | 5.8 | 2,083 | 2,450 | 3.9 | 29.2 |
| Upper Colorado River | 182 | 66.1 | 584 | 5,463 | 1.6 | 31.4 |
| Willamette River | 871.5 | 29.5 | 5,443 | 8,461 | 13.8 | 121.3 |

Note: TSS, total suspended solids; TP, total phosphorus; TN, total nitrogen.

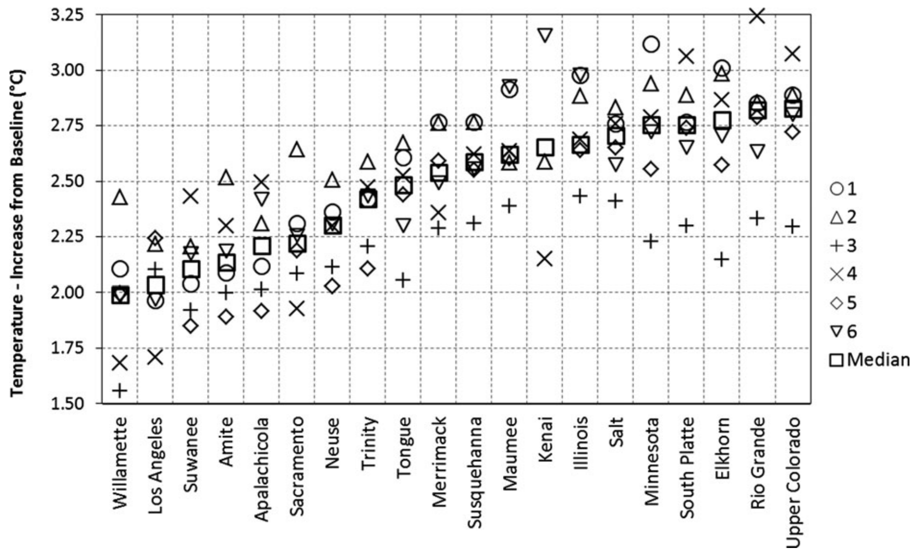


FIGURE 2. Projected Mid-21st Century Changes in Average Annual Air Temperature. Sites are ordered on the *x*-axis from low to high median value. Values shown are for the six North American Regional Climate Change Assessment Program (NARCCAP) scenarios. A key to NARCCAP scenarios is shown in Table 2.

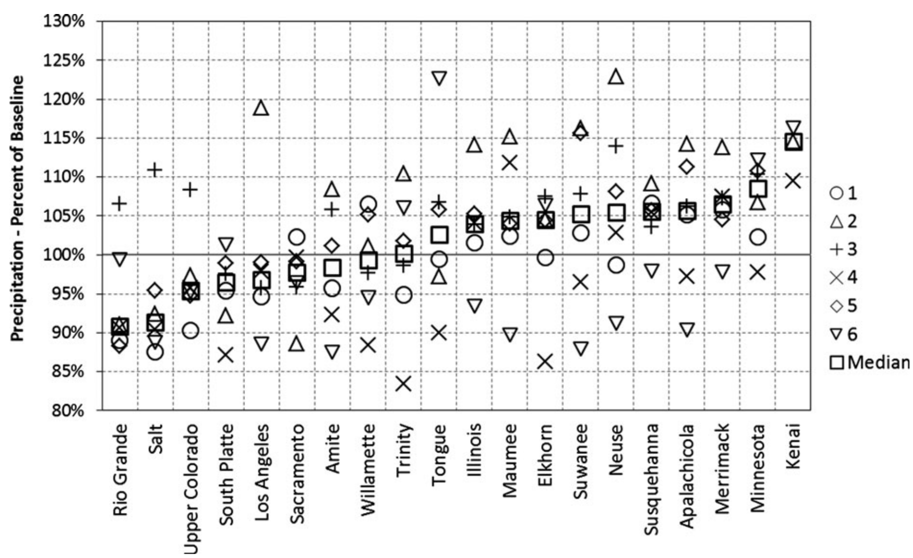


FIGURE 3. Projected Mid-21st Century Changes in Average Annual Precipitation. Sites are ordered on the *x*-axis from low to high median value. Values shown are for the six North American Regional Climate Change Assessment Program (NARCCAP) scenarios, and are expressed as the percent of historical baseline values. A key to NARCCAP scenarios is shown in Table 2.

greatest projected changes, about 4%, were for the Los Angeles River (Table 4). While several fast-growing metropolitan areas are included within the study watersheds, the concentrated development in these areas is relatively small when expressed as a percentage of the larger study watersheds. Development scenarios were not evaluated for the Kenai River in Alaska because ICLUS projections are not available at this location.

*Watershed Responses to Climate Change and Urban/Residential Development Scenarios*

GLS statistical models show a significant interaction between study watershed and climate scenario for all streamflow and water quality endpoints, indicating that the direction and spread of responses to climate change scenarios differed among study watersheds. The response to the urban/residential develop-

TABLE 4. Simulated Watershed Response to Mid-21st Century Urban and Residential Development Scenarios in the 20 Study Watersheds.

| Study Watershed | Baseline (2001) Watershed Impervious Cover (%) | ICLUS Change in Watershed Impervious Cover (%) | Median Simulated Change in Streamflow (%) | Median Simulated Change in TSS Loads (%) | Median Simulated Change in TP Loads (%) | Median Simulated Change in TN Loads (%) |
|---|---|---|---|---|---|---|
| Amite River | 2.8 | 1.3 | 0.8 | −1.3 | 6.8 | 3.9 |
| Apalachicola River | 2 | 1 | 0.3 | 0.6 | 1.1 | 0.5 |
| Elkhorn River | 0.6 | 0.1 | 0.3 | 0.1 | 0.1 | −0.2 |
| Illinois River at Beardstown | 6.2 | 2 | 2.4 | 0.5 | 0.2 | −0.8 |
| Los Angeles River | 30.2 | 3.9 | 1.4 | 6.6 | 38 | 11.1 |
| Maumee River | 2.4 | 0.3 | 0.5 | 0.6 | 1.3 | −0.4 |
| Merrimack River | 5 | 1.2 | 0.4 | 1.2 | 3.8 | 2 |
| Minnesota River | 0.4 | 0 | 0.2 | −2 | −0.7 | −0.5 |
| Neuse River | 2.2 | 1.4 | 1.7 | 2.3 | 6.7 | 3.3 |
| Rio Grande at Albuquerque | 0.6 | 0.3 | 0.1 | 1.1 | −4.6 | −0.4 |
| South Platte River at Henderson | 2.1 | 2.2 | 2.8 | 3.9 | 4 | 3.4 |
| Sacramento River | 0.7 | 0.2 | 0.1 | −0.3 | 2.1 | 4.7 |
| Salt River at Roosevelt | 0.1 | 0 | 0.1 | 0.2 | 0.4 | 0.2 |
| Susquehanna River | 1.6 | 0.1 | 0.2 | 0.2 | −0.3 | −0.8 |
| Suwanee River | 0.9 | 1.1 | 0.3 | 0.4 | 8.9 | 2.5 |
| Tongue River | 0.1 | 0 | 0 | 0 | 0 | 0 |
| Trinity River | 4.2 | 3.2 | 6.4 | −38 | 0 | 6.2 |
| Upper Colorado River | 0.4 | 0.2 | 0.1 | 0 | 0.8 | 0.2 |
| Willamette River | 2.5 | 0.6 | −0.1 | −0.3 | −0.1 | 2.5 |

Note: ICLUS, Integrated Climate and Land Use Scenarios; TSS, total suspended solids; TP, total phosphorus; TN, total nitrogen.

ment scenario was insignificant in all GLS models. GLS outputs are provided in Table S4 in the Supporting Information.

The distribution of SWAT simulations and GLS multiple comparison results are shown in Figures 4-10. In each figure, the top panel shows the distribution of simulated mean endpoint responses (maximum, minimum, median, 25th and 75th percentile) to mid-21st Century climate change and urban/residential development scenarios expressed as percent change relative to simulated baseline conditions. The bottom panel shows results of the GLS multiple comparisons. Endpoint responses here are expressed relative to baseline conditions (i.e., as standard deviation shifts away from the baseline mean; baseline values are provided in Table S3 in the Supporting Information). Normalized values facilitate comparisons across study watersheds, and may also provide a better indicator of risk, as watersheds with higher baseline variability are likely to have a greater capacity for adapting to change. Symbols highlighted in bold indicate climate scenarios resulting in endpoint responses significantly different from baseline. The ensemble mean response is shown by square symbols. Note that simulation results for the Kenai River study watershed are not included because of the reduced set of scenarios available at this location.

Simulation results for the four streamflow endpoints; total streamflow, average annual seven-day minimum streamflow, average annual one-day maximum streamflow, and the date of annual streamflow centroid, respectively, are shown in Figures 4-7. Simulated changes in total streamflow across study watersheds range from approximately ±50% of simulated baseline values (Figure 4; top panel), and are frequently outside the model 95% confidence limits on the baseline monthly means, indicating that the climate signal is larger than the uncertainty in the watershed model. GLS multiple comparison results found significant ensemble mean changes in 32% of study watersheds, and the streamflow response to at least one climate change scenario significantly different from baseline in 95% of study watersheds (Figure 4; bottom panel). Specifically, the ensemble mean streamflow response was significantly less than baseline in the Rio Grande, and significantly greater than baseline in the Minnesota, Suwanee, Elkhorn, Neuse, and Maumee rivers. Variability within individual study watersheds ranges on the order of 25-100% of baseline values. In 32% of study watersheds the ensemble response to climate change includes scenarios significantly different from baseline that disagree in the direction of change, i.e., plus/minus relative to baseline. One simulation, Scenario 6 (CCSM/WRFG models) for the Tongue River, shows an anomalous increase relative to other locations and scenarios. This is likely due to large projected increases in precipitation coupled with greater

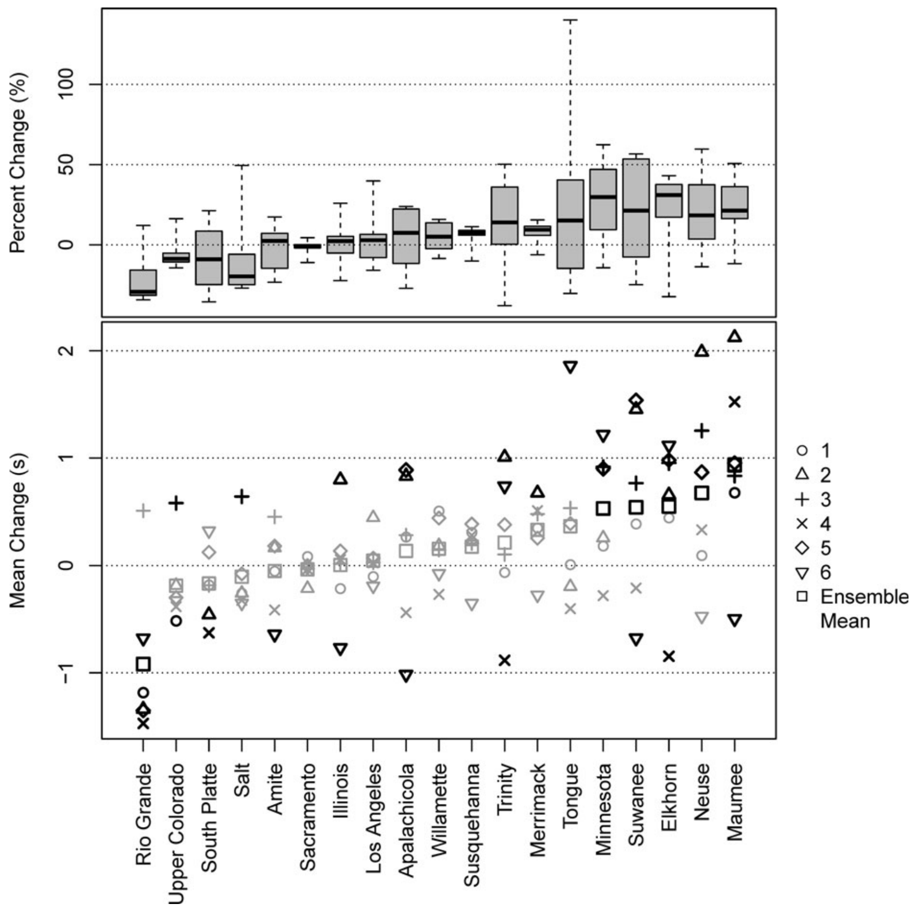


FIGURE 4. Simulated Total Streamflow Response to Six North American Regional Climate Change Assessment Program (NARCCAP) Climate Change Scenarios. Top panel shows the distribution of future scenarios as percent change relative to baseline conditions. Bottom panel shows generalized least squares model multiple comparison results expressed relative to baseline variability (standard deviation). Bold symbols represent significant differences from baseline. A key to NARCCAP scenarios is shown in Table 2.

intensity in summer precipitation at lower elevations in this study area.

Notably, the percent change in streamflow endpoints is generally greater than the percent change in precipitation (Figures 3 and 4). Areas where the median of projected total streamflow volume is less than current baseline are mostly those where total precipitation volume is projected to decrease (mostly in the interior Southwest), but the effect is magnified by simultaneous increases in evapotranspiration. In other areas, increase in streamflow volumes are associated with increases in total precipitation, but the effect is magnified where there is a shift from snow dominance to mixed winter precipitation and more winter runoff, or an increase in event intensity during the growing season.

Analysis of seasonal changes in total streamflow shows a wider range of responses across the study watersheds than annual average streamflow; here 68% of study watersheds showed at least one seasonally significant ensemble mean change in streamflow. In some study watersheds seasonal changes are relatively uniform throughout the year (e.g., Rio Grande, Neuse, Suwanee), while in others annual changes are driven by relatively large changes at certain times of the year (e.g., streamflow increases during autumn and winter in the Minnesota, Elkhorn, and Merrimack, and during the spring in the Upper Colorado and S. Platte; all watersheds where changes in snowfall and snowmelt regime are anticipated). Results of analyses based on seasonal total streamflow are included in Figures S1-S4 in the Supporting Information.

Simulated changes in low and high streamflows across study watersheds follow a pattern similar to total streamflow. Changes in annual average seven-day minimum flows across the study watersheds range from approximately −50% to +100% of simulated baseline values (Figure 5; top panel). GLS multiple comparison results found significant ensemble mean changes in 42% of study watersheds, and the response to at least one climate change scenario

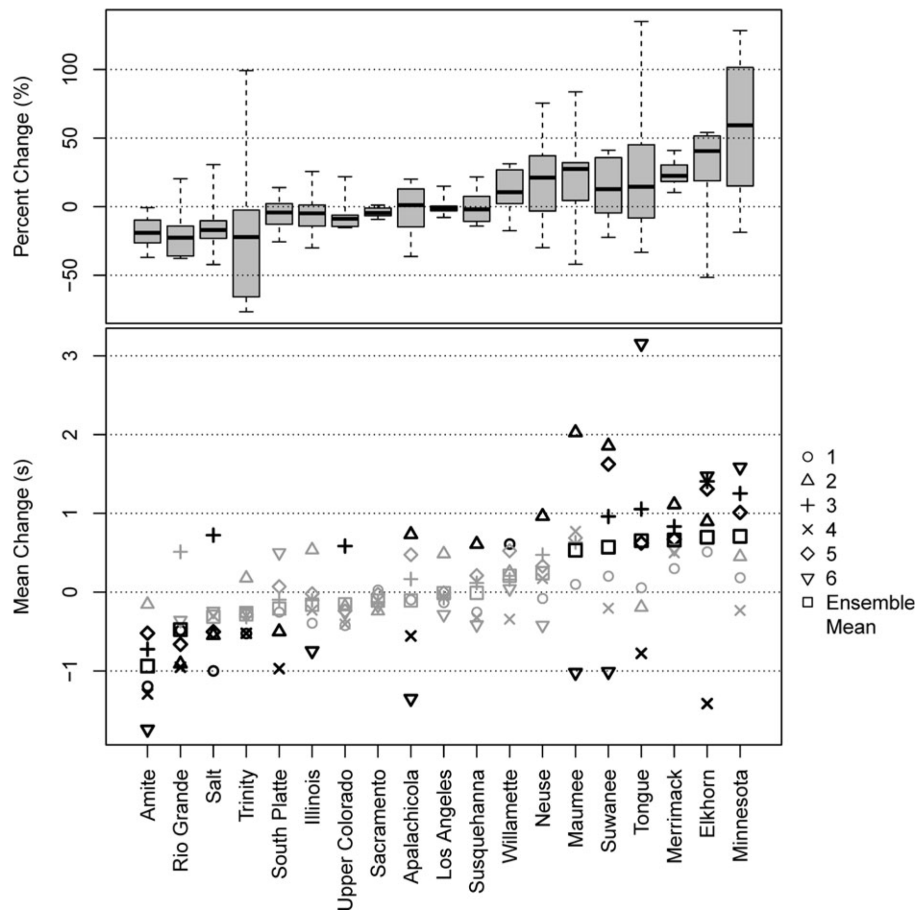


FIGURE 5. Simulated Annual Average Seven-Day Minimum Streamflow Response to Six North American Regional Climate Change Assessment Program (NARCCAP) Climate Change Scenarios. Top panel shows the distribution of future scenarios as percent change relative to baseline conditions. Bottom panel shows generalized least squares model multiple comparison results expressed relative to baseline variability (standard deviation). Bold symbols represent significant differences from baseline. A key to NARCCAP scenarios is shown in Table 2.

significantly different from baseline in 90% of study watersheds (Figure 5; bottom panel). The ensemble mean response was significantly less than baseline in the Amite and Rio Grande, and significantly greater than baseline in the Maumee, Suwanee, Tongue, Merrimack, Elkhorn, and Minnesota rivers. Variability within individual study watersheds ranges on the order of 25-150% of baseline values. In 32% of study watersheds the ensemble response to climate change includes scenarios significantly different from baseline that disagree in the direction of change.

Changes in average annual one-day maximum streamflow range in most locations from approximately −25% to +75% of simulated baseline values (Figure 6; top panel). GLS multiple comparison results found significant ensemble mean changes in 32% of study watersheds, and the response to at least one climate change scenario significantly different from baseline in 63% of study watersheds (Figure 6; bottom panel). The ensemble mean maximum daily streamflow response was significantly less than baseline in the Rio Grande, and significantly greater than baseline in the Minnesota, Maumee, Susquehanna, Suwanee, and Neuse rivers. In the Rio Grande, decreases are more pronounced when normalized for baseline variability due to low baseline variability in this study watershed. Variability within individual study watersheds ranges on the order of 25-125% of baseline values. In 11% of study watersheds there exist scenarios significantly different from baseline that also disagree in the direction of change.

The largest projected increase in high flows, in contrast with other streamflow endpoints, is in the Neuse Basin on the East Coast. Several climate scenarios for this watershed suggest strong increases in late summer and early fall precipitation intensity resulting in large increases in associated peak runoff events.

Anticipated changes in seasonal dynamics of streamflow could shift the annual date of streamflow centroid. Simulated changes in the date of streamflow centroid range from approximately 20 days earlier to

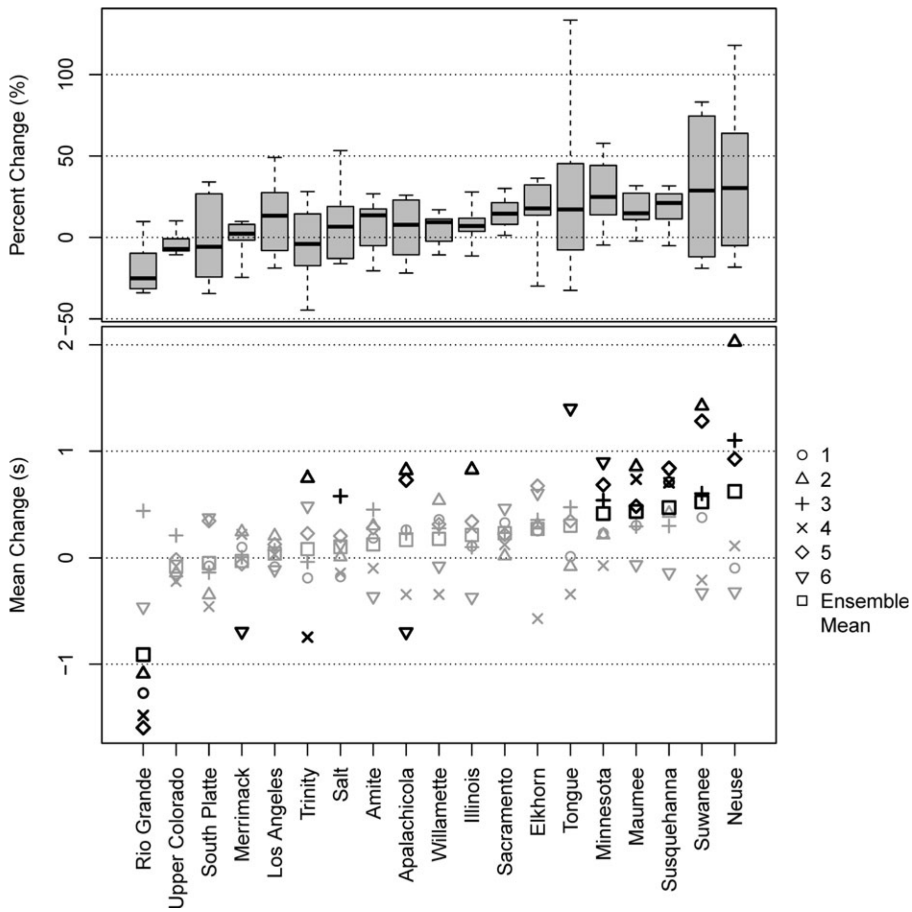


FIGURE 6. Simulated Annual One-Day Maximum Streamflow in Response to Six North American Regional Climate Change Assessment Program (NARCCAP) Climate Change Scenarios. Top panel shows the distribution of future scenarios as percent change relative to baseline conditions. Bottom panel shows generalized least squares model multiple comparison results expressed relative to baseline variability (standard deviation). Bold symbols represent significant differences from baseline. A key to NARCCAP scenarios is shown in Table 2.

40 days later than under current climate conditions across the study watersheds (Figure 7; top panel). GLS multiple comparison results found significant ensemble mean changes in 16% of study watersheds, and the response to at least one climate change scenario significantly different from baseline in 48% of study watersheds (Figure 7; bottom panel). Variability within individual study watersheds ranges in most locations on the order of 10-60 days. The date of the streamflow centroid in study watersheds most influenced by snow tends to decrease, due to a shift from snow-dominated to more transient snow/rain hydrology as air temperatures warm (Hamlet and Lettenmaier, 2007), while for some scenarios, simulations suggest this effect will be overwhelmed by increased summer precipitation (Figure 3). In the Merrimack, Upper Colorado, and South Platte study watersheds, locations influenced by snow, all scenarios were significantly earlier than under baseline conditions.

SWAT simulation results for the three water quality endpoints; TSS load, TP load, and TN load, respectively, are shown in Figures 8-10. Simulated median changes in pollutant loads follow a pattern generally consistent with changes in total streamflow volume, but with greater variability associated with differences in nutrient and sediment sources and pathways, biogeochemical cycling, soil erosion, and other factors.

Simulated changes in TSS loads range from approximately ±100% of baseline values across study watersheds (Figure 8; top panel). GLS multiple comparison results found significant ensemble mean changes in 42% of study watersheds, and the response to at least one climate change scenario significantly different from baseline in 79% of study watersheds (Figure 8; bottom panel). The ensemble mean response was significantly less than baseline in the Rio Grande, and significantly greater than baseline in the Merrimack, Illinois, Elkhorn, Minnesota, Suwanee, Neuse, and Maumee rivers. Variability within individual study watersheds ranges on the order of 25-125% of simulated baseline values. In 26% of study watersheds, the ensemble response to

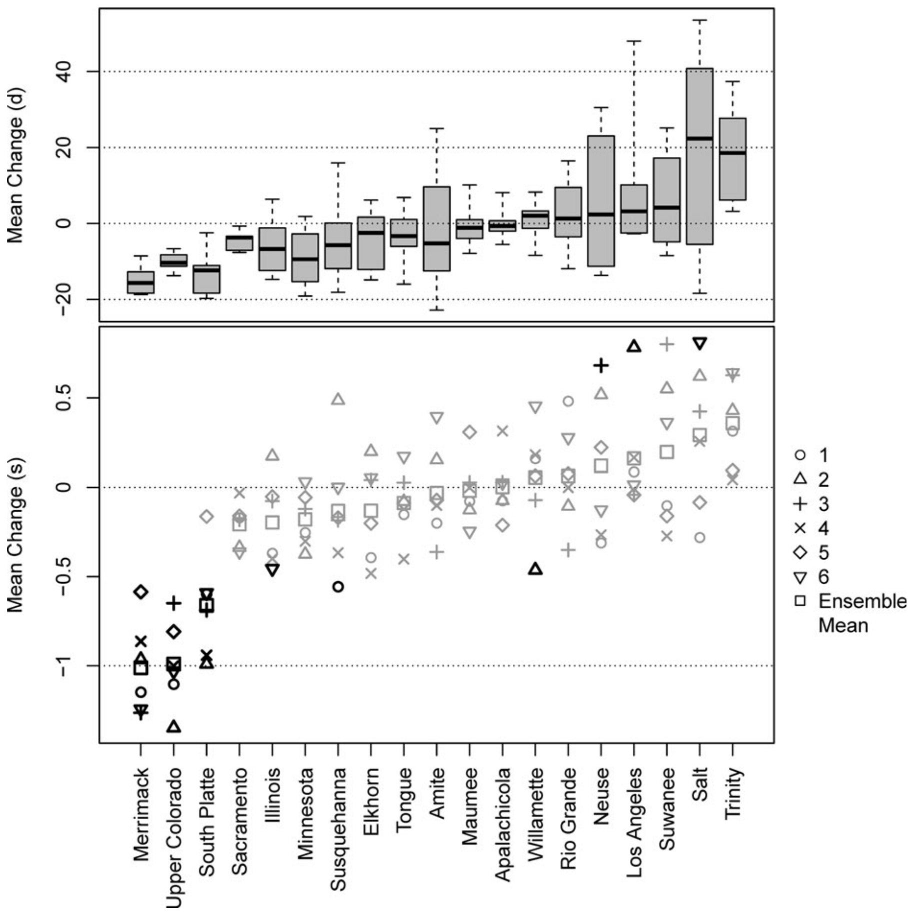


FIGURE 7. Simulated Streamflow Centroid Response to Six North American Regional Climate Change Assessment Program (NARCCAP) Climate Change Scenarios. Top panel shows the distribution of future scenarios as days relative to baseline conditions. Bottom panel shows generalized least squares model multiple comparison results expressed relative to baseline variability (standard deviation). Bold symbols represent significant differences from baseline. A key to NARCCAP scenarios is shown in Table 2.

climate change scenarios includes scenarios significantly different from baseline that disagree in the direction of change relative to baseline.

Simulated TSS loads approximate changes in streamflow, but with additional variability introduced by the degree to which a given watershed model is sensitive to simulated instream scour and deposition. In 75% of study watersheds with significant changes in TSS loads, there were also significant increases in streamflow (Figures 4 and 8). Simulations that differ most from the central trend correspond to locations and scenarios for which large changes in total runoff volume are simulated (e.g., Scenario 6 [CCSM/WRFG models] for the Tongue River; Figure 4). The large increases in TSS are mostly driven by simulated channel scour. These results should be taken with caution, however, given the simplified approach used in SWAT to represent this process. As seen with daily maximum flows, simulated TSS changes in the Rio Grande as a percent of baseline are generally within the range of changes at other study watersheds, but are more pronounced due to relatively lower baseline variability in TSS loads.

Analysis of seasonal changes in TSS loads shows a much wider range of responses than annual average loads; here 79% of study watersheds showed at least one seasonally significant ensemble mean change in TSS. As with streamflow, in many study watersheds seasonal changes are relatively uniform throughout the year (e.g., Rio Grande), while in other locations annual changes are driven by relatively large changes at certain times of the year (e.g., TSS increases during autumn and winter in the Minnesota, Elkhorn, and Merrimack, and during the spring in the Upper Colorado). Notably at the Salt River, variability among simulated TSS loads for the six scenarios in summer is exceptionally high. Results of analyses based on seasonal TSS endpoints are included in Figures S5-S8 in the Supporting Information.

Simulated changes in TP loads range across study watersheds from approximately −50% to +100% of

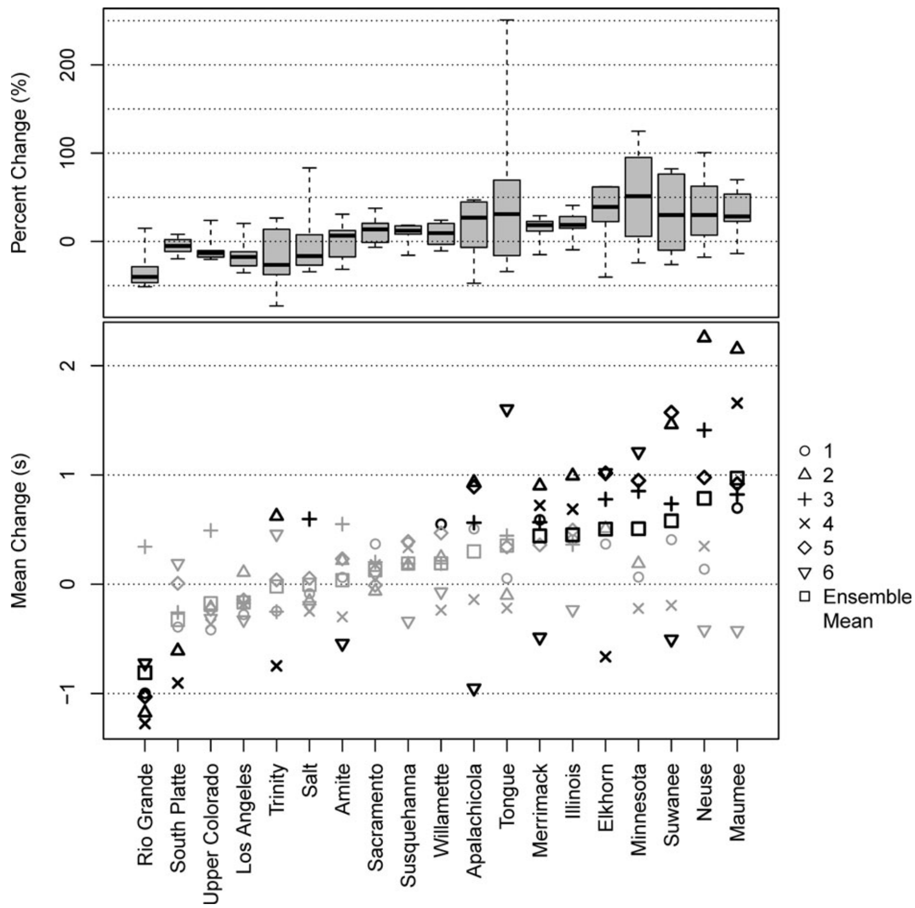


FIGURE 8. Simulated Annual Total Suspended Solids Load Response to Six North American Regional Climate Change Assessment Program (NARCCAP) Climate Change Scenarios. Top panel shows the distribution of future scenarios as percent change relative to baseline conditions. Bottom panel shows generalized least squares model multiple comparison results expressed relative to baseline variability (standard deviation). Bold symbols represent significant differences from baseline. A key to NARCCAP scenarios is shown in Table 2.

baseline values (Figure 9; top panel). GLS multiple comparison results found significant ensemble mean changes in 63% of study watersheds, and the response to at least one climate change scenario significantly different from baseline in 90% of study watersheds (Figure 9; bottom panel). The ensemble mean response was significantly less than baseline in the Rio Grande, and significantly greater than baseline in the Merrimack, Illinois, Minnesota, Amite, Elkhorn, Suwanee, Susquehanna, Maumee, Trinity, Apalachicola, and Neuse rivers. Variability within individual study watersheds ranges on the order of 25-150% of baseline values. In 16% of study watersheds the ensemble response to climate change scenarios includes scenarios significantly different from baseline that also disagree in the direction of change.

TP loads are influenced by changes in streamflow volume and suspended solids loads. In 50 and 75% of study watersheds with significant changes in TP loads, there were also significant increases in streamflow and TSS, respectively (Figures 4, 8, and 9). As with simulated TSS loads, TP simulations that differ most from the central trend correspond to locations and scenarios for which extreme changes in total runoff volume and TSS are simulated, e.g., Scenario 6 (CCSM/WRFG) for the Tongue River (Figure 4).

Analysis of seasonal TP loads shows results similar to streamflow and TSS; here 79% of study watersheds showed at least one seasonally significant ensemble mean change in TP. In Rio Grande, annual reductions in TP are largely due to decreased loads during the spring. In other locations, annual changes are driven by relatively large changes at certain times of the year (e.g., TP increases during autumn and winter in the Minnesota, Elkhorn, and during summer for the Salt). Similar to TSS, variability among simulated TP loads for the six scenarios at the Salt River in summer is exceptionally high. Results of analyses based on seasonal TP endpoints are included in Figures S9-S12 in the Supporting Information.

Simulated changes in TN loads across study watersheds ranges from approximately −50% to +75% of

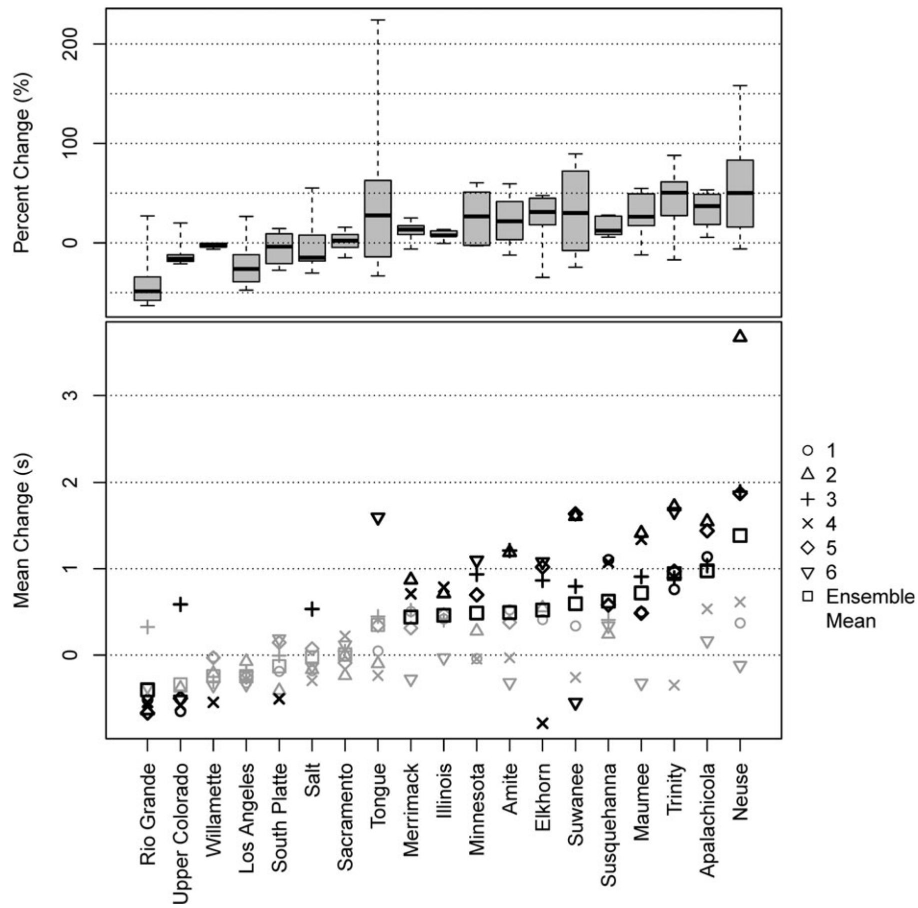


FIGURE 9. Simulated Annual Total Phosphorus Load Response to Six North American Regional Climate Change Assessment Program (NARCCAP) Climate Change Scenarios. Top panel shows the distribution of future scenarios as percent change relative to baseline conditions. Bottom panel shows generalized least squares model multiple comparison results expressed relative to baseline variability (standard deviation). Bold symbols represent significant differences from baseline. A key to NARCCAP scenarios is provided in Table 2.

simulated baseline values (Figure 10; top panel). GLS multiple comparison results found significant ensemble mean changes in 58% of study watersheds, and the response to at least one climate change scenario significantly different from baseline in 74% of study watersheds (Figure 10; bottom panel). The ensemble mean response was significantly less than baseline in the Upper Colorado and Rio Grande, and significantly greater than baseline in the Amite, Apalachicola, Minnesota, Merrimack, Trinity, Suwanee, Neuse, Maumee, and Susquehanna rivers. Variability within individual study watersheds ranges on the order of 25-100% of baseline values. In most locations, ensemble means that are significantly different from baseline suggested increased loads. None of the study watersheds have scenarios significantly different from baseline that disagree on the direction of change. TN loads are correlated with streamflow volume. In 46% of study watersheds with significant changes in TN loads, there were also significant increases in streamflow (Figures 4 and 10). As noted for streamflow and other endpoints, Scenario 6 (CCSM/WRFG) for the Tongue River, suggests a large increase in TN and is an outlier relative to other scenarios.

Analysis of seasonal changes in total TN loads similarly shows a wider range of responses across the study watersheds than annual averages; here 74% of study watersheds showed at least one seasonally significant ensemble mean change in TN loads. Analysis of seasonal changes in TN loads shows some study watersheds seasonal changes are relatively uniform throughout the year (e.g., Rio Grande), while in others annual changes are driven by relatively large changes at certain times of the year (e.g., TN increases during autumn and winter in the Minnesota, Maumee, Susquehanna, and during the spring in the Upper Colorado). Results of analyses based on seasonal TN endpoints are included in Figures S13-S16 in the Supporting Information.

Simulation results for the Kenai study watershed were analyzed independently due to the reduced set of scenarios available at this location. Results for

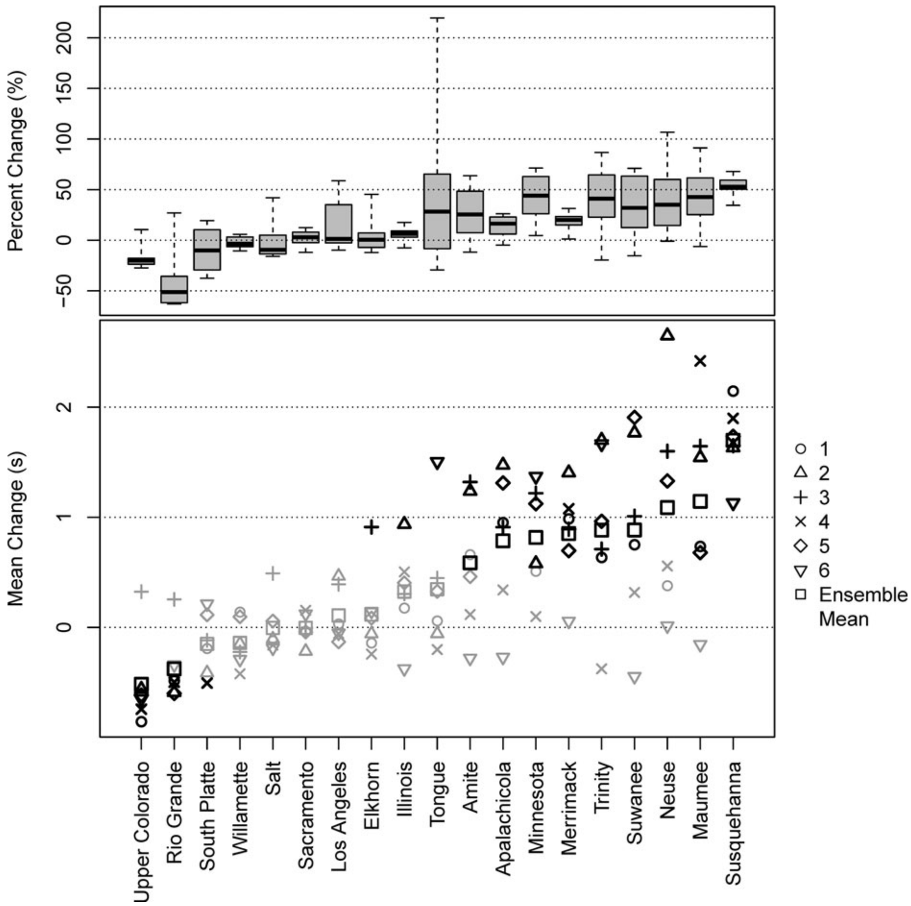


FIGURE 10. Simulated Annual Total Nitrogen Load Response to Six North American Regional Climate Change Assessment Program (NARCCAP) Climate Change Scenarios. Top panel shows the distribution of future scenarios as percent change relative to baseline conditions. Bottom panel shows generalized least squares model multiple comparison results expressed relative to baseline variability (standard deviation). Bold symbols represent significant differences from baseline. A key to NARCCAP scenarios is shown in Table 2.

these scenarios show increases in all annual endpoints except TP loads. GLS multiple comparison results show significant increases in ensemble means for all endpoints except for TP loads and the date of streamflow centroid. Simulated changes in annual endpoints appear to be driven largely by warming during the winter season. All seasonal streamflow and water quality endpoints showed significant increases in winter. For TP, significantly larger winter loads were balanced by decreases in other seasons. GLS model results for the Kenai study watershed are shown in Table S6 and Figures S17-S18 in the Supporting Information.

GLS models did not detect significant shifts in streamflow or water quality endpoint in response to mid-21st Century development scenarios or related interactions (see Tables S4 and S5 in the Supporting Information). The simulated responses to mid-21st Century urban/residential development scenarios for total streamflow, TSS, TP, and TN loads are shown in Table 4. Simulated changes in most study watersheds are small, typically less than 1%. The largest projected changes in impervious surface were in the Los Angeles and Trinity rivers. In these two basins, changes in impervious surface corresponded to relatively large changes in streamflow and pollution loads, but these changes were not large enough to create detectable effects in the GLS analyses. In general, the effects of development typically fell within the range of natural variability for each watershed. As an extreme example, the coefficient of variation for TP loads in the Los Angeles River in the baseline climate and development scenario was 1.7.

It is important to note that urban and residential development is a well-documented cause of hydrologic change and water quality degradation at local scales (e.g., U.S. EPA, 1984; Walsh *et al.*, 2005). The small response to urban/residential development scenarios in this analysis is not surprising given the correspondingly small changes in developed lands, as a percent of total watershed area, at the large spatial scale of our study watersheds. At this scale, the effects of development are largely obscured; such effects are greater in upstream subbasins within study watersheds where development is concentrated.

In addition to climate change and urban/residential development scenarios, SWAT simulations in this study represent projected mid-21st Century increases in atmospheric $CO_2$. Atmospheric $CO_2$ concentrations have direct impacts on plant physiology, and indirect impacts on the water balance and nutrient cycling. Representation of potential mid-21st Century increases in $CO_2$ resulted in increases in simulated future streamflow, with a median increase of 11% relative to simulations with present-day $CO_2$ across the 20 study watersheds (Butcher *et al.*, 2014). The simulated effect is in the same approximate range as the observations summarized by Leakey *et al.* (2009) and is consistent with modeling studies reported by Prudhomme *et al.* (2014). Simulations also suggest increases in nutrient and sediment loads associated with streamflow increases due to increased atmospheric $CO_2$. Note that the effects of increased $CO_2$ in these simulations are similar or additive with the effects of increasing precipitation due to climate change. Conversely, the effects of increased $CO_2$ may offset changes resulting from reductions in precipitation and increased ET losses associated with rising air temperatures.

The geographic distribution of simulated streamflow and water quality responses to combined climate change and urban/residential development scenarios is shown in Figure 11 (with response to climate change only for the Kenai River). Note that median values are presented here as a simplified indicator of regional variability across study areas, but are not necessarily representative of regional trends. Results suggest a general pattern of decreasing total streamflow volume in the central Rockies and Southwest, and increases on the East Coast and Northern Plains (Figure 11). Simulated high and low flows in most locations change in concert with total streamflow volume, although with varying magnitude. In the Northern Midwest (Minnesota and Maumee rivers), simulated high flows decrease while total streamflow increases, likely due to intermittent snowmelt over the winter months replacing the large spring thaw.

Streamflow is a major control on sediment and nutrient loads across the 20 study watersheds, but with additional variability due to spatial and temporal differences in nutrient and sediment sources and pathways. Simulations generally show decreases in nutrient loads in study watersheds where streamflow is projected to decrease (mostly in the interior Southwest). Increases in loads mostly occur where streamflow is projected to increase (Figure 11). TSS loads are projected to increase in most central and eastern basins, and decrease in the Rocky Mountain and Southwest study areas where streamflow decreases. Changes in TP loads generally follow changes in total solids loads. Nitrogen loads generally increase in the

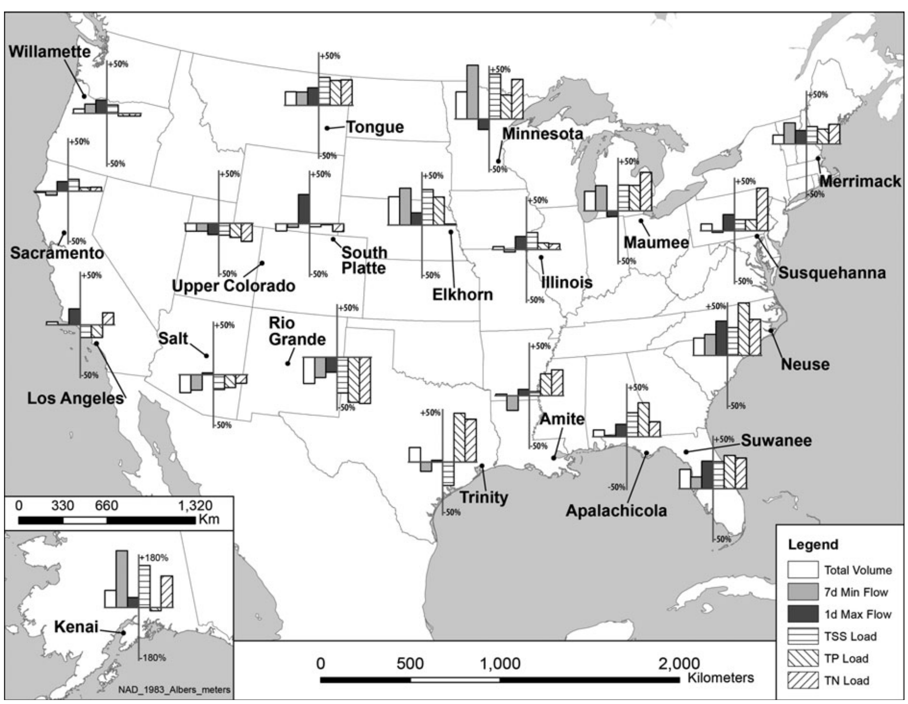


FIGURE 11. Median Simulated Changes in Streamflow and Water Quality Endpoints in Response to Combined Mid-21st Century Climate Change and Urban/Residential Development Scenarios. Changes are expressed as percent change relative to baseline values.

central and eastern portions of the country, with decreases in some western basins where streamflow decreases. Some of the largest simulated nutrient increases are in eastern and midwestern basins where there is already concern overloading to nutrient sensitive waters (e.g., Suwanee River to Florida Gulf coast, Maumee River to Lake Erie, Susquehanna River to Chesapeake Bay).

Analyses in this study focus on streamflow and water quality responses at the relatively large spatial scale of study watersheds. Our modeling methodology was developed to assess potential broad scale, regional changes in watershed response to climate change and urban/residential development in different regions of the U.S. While not a focus of this analysis, it should be noted that variability in watershed response also occurs at the scale of smaller subbasins within study areas. Intra-site variability in streamflow and water quality responses result from a range of factors including elevation differences and associated changes in orographic precipitation and the snow regime at higher elevations, and, in water-limited basins, relatively small changes in the ratios and timing of precipitation and PET. An illustration of intrasite variability in selected streamflow and water quality endpoints at the scale of HUC 8-digit subbasins within study areas is shown in Figures S19-S22 in the Supporting Information.

### *Modeling Assumptions and Limitations*

The modeling methodology in this study was developed to assess broad scale, regional watershed sensitivity to mid-21st Century climate change and urban/residential development scenarios throughout the U.S. The development and application of models uses a consistent set of data sources and follows established principles and practices for watershed modeling. As with any modeling study, however, a number of assumptions and sources of uncertainty must be acknowledged.

Simulations in this study may be limited by the setup and calibration of SWAT models, as well as structural limitations in our SWAT models, including use of a simplified curve number approach to partition direct runoff and infiltration (Garen and Moore, 2005), and representation of the processes affecting plant growth, nutrient dynamics, and water budgets under conditions of increased $CO_2$ (Reich *et al.*, 2006; Wu *et al.*, 2012). Given these limitations, simulations are also best viewed as providing information about potential streamflow and water quality changes relative to baseline conditions.

The NARCCAP and ICLUS scenarios evaluated in this study represent a plausible range but are not comprehensive of all possible futures. For example, NARCCAP scenarios are based on a single assumption about future greenhouse gas emissions, the relatively high IPCC A2 storyline. The differences across the emissions scenarios, however, are not large for the mid-21st Century considered in this study. Future changes in agriculture, fire regimes, and other land-use changes were also not represented in our scenarios. Consideration of other scenarios may alter projected ranges of change. Many study watersheds are also highly managed systems influenced by dams, water withdrawals, and other human uses. Management activities were represented in limited detail due to the large spatial scale of modeling of in this study. Simulation results should thus be considered as analyses of system behavior and sensitivity and not quantitative forecasts.

## CONCLUSIONS

Watershed modeling in 20 large, U.S. watersheds addresses gaps in our knowledge of streamflow, nutrient (nitrogen and phosphorus), and sediment loading sensitivity to potential mid-21st Century climate change and urban/residential development scenarios. Use of a consistent methodology facilitates regional scale comparisons across the study watersheds. Ensemble mean results suggest that by the mid-21st Century, statistically significant changes in streamflow and TSS loads (relative to baseline conditions) are possible in roughly 30-40% of study watersheds. These proportions increase to around 60% for TP and TN loads. It is important to note that these results are descriptive only of scenario simulations in this study, and do not imply future probabilities of occurrence.

Simulations suggest potential streamflow volume decreases in the Rockies and interior Southwest, and increases in the East and Southeast Coasts. Wetter winters and earlier snowmelt are likely in many of the northern and higher elevation watersheds. In general, simulated changes in pollutant loads follow a similar pattern to streamflow, but with additional variability associated with watershed differences in nutrient and sediment sources and pathways. Simulated streamflow and water quality responses to mid-21st Century urban and residential development are small at the large spatial scale of study watersheds evaluated in this study. The effects of development are likely greater in upstream subbasins where development is concentrated (Paul and Meyer, 2001; Walsh *et al.*, 2005).

Successful climate change adaptation strategies will need to encompass practices and decisions to reduce vulnerabilities across a range of plausible future climatic conditions. Meeting this goal requires an understanding of how watersheds in different regions of the U.S. could be affected. Results presented here provide a plausible set of potential changes in streamflow and water quality responses to mid-21st Century climate change and urban/residential development scenarios in different regions of the U.S. This information can be used to facilitate discussion and help guide the development of response strategies for managing climate risk. Results can also help to focus and prioritize future studies in these locations.

## SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article: (1) More detailed description of model calibration and validation results, (2) tables with detailed statistical results for analyses presented in the main paper, (3) simulation and statistical results for streamflow and water quality endpoints based on seasonal values not included in the main paper, (4) simulation results for Kenai River, Alaska, for the reduced set of 3 NARCCAP scenarios available at that location, and (5) simulation results for streamflow and water quality endpoints at the HUC 8-digit subwatershed scale within the larger study areas.

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