Climate change sensitivity assessment of streamflow and agricultural pollutant transport in California’s Central Valley using Latin hypercube sampling

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Abstract:
Bracketing the uncertainty of streamflow and agricultural runoff under climate change is critical for proper future water resource management in agricultural watersheds. This study used the Soil and Water Assessment Tool (SWAT) in conjunction with a Latin hypercube climate change sampling algorithm to construct a 95% confidence interval (95CI) around streamflow, sediment load, and nitrate load predictions under changes in climate for the Sacramento and San Joaquin River watersheds in California’s Central Valley. The Latin hypercube algorithm sampled 2000 combinations of precipitation and temperature changes based on Intergovernmental Panel on Climate Change projections from multiple General Circulation Models. Average monthly percent changes of the upper and lower 95CI limits compared to the present-day simulation and a statistic termed the “r-factor” (average width of the 95CI band divided by the standard deviation of the 95CI bandwidth) were used to assess watershed sensitivities. 95CI results indicate that streamflow and sediment runoff in the Sacramento River watershed are more likely to decrease under climate change compared to present-day conditions, whereas the increase and decrease for nitrate runoff were found to be equal. For the San Joaquin River watershed, streamflow slightly decreased under climate change, whereas sediment and nitrate runoff increased compared to present-day climate. Comparisons of watershed sensitivities indicate that the San Joaquin River watershed is more sensitive to climate changes than the Sacramento River watershed, which is largely caused by the high density of agricultural land. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS SWAT; climate change; agricultural pollution; streamflow; sediment; nitrate

Received 26 July 2011; Accepted 11 April 2012

INTRODUCTION
The uncertainty associated with climate change has been described as “persistent,” “deep,” and “irreducible” (Preston, 2005). These uncertainties exist at the global (e.g. climate feedback processes and climate sensitivity) and regional scale (e.g. greenhouse gas emissions and population growth). Many General Circulation Models (GCMs) have been created to investigate the effects of increasing greenhouse gas concentrations on the climate. These studies indicate an increase in global mean temperature, on average, between 1.1 and 6.4 °C compared to the 20th century average temperature depending on the greenhouse gas emission scenario [Intergovernmental Panel on Climate Change (IPCC), 2007]. End of 21st century GCM projections for California, which is the area of this study, show an increase in air temperature of 1 to 4.5 °C (e.g. Maurer, 2007; Cayan et al., 2008; Ficklin et al., 2012a). Changes in precipitation, however, are more speculative than temperature, especially for smaller regions where GCMs predict a wide range of positive and negative precipitation projections compared to present-day totals. In California, for example, GCMs project a wide array of precipitation projections, with a median projection of an 8% decrease from present-day precipitation totals (Cayan et al., 2008; Ficklin et al., 2012a). Any change in temperature and precipitation will affect the hydrological cycle, resulting in a large variation of streamflow and agricultural pollutant fate and transport. Climate change uncertainties create a range of challenges for scientific investigations and decision-making processes. Ideally, information from each plausible climate change scenario should be used to make informed risk management decisions at the watershed level (Preston, 2005).

The integration of risk management considerations is not a trivial matter, particularly for systems with multiple uncertainties. Stochastic simulations such as Monte Carlo and Latin hypercube analysis are useful for achieving such integration for complex modelling of the environment. Baalousha (2006) used a modified Latin hypercube sampling (LHS) technique with success to assess groundwater pollution risk. Seibert and McDonnell (2010) used a Monte Carlo technique to bracket the 95% confidence interval (95CI) of streamflow simulations from different land-cover regimes in Oregon, USA. Many other studies use LHS as a way to collect information about the hydrological characteristics of a region for a wide array of model input parameter sets (e.g. Abbaspour et al., 2004; Yang et al., 2008). For this study, we employ the LHS method because of its widespread use in uncertainty analyses and ease of use, as it is included in
the popular Soil and Water Assessment Tool Calibration Uncertainty Program (SWAT-CUP; Abbaspour et al., 2007). Furthermore, in comparing uncertainty analysis methods, Yu et al. (2001) and Melching (1992) investigated the efficiency of different uncertainty analysis sampling methods, concluding that LHS could generate representative sampling more efficiently than the Monte Carlo technique due to uniform sampling of the parameter space.

Although a plethora of studies have investigated the changes in surface runoff and streamflow associated with climate change, only a few have investigated how warmer climates and precipitation changes could affect water quality (e.g. Cruise et al., 1999; Chaplot, 2007; Ficklin et al., 2010). The relationship between precipitation changes and increased agricultural pollutant runoff is easily understood, as rainfall impacts and runoff are the driving mechanisms for pollutant transport within watersheds. The relationship between temperature increases and agricultural pollutant runoff is not as easily understood due to changes in evapotranspiration and irrigation water use. Our previous study (Ficklin et al., 2010) found that agricultural pollutant runoff decreased with increases in temperature.

The goal of this study is to assess the sensitivity of climate change on the Sacramento and San Joaquin River watersheds using a stochastic method with bracketed output from multiple GCMs and emission scenarios to determine the 95CI of streamflow and agricultural pollutant transport (sediment and nitrate) using SWAT (Arnold et al., 1998). These watersheds drain into the Sacramento–San Joaquin Delta (Delta), which in recent years has seen an appreciable decline in aquatic species, attributed in part to an increase of in-stream agricultural pollution (Werner et al., 1999). Therefore, this type of analysis is extremely beneficial to all parties interested in the health and security of the Delta. The probabilistic climate change assessment offers a useful framework for managing decision-making events by uncertainty.

METHODS

Study sites

Sacramento River watershed. The Sacramento River watershed area, as defined by this study, is approximately 23,300 km² (Figure 1). The Sacramento River monitoring gauge maintained by the United States Geological Survey (USGS) at Freeport, CA (USGS gauge #11447650), is the outlet of the simulated watershed. The watershed boundary is defined by the discharge inlets listed in Table I. The western side is bordered by the Black Butte Dam on Stony Creek; the eastern side is bordered by the Oroville Dam on the Feather River, the Yuba River at Marysville USGS gauge, the Camp Far West Dam on Bear River, and the Folsom Dam on the American River; the northern side is bordered by the Shasta Dam on the Sacramento River and the Whiskeytown Dam on Clear Creek. The study area includes the majority of agricultural land in the northern Central Valley, from Sacramento, CA, to Red Bluff, CA. The majority of the land use in the study area is rangeland composing approximately 62% of the total watershed area, whereas agricultural land composes approximately 33% of the total area. The remaining 5% contains urban land use, waterways/wetlands, and forested areas.

San Joaquin River watershed. The San Joaquin River watershed, as defined by this study, is 14983 km², with approximately 66% of the total area in the San Joaquin Valley, 15% in the Coastal Range, and 19% in the Sierra Nevada mountains (Figure 1). The USGS monitoring site at Vernalis (USGS gauge #11303500) is the outlet for the watershed. The USGS gauges of the upper San Joaquin River at the Friant Dam, the upper Merced River at the

Figure 1. Sacramento and San Joaquin River watersheds modelled in the study. The numerical value refers to the ID in Table I

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Merced Falls Dam, the upper Tuolumne River at the La Grange Dam, and the upper Stanislaus River at the Goodwin Dam are the inlets for the watershed (Figure 1, Table I). The watershed is highly agricultural; of the total cropland in the study area, 38% is covered by fruits and nuts, 36% by field crops (corn, tomatoes, pumpkins, watermelon, asparagus, cotton, beans, etc.), 17% by truck, nursery, and berry crops, and 4% by grain crops (DWR, 2007).

The San Joaquin Valley has a Mediterranean climate with hot, dry summers and cool, wet winters. Average annual rainfall is approximately 20 to 30 cm, with most of the precipitation falling between November and April. Average temperatures range from 11°C in the winter to 25°C in the summer (NOAA, 2008). Due to the arid climate, agriculture in the San Joaquin Valley critically depends on irrigation. Farmers in the San Joaquin Valley use a combination of groundwater and surface water to meet irrigation needs.

**SWAT model description**

The Soil and Water Assessment Tool is a model designed to simulate watershed processes at a river-basin scale (Arnold et al., 1998) that has been successfully applied in many environments (Gassman et al., 2007). SWAT simulates the entire hydrological cycle, including surface flow, lateral soil flow, evapotranspiration, infiltration, deep percolation, and groundwater return flows. For this study, surface runoff was estimated using the Soil Conservation Service Curve Number (CN), an empirical parameter for predicting runoff based on soil properties and land use (SCS, 1984), and evapotranspiration was estimated using the Penman–Monteith method (Penman, 1956; Monteith, 1965). Water within the soil column can be removed by evaporation or plant water uptake, deep percolation for aquifer recharge, or lateral movement in the soil column for streamflow contribution. Groundwater return flow is estimated based on the groundwater balance, where shallow and deep aquifers can contribute to streamflow. A temperature index–based approach is used to estimate snow accumulation and snowmelt processes. Irrigation was automatically scheduled and based on a soil water deficit, where water is added to the soil column when the soil water is below user-defined percentage of field capacity. For this study, irrigation occurs only when the soil water is at 85% of field capacity. Fertilizer was automatically added to the top layer of the soil based on a user-defined nitrogen stress threshold, which is a fraction of potential plant growth. Anytime the actual plant growth falls below this threshold, the model will automatically apply fertilizers. The nitrogen stress threshold used in this study was 0.95. We assume that growers will irrigate and apply nitrogen to the soil using the same thresholds as the present-day figures, and thus, the irrigation and nitrogen stress values remained constant for all simulations. Input data for SWAT include spatially distributed information basin topography, soil properties, land use/land cover, and climate time-series data. The model was run at a monthly time step. A full description of SWAT can be found in Neitsch et al. (2005).

**SWAT model input data**

Compiled from state and government agency databases were SWAT input parameter values from topography, land use/land cover, soil, and climate data. Data extracted from the Environmental Protection Agency include 1:250 000-scale quadrangles of land use/land cover data, 1:24 000-scale digital elevation models, and 1:100 000-scale stream network data from the National Hydrography Dataset. Cropland was defined based on the land-use survey database completed by the California Department of Water Resources (DWR) during 1996–2004. Cropland information will be assumed to have remained unchanged since the date of survey completion. Land use/land cover remained constant throughout the climate change simulations. Soil properties in the watershed were extracted from the 1:24 000 Soil Survey Geographic database. Daily weather data, including precipitation and minimum and maximum temperatures, were retrieved from the California Irrigation Management Information System.
Irrigation was automatically simulated by SWAT based on the soil water deficit. Depending on the subwatershed, irrigation water was extracted from the nearby reach or a source outside the watershed. Fertilization was automatically applied based on a plant growth threshold.

**Climate change projections**

Recent hydrological studies incorporate projections from GCMs, downscaled to a higher resolution for California (e.g. Maurer and Duffy, 2005; Maurer, 2007; Cayan et al., 2008). These studies show general agreement with temperature increases but great variability in projected precipitation for California. Consequently, no GCM should be considered superior to others in predicting California precipitation, and any projection should therefore be regarded as equally plausible. For this study, we will use the upper limit for IPCC temperature projections of +6.4 °C and a ±20% precipitation change compared to the present-day climate. These values bracket the range of plausible climate change scenarios for LHS.

**Latin hypercube sampling**

The LHS technique is a type of stratified Monte Carlo simulation first suggested by McKay et al. (1979). It has been used in a wide array of research topics for sensitivity and uncertainty analysis (Iman et al., 1981; Helton and Davis, 2003). The idea of LHS depends on the subdivision of a sampling space (in this case, temperature and precipitation) into $N_s$ numbers of non-overlapping segments with equal probability. LHS then draws a sample from each segment. Once the segments are defined, each individual parameter is randomized until a value that lies within each probability segment is found. Each round of sampling chooses randomly in a way that every interval within each probability segment is found. Each round of sampling chooses randomly in a way that every interval within each probability segment is found. Each round of sampling chooses randomly in a way that every interval within each probability segment is found.

After the LHS is performed, the temperature and precipitation values were input into SWAT to simulate streamflow and agricultural pollutant transport. In total, there were 2000 simulations for each scenario, with varying precipitation and temperature inputs. The 95CI was calculated from the output of these simulations based on the algorithm developed by Abbaspour et al. (2007). This algorithm is normally used for hydrological model calibration, where the 95CI is calculated from changes in model parameters on an uncalibrated model. The 95CI would then give a result of parameter uncertainty, and subsequent steps would decrease this uncertainty by narrowing the parameter ranges. For this study, temperature and precipitation are the only variables changed and are varied upon a calibrated SWAT model. Therefore, the 95CI calculated in our study is only from changes in precipitation and temperature, which we assume to be a climate change sensitivity assessment.

In the first step, a sensitivity matrix, $J$, is computed using

$$J_{ij} = \frac{\Delta g_i}{\Delta b_j}$$

where $i$ is the number of rows (equal to all possible combinations), $j$ is the number of columns (precipitation and temperature), $g$ is the objective function value [in this case, the Nash–Sutcliffe coefficient (NS; Nash and Sutcliffe, 1970)] of the climate change simulation compared to the present-day climate simulation, and $b$ is the climate change parameter (temperature or precipitation). The Hessian matrix, $H$, is then calculated by following the Gauss–Newton method:

$$H = J^T J$$

Then, based on the Cramer-Rao theorem (Press et al., 1992), an estimate of the lower bound of the parameter covariance matrix, $C$, is calculated from
where $s_2^g$ is the variance of the climate change simulations compared to the present-day climate from the $n$ runs. The estimated standard deviation and 95CI interval of a parameter, $b_j$, are calculated from the diagonal elements of $C$ from

\[ s_j = \sqrt{C_{jj}} \] (5)

\[ b_{j,\text{upper}} = b_j^* + z * s_j \] (6)

\[ b_{j,\text{lower}} = b_j^* - z * s_j \] (7)

where $b_j^*$ is the parameter $b$ for the solution with no temperature and precipitation change, and $z$ is the upper critical value of the $t$-distribution with $n-1$ degrees of freedom (1999 for this study).

Statistical analyses

Absolute percent change compared to the long-term average (also termed “upper and lower limit”) was calculated for each month for all model output. $T$-tests for dependent samples were performed on streamflow, sediment, and nitrate scenarios at the 0.05 significance level.

RESULTS AND DISCUSSION

SWAT model calibration and validation

The calibration and validation procedures can be found in Luo et al. (2008) for the San Joaquin River watershed and Ficklin et al. (2012b) for the Sacramento River watershed. Both models were previously calibrated and validated for streamflow, sediment loads, and nitrate loads measured at USGS gauges located within the Sacramento and San Joaquin River watersheds. At the Freeport USGS site for the Sacramento River watershed (Figure 1, Table I), the NS coefficients for validation were 0.86 for streamflow, 0.64 for sediments, and 0.51 for nitrate (Ficklin et al., 2012b). Average monthly streamflow, sediment loads, and nitrate loads during the present-day simulation were 778 m$^3$/s, 165 833 tons/month, and 1 502 220 kg/month, respectively. At the Vernalis USGS site for the San Joaquin River watershed (Figure 1, Table I), the NS for the validation period was 0.95 for streamflow, 0.74 for sediments, and 0.85 for nitrate (Luo et al., 2008). Average monthly streamflow, sediment loads, and nitrate loads during the present-day simulation were 121 m$^3$/s, 23 324 tons/month, and 278 735 kg/month, respectively. Both models provided satisfactory simulation results in estimating the temporal trend and variation of streamflow and agricultural pollutant loads, and therefore, the models were deemed suitable for evaluating the sensitivity to climate change.

Latin hypercube sampling

Figure 2 displays the results of the Latin hypercube temperature and precipitation sampling for the 2000 SWAT model runs. As shown from the even scattering of data points in Figure 2, the sampling did a satisfactory job at pairing nearly all possible combinations of precipitation and temperature. Most importantly, the temperature (+0 and 6.4 °C) and precipitation (−20% and +20%) extremes were sufficiently sampled (Figure 2).

Hydrological and agricultural pollutant changes

Presented streamflow, sediment load, and nitrate load results are from the Sacramento River—Freeport and the San Joaquin River—Vernalis USGS gauging stations and are considered the outlet for their respective watersheds (Figure 1, Table I). For both watersheds, the streamflow is highly controlled by the upstream reservoir releases, and therefore, any changes in model output compared to present-day simulations are dependent on hydrological conditions within the watersheds and not from changes in reservoir management.

Streamflow. For the Sacramento River watershed streamflow, $t$-tests indicate that the upper and lower 95CI limits were not significantly different ($p < 0.05$) from present-day streamflow rates, which is due to the managed reservoir releases into the watershed (Figure 3). The average monthly absolute percent change for the 95CI upper limit was 3%, whereas the lower limit was 10% compared to the present-day streamflow (Table II). This
indicates that long-term streamflow in the Sacramento River watershed is more likely to decrease with changes in climate. The change in the 95CI lower limit was greater than the upper limit for each month, with the smallest difference occurring during the dry season months of August through October (Table II). The largest decrease occurred in December with a 15% change compared to present-day streamflow, whereas the smallest decrease occurred during October with a 5% change.

Flood weirs on the Sacramento River muted the change in the upper limit of 95CI. Six major flood control structures are located on the Sacramento River. When the river is above a particular discharge value, water spills over the weir structures, capturing streamflow that would have originally remained in the river. The weirs transport water into wetlands, other streams, or completely out of the modelled watershed. Therefore, increases in streamflow from precipitation increase may be captured by the flood weirs. These flood weir structures are accounted for within the SWAT model (Ficklin et al., 2012b). Within the model, if the streamflow is above a certain discharge (from Feyrer et al., 2006), the water is routed to the diversion destination.

For the San Joaquin River watershed streamflow, the overall mean monthly absolute percent change values for the 95CI upper and lower limits were 27% and 28% compared to the present-day climate, respectively (Figure 3, Table II). T-tests indicate that both 95CI limits were not significantly different ($p < 0.05$) from the present-day streamflow rates, which is, again, due to the managed reservoir releases into the watershed. There was high variability within seasons. Generally, the upper limit of the 95CI was greater in January through June compared to the lower limit. Conversely, the lower limit of the 95CI was...
generally greater than the upper limit from July through December. The largest absolute percent change increase and decrease were 42% and 39% and occurred in June and September, respectively (Table II).

Sediment Loads. The average monthly absolute percent change for the Sacramento River watershed sediment load was 20% for the upper 95CI limit and 26% for the lower 95CI limit; these were found to be significantly different from present-day sediment loads \((p > 0.05)\) (Figure 4, Table II). This indicates that there is a high variability in sediment loads, with a tendency to decrease under climatic changes. The monthly sediment load absolute percent change for the Sacramento River watershed indicates that there is likely to be an increase for late winter/early spring and decreases for the rest of the year. This is potentially caused by the presence of large precipitation events during late winter/spring. The largest increase and decrease occurred during March and September, with an absolute percent change of 43% and 34%, respectively (Table II).

The average monthly absolute percent change for the San Joaquin River watershed sediment load 95CI upper limit was 73% and 49% for the lower limit compared to the present-day simulation, indicating a tendency for an increase in sediment runoff under climatic change (Figure 4, Table II). However, the upper and lower 95CIs were not significantly different \((p < 0.05)\) from the present-day simulations. Sediment load increased for every month except for September and October (Table II). The largest increases occurred during the late spring/early summer. The lower 95CI limits remained consistent for each month, with a standard deviation of approximately 4.6%. The largest sediment load increase occurred in June with an absolute percent change of 165%, and the largest sediment load decrease occurred in September with a 57% decrease. It is worthy to note that, although large sediment loads are observed during the wet season, high loads are also found in the irrigation season.

For the winter and spring months, large changes in sediment loads are expected. Sediment is largely generated by winter and spring precipitation events, and therefore, any change in those events will have a large effect on the amount of sediment transported out of the watershed. For the summer months, sediment movement is transported by sediment runoff from irrigation applications and streambed erosion. If the streamflow energy is low enough, sediment can be deposited within the streams, resulting in a decrease in sediment loads. Therefore, the high correlation \((r > 0.90)\) between changes in sediment loads and streamflow is to be expected.

Nitrate Loads. The Sacramento River watershed average monthly absolute percent change in nitrate was 13% for the 95CI upper limit and 13% for the 95CI lower limit compared to the present-day simulation (Figure 5, Table II). T-tests indicate, however, that the 95CI upper limit was not significantly different \((p > 0.05)\), whereas the 95CI lower limit was \((p < 0.05)\). The monthly absolute percent changes showed high variability compared to
present-day nitrate loads, with no consistent increase or decrease throughout the year. Nitrate loads generally had the tendency to increase during the late fall and winter months and to decrease during the summer months. The largest increase was 32% and occurred in February, whereas the largest decrease was 21% and occurred in January (Table II). This result is expected, as an increase or decrease in rainfall will result in corresponding increases or decreases in nitrate runoff.

The average monthly percent change for the San Joaquin River watershed nitrate loads was 28% for the 95CI upper limit and 26% for the lower limit (Figure 5). Both 95CI limits were found to be significantly different ($p < 0.05$). This suggests a slight tendency for nitrate to increase with climatic changes. The largest absolute percent change increase and decrease were 71% and 42% and occurred in September and March, respectively (Table II). Table II indicates a strong seasonal variation in nitrate runoff. During the early spring and summer, nitrate loads have the tendency to decrease, whereas in the late summer and winter months, they have the tendency to increase. This can be attributed to changes in plant growth. Our previous study (Ficklin et al., 2009) found that the watershed-wide average leaf area index with elevated temperature peaked up to two months relative to the present-day climate. This resulted in changes in evapotranspiration as well as changes in agricultural management.

Nitrate load results are associated with dissolved-phase nitrate only, and thus, all nitrate yield is water associated. Therefore, nitrate runoff is dependent on the hydrological balance, the quantities present in the soil either from natural sources or from fertilizer inputs, and the degree to which they are removed by plants at the site (Ferrier et al., 1995). Changes in surface water runoff appeared to be the most significant factor in fertilizer runoff changes in a study by Mander et al. (2000). In our study, changes in nitrate runoff for both watersheds were moderately correlated ($r$ greater than 0.50, but less than 0.75; $p < 0.05$) with changes in streamflow. Annual fertilizer use did not significantly decrease under climate change. However, it was found that less fertilizer was applied during the summer months for both watersheds due to the shift in plant growth patterns from an increase in air temperature. In our previous study (Ficklin et al., 2009), we showed that watershed-wide average leaf area index in the San Joaquin River watershed shifted ahead one month with a 1.1°C air temperature increase and three months with a 6.4°C air temperature increase. A shift in plant growth results in a shift in fertilizer use, thus reducing the amount used in the summer months.

**Comparison and differences in watershed sensitivities.** Before discussion, it is important to note the differences in volumes in both watershed outputs. Whereas the San Joaquin River watershed may have a larger absolute percent difference (representing sensitivity), the Sacramento River watershed may have overall larger output caused by the difference in watershed size. Therefore, the watersheds must be compared by normalized statistics.

The 2000 Latin hypercube simulations for each watershed were used for the calculation of the 95CI. The average width of the 95CI band divided by the standard deviation of the 95CI bandwidth (termed the "r-factor" by Abbaspour et al., 2004) is a good indicator to use for the comparison of watershed sensitivities. Generally, sensitivity decreases as the $r$-factor decreases, indicating a small 95CI width. The streamflow $r$-factors for the Sacramento and San Joaquin watersheds were 1.44 and 1.42, indicating that the streamflow within both watersheds was equally sensitive to climate change (Figure 3). This is most likely caused by the large effect of reservoir releases into the watersheds. Based on the absolute percent change sediment load statistics, the San Joaquin River watershed is nearly twice as sensitive as the Sacramento River watershed (Table II). The sediment load $r$-factors were 0.59 for the Sacramento River watershed and 0.68 for the San Joaquin River watershed, which represents a higher sensitivity for the San Joaquin River watershed (Figure 4). Compared to the San Joaquin River watershed, more sediment may be transported out of the Sacramento River watershed between the months of January and April whereas less may be transported during the rest of the year compared to the present-day climate simulations. For nitrate loads, the absolute percent change statistics indicate that the San Joaquin River watershed is more sensitive than the Sacramento River watershed (Table II). The nitrate load $r$-factors were 0.69 for the Sacramento River watershed and 1.02 for the San Joaquin River watershed, indicating a higher sensitivity of nitrate runoff to climate change for the San Joaquin River watershed compared to the Sacramento River watershed (Figure 5).

Climate change sensitivity differences between the two watersheds can be attributed to two factors: differences in land use and soil properties. Precipitation was varied by the same percentage for both watersheds and was assumed not to be a factor. The differences between land use and soil properties between the watersheds may seem nominal but can be large when extrapolated over large areas. A comparison of the agricultural land acreage from DWR land-use data indicates that the San Joaquin River watershed contains approximately twice as much agricultural land than the Sacramento River watershed. The San Joaquin watershed area is approximately 8500 km$^2$ less than the Sacramento River watershed, leading to a higher agricultural land density. A difference in agricultural acreage will have large effects on (1) irrigation water use, (2) evapotranspiration water loss, (3) agricultural management practices leading to susceptibility of field erosion, and (4) a higher density of fertilizer use, leading to increased nitrate runoff susceptibility.

There are several differences in soil properties that may lead to the differences with climate change sensitivities. SWAT uses the Modified Universal Soil Loss Equation (MUSLE; Williams, 1975) to estimate sediment yield from each subbasin:

where \( Sed \) is the sediment yield on a given day (metric tons), \( Q_{surf} \) is the surface runoff volume (mm \( H_2O/ha \)), \( q_{peak} \) is the peak runoff rate (m\(^3\)/s), \( area_{HRU} \) is the area of the Hydrologic Response Unit (ha), \( K_{usle} \) is the USLE soil erodibility factor [0.013 metric ton m\(^2\) h/(m\(^3\)-metric ton cm)], \( C_{usle} \) is the USLE cover and management factor, \( P_{usle} \) is the USLE support practice factor, \( LS_{usle} \) is the USLE topographic factor, and \( CFRG \) is the coarse fragment factor. The slopes of the two watersheds are approximately equal, and therefore, the \( LS_{usle} \) will be equal as well.

Differences in MUSLE soil parameters leading to differences in sensitivities include \( K_{usle} \), soil organicmatter, \( C_{usle}, P_{usle}, \) and \( CFRG \) within the first soil layer. A higher \( K_{usle} \) factor will lead to more surface erosion. The area-weighted average \( K_{usle} \) value was 0.29 for the Sacramento River watershed and 0.32 for the San Joaquin River watershed, indicating that the San Joaquin River watershed is more susceptible for sediment runoff. Additionally, a soil with higher organic matter is less likely to erode than a soil with less organic matter because of sediment cohesion. The area-weighted average for soil carbon content was 1.22\% of the soil weight for the Sacramento River watershed and 0.71\% of the soil weight for the San Joaquin River watershed. A higher \( CFRG \) value indicates soils that are more susceptible to sediment erosion. Area-weighted average \( CFRG \) values were 0.5 for the Sacramento River watershed and 0.8 for the San Joaquin River watershed. Because the San Joaquin River watershed has nearly twice as much agricultural land as the Sacramento River watershed, \( C_{usle} \) and \( P_{usle} \) values are also higher for the San Joaquin River watershed compared to the Sacramento River watershed.

**Implications.** The aim of this work is to assess the sensitivity of the Sacramento and San Joaquin River watersheds to climate change using an LHS technique on temperature and precipitation projections. Our sensitivity approach and assumptions are not without fault. As previously mentioned, our LHS scheme assumes that temperature and precipitation are independent. In reality, this is not the case, as temperature and precipitation are inversely related. However, the goal of this study is to assess the sensitivity of the watersheds to changes in temperature and precipitation by using all possible temperature and precipitation projections to bracket the potential ranges of streamflow and agricultural pollutant transport.

Additionally, land-use change is not simulated, and therefore, we assume all climate change projections on current land-use scenarios and management practices. Changes in land use are likely to have significant impact on streamflow and agricultural pollutant fate and transport. However, it is not well known how agricultural land use will change under climate change. The SWAT model used in this study allows changes in irrigation use and fertilization based on changes in soil moisture and plant growth thresholds. This assumes that growers will change their agricultural management techniques based on changes in the soil and crop and is thus a constrained estimate of the changes in irrigation and fertilization. It is important to understand that these inputs may change in the future with changing agricultural management techniques, which may alleviate or increase water quality concerns in a changing climate. Moreover, the results from this study do not include changes in urbanization or agricultural acreage. Increases in urbanization will result in decreases of streamflow either by streamflow or groundwater extraction. An increase in groundwater extraction may decrease stream–aquifer connectivity, resulting in a streamflow baseflow decrease. A decrease in streamflow will further exacerbate the water quality problem, as decreases in streamflow either by streamflow or groundwater extraction may result in increases of contaminant concentrations. Potential future work would include multiple land-use scenarios coupled with climate change scenarios.

Lastly, streamflow in both watersheds are highly controlled by reservoir releases, and the sensitivity of streamflow may not represent the natural sensitivity signal. However, inasmuch as we assume no sediment or nitrate concentrations in the reservoir releases, sediment and nitrate sensitivities are adequately assessed. In conclusion, we present a simple sensitivity assessment of plausible climate change scenarios using current land-use scenarios and management practices, which should therefore be treated with caution.

**CONCLUSIONS**

This study used the SWAT watershed model to simulate changes in streamflow and agricultural runoff in the Sacramento and San Joaquin River watersheds using LHS from a temperature and precipitation range of 0 to 6.4 \(^\circ\)C and ±20\%, respectively, compared to the present-day climate. Using 2000 climate change simulations, the 95CI was calculated for streamflow, sediment loads, and nitrate loads. The 95CI results indicate that streamflow and sediment in the Sacramento River watershed are more likely to decrease under climate changes compared to present-day conditions, whereas nitrate runoff was found to increase and decrease by equal amounts. For the San Joaquin River watershed, streamflow slightly decreased under climate change, whereas sediment and nitrate had the tendency to increase compared to the present-day climate. Comparisons of watershed sensitivities indicate that the San Joaquin River watershed is more sensitive to climate change than the Sacramento River watershed. Streamflow, sediment load, and nitrate load \( r \)-factors were 1.44 and 1.42, 0.59 and 0.68, and 0.69 and 1.02 for the Sacramento and San Joaquin River watersheds, respectively. Climate change sensitivity differences can be attributed to differences in land use and soil properties. The results generated from this study are valuable as a tool for guiding water resource managers and those required to comply with legislation for water quality guidelines to make appropriate decisions on land management and/or measures for environmental protection.
REFERENCES


