Key Points:
- Snowpack below the major reservoirs is projected to decrease dramatically as air temperature increases 1.6–5.3 degrees C by end-of-century
- Peak streamflow increases by 62% and 96% by end-of-century for moderate- and high-emission scenarios, respectively
- Sediment transport increases by 39% and 69% by end-of-century for moderate- and high-emission scenarios, respectively

Correspondence to:
M. A. Stern,
mstern@usgs.gov

The Future of Sediment Transport and Streamflow Under a Changing Climate and the Implications for Long-Term Resilience of the San Francisco Bay-Delta

Michelle A. Stern[1] [iD], Lorraine E. Flint[1] [iD], Alan L. Flint[1] [iD], Noah Knowles[2] [iD], and Scott A. Wright[1] [iD]

[1]U.S. Geological Survey, California Water Science Center, Sacramento, CA, USA, [2]U.S. Geological Survey, California Water Science Center, Menlo Park, CA, USA

Abstract Sedimentation and turbidity have effects on habitat suitability in the San Francisco Bay-Delta (Bay-Delta), concerning key species in the bay as well as the ability of the delta marshes to keep pace with sea level rise. A daily rainfall runoff and transport model of the Sacramento River Basin of northern California was developed to simulate streamflow and suspended sediment transport to the Bay-Delta for the next century (water years, WY2010–2099). The model was calibrated to historical streamflow and sediment data and applied using 10 Global Climate Models with two representative concentration pathways (RCP) each for WY1980–2099 from the IPCC 5th Assessment Report. Results indicate average increases in peak streamflow of +58% and +66% for the RCP 4.5 and 8.5 ensembles, respectively, by mid-century and +62 and +96% by end-of-century. Sediment loads increased by +39% and +69% by end-of-century. Suspended sediment concentrations (SSC) increased on average by +4.6% and +6.7% for RCP 4.5 and 8.5, respectively, by end-of-century. Individual scenario results varied, and statistically significant increasing trends of sediment loads to the Bay-Delta were found for the RCP 4.5 and 8.5 ensembles and five individual scenarios. Increased suspended sediment loads may have negative effects such as contaminant transport but also have positive effects that help protect against sea level rise, increase turbidity and fish habitat, and sustain wetland habitats in the Bay-Delta.

Plain Language Summary The health of the San Francisco Bay-Delta depends on a sediment supply that has been recently declining. Future climate scenarios were run through a model to determine changes in streamflow and sediment transport. Results from the model showed increases in large flow events and sediment transport over the next century. Increased sediment supply can help buffer wetland habitats against the deleterious effects of sea level rise with benefits to native fishes.

1. Introduction

Coastal wetlands like the San Francisco Bay-Delta (Bay-Delta) on the West Coast of California (Figure 1), which is the focus of this study, are under direct and increasing threat from land use change pressures, from indirect impacts of upstream disruption to sediment supply, and from development pressures and rising sea level on the coastline (Syvitski et al., 2009). The Bay-Delta physically consists of the confluence of the Sacramento and San Joaquin Rivers (Delta) with upstream watersheds encompassing approximately 40 percent of the area of California (Porterfield, 1980). The Delta flows into the San Francisco Bay (Bay) and then to the Pacific Ocean. Water and sediment supply to the Bay-Delta and the ecosystem have been impaired as have many systems worldwide.

Around the world, altered sediment supply and delta subsidence exacerbate sea level rise, with local rates of regularly twice and up to 10 times the global rates (Crooks et al., 2011). Coastal wetlands and marine ecosystems hold vast stores of carbon; yet, large areas of coastal wetlands have been drained and converted to other uses globally. Sustainable management of coastal wetlands and marine ecosystems offer a wide range of co-benefits, including shoreline protection, nutrient cycling, water quality maintenance, flood control, habitat for birds and other wildlife such as fish, and opportunities for recreation. Damming projects upstream of deltas have changed water flows and affected sediment delivery to main-stem rivers and deltas, with recent estimates showing a 30% global reduction of sediment delivery to coastal areas, impacting 47% of rivers (UNEP, 2006). Many large deltas are potentially compromised by a disruption of sediment supply, some
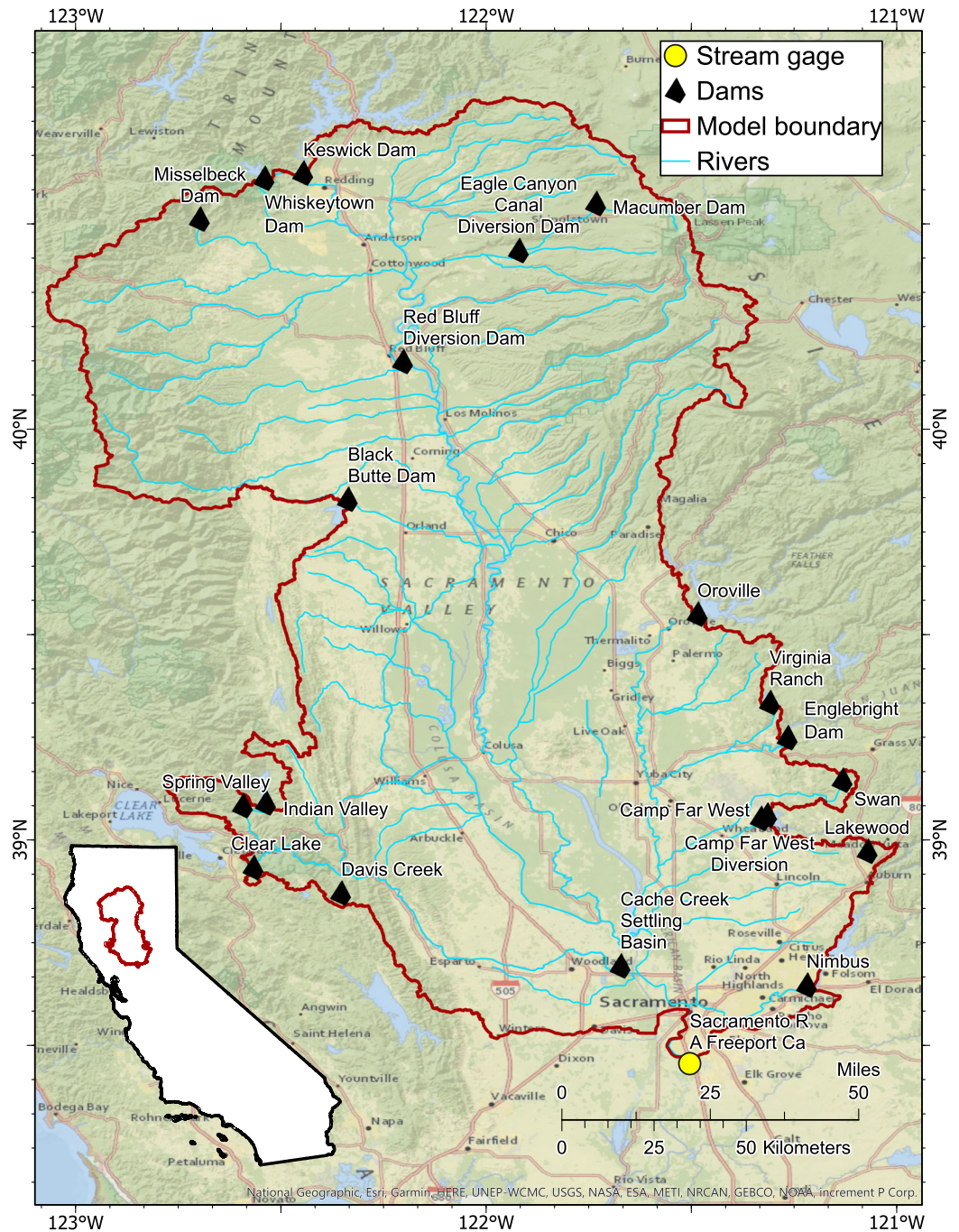
Figure 1. Location of Sacramento River Basin study area and model domain, including major dams and streamgages.

with nearly complete sediment starvation conditions, leaving habitats and human infrastructure vulnerable to inundation and rising sea levels (Syvitski et al., 2009).

Climate change is exacerbating impacts on coastal and estuarine ecosystems, which include accelerated sea level rise, increased temperatures, changes in rainfall distribution and freshwater inputs, and increased frequency and intensity of storms, all operating over a range of temporal and spatial scales that result in changes in the ecogeomorphology of coastal and estuarine wetlands by changes in freshwater, sediment, and nutrient inputs. An example of a sensitive system in decline, starved of sediment and fragmented by

economic development, is the Mississippi Delta in North America. This large delta is shrinking by tens of square kilometers per year. Over the past few centuries, 25% of the deltaic wetlands associated with the Mississippi Delta have been eroded from coastal processes (Blum & Roberts, 2009). The diverse delta ecosystem and the services it provides—storm protection, nutrient and pollution removal, and carbon storage—are being compromised, fisheries and the bayou cultural heritage are threatened, and deltas worldwide share this trend (Blum & Roberts, 2009; Syvitski et al., 2009). In Pakistan, one-fifth of the Indus delta plain has been eroded since the river was first dammed in 1932 (Giosan et al., 2014). In China, the northern shore of the Yellow River delta has retreated 300 meters each year for the past 35 years (Giosan et al., 2014). Rising seas compound the sediment crisis. Coastal lowlands less than a meter above sea level are likely to be inundated by the turn of the century, and areas at risk of flooding in deltas are likely to expand by 50% (Giosan et al., 2014). This global scale of potential delta reduction has been unprecedented in the past 7,000 years (Giosan et al., 2014).

Coastal ecosystems are being impacted worldwide as a result of climate change. Another example of a sensitive ecosystem is the mangrove, which is struggling to adapt to sea level rise and is limited by available sediment (Krauss et al., 2014). For mangrove ecosystems, if net vertical accretion does not keep up with relative sea level rise then adaptation must occur by inland migration, depending on suitable topography and available areas (Faraco et al., 2010; Gilman et al., 2008). Sea level rise is regionally variable and is likely to have a lesser impact in areas with high sediment availability, tectonically uplifting or stable coasts, or high productivity and large tidal ranges such as the Amazon estuary and Parnaiba River delta. However, the more vulnerable systems are located where there is extensive coastal development such as in Asia or South and North America, areas with very high rates of local sea level rise such as Indonesia and Mississippi Delta, or in low island mangroves such as in the Pacific (Ward et al., 2016).

Ecosystem assessments commonly include evaluation and measurement of sediments, focused on land and water use, management on the landscape scale, and the consequences for biodiversity and the provision and resilience of ecosystem functions and services (MES, 2005). As a movable connecting avenue between various parts of the ecosystem via the hydrological cycle, changes in sediment result in both positive and negative effects for sustainability and ecological objectives. Understanding and managing the dynamic interactions of sediment on a diverse range of endpoints at the watershed scale are vital for effective sediment management (Apitz, 2011).

The geographic focus of this study, the San Francisco Bay-Delta (Bay-Delta), is home to a vulnerable ecosystem threatened by climate change, which supplies freshwater to more than 27 million people and supports diverse ecosystems that provide habitat for many endangered species. The Sacramento River is the dominant source of freshwater and sediment to the Bay-Delta (Wright & Schoellhamer, 2005). Water and sediment supply to the Bay-Delta and the coastal zone impacts primary production, delta geomorphology, human health, water quality, navigation, and flood control (Fisher et al., 1982; Milligan & Holmes, 2017; Robinson et al., 2016; Schoellhamer et al., 2018; Yang et al., 2003). The Bay-Delta is critical to the country's most productive agricultural sector in the eighth largest economy in the world (Luoma et al., 2015; Milligan & Holmes, 2017) and physically provides more than 10,000 km^2 of land for farming. Historically, the Bay-Delta was covered in more than 2,200 km^2 of marshland; yet, all but 5% have been converted to other uses (Mitsch & Hernandez, 2013). Widespread salt production and agriculture caused extensive clearing of native vegetation and diking and draining of the marshlands. Over the past several decades, the health of the Bay-Delta has been in decline (Healey et al., 2008) due to a reduction in water and sediment supply, invasive species, toxic pollutants, land use changes, levee systems in the Delta, and land subsidence from the draining of wetlands. Suspended sediment concentration (SSC) is an important estuarine health indicator (Achete et al., 2017), and sediment supply to the Bay-Delta, which is derived from the upstream watershed, has been declining over the past half-century (Stern et al., 2016; Wright & Schoellhamer, 2004). Anthropogenic and natural changes to the watershed can contribute to a decline or increase in sediment supply, which in turn impacts primary production, fish habitat conditions, contaminant transport, marshlands, and protection against sea level rise.

It is uncertain whether tidal marsh accretion in the Bay-Delta will be able to keep up with sea level rise; however, many studies have concluded that the future of tidal marshes greatly depends on sediment supply from

riverine systems (Orr et al., 2003; Stralberg et al., 2011; Swanson et al., 2014). Future assessments using climate and management scenarios are imperative to help manage the Bay-Delta during future natural and anthropogenic changes in sediment supply. The Computational Assessments of Scenarios of Change for the Delta Ecosystem (CASCaDE II, http://cascade.wr.usgs.gov/) project is composed of a diverse set of interconnected models that work together to quantify effects of climate change and management on the overall health of the San Francisco Bay-Delta ecosystem. These models include downscaled global climate models (GCMs), hydrodynamic, operational, marsh accretion, contaminants, and biological models in the Bay-Delta. In support of the CASCaDE II project, a daily watershed model of the Sacramento River Basin of northern California (Figure 1) was developed to simulate streamflow and suspended sediment transport to the Bay-Delta for the next century (water years, WY2010–2099) using the Hydrological Simulation Program—FORTRAN (HSPF).

As part of the CASCaDE II project, a calibrated hydrologic and sediment HSPF model was developed for the Sacramento River to simulate historical trends of sediment supply to the Bay-Delta (Stern et al., 2016). The modeled sediment results successfully replicated the historical decline of sediment load of ~50% over the last 50 years. The mechanisms responsible for the decline in sediment loads and SSC have been studied extensively (Schoellhamer et al., 2012; Schoellhamer et al., 2013; Wright & Schoellhamer, 2004) and have generally been found to be unrelated to changes in streamflow, although these studies did not directly consider changes in climate. Schoellhamer et al. (2018) hypothesized that sediment supply to the delta could decrease in the future but recognized that a record flood could greatly alter sediment supply. While streamflow has clearly been affected by the anthropogenic development of the Sacramento River watershed, it is likely that a combination of other factors, such as hydraulic mining, dam construction (reservoir sedimentation), land use changes, agricultural practices, logging, and river engineering works (levees, navigation dredging, etc.), and changes in climate have had a greater influence on sediment supply than streamflow. Reservoir sedimentation has been determined to be one of the main factors in the decline in sediment supply over the recent decades (Wright & Schoellhamer, 2004). However, most of the dams and river engineering works have been in place for decades, likely resulting in a sediment supply that has adjusted to their effects, as proposed by Schoellhamer et al. (2013). Future changes in streamflow will likely be a relatively dominant factor in future sediment supply.

The future of sediment supply to the Bay-Delta is largely unknown; one recent study suggested a potential increase in the next century (Schoellhamer et al., 2018). A study by Sankey et al. (2017) suggests that an increase in wildfires and burned area in the watersheds and above reservoirs will mobilize more sediment in the watershed and cause more dam sedimentation problems. Sensitivity analyses have shown that increases in storm frequency and magnitude will lead to increases in streamflow, suspended sediment concentration, and sediment discharge (Stern et al., 2016), which logically extends to a hypothesis that sediment supply could increase if (1) more precipitation falls as rain rather than snow, causing greater runoff in winter and less in spring, (2) storm intensity and frequency increases, (3) there are no changes in reservoir trapping efficiency, and (4) no more post-hydraulic mining geomorphic adjustments occur (Schoellhamer et al., 2016). Annual variability of precipitation is higher in California than the rest of the United States, and the wettest 5% of wet days contribute about a third of the annual precipitation and two-thirds of the variance (Dettinger, 2016). Contributions from the largest storms and storm intensities are expected to increase into the next century (Dettinger, 2016).

Previous studies have also proposed that there will potentially be decreases in sediment to the Bay-Delta in the future (Cloern et al., 2011; Schoellhamer, 2011; Schoellhamer et al., 2012) based on the concept that the watershed is adjusting to less sediment, and larger floods will be required to exceed greater and greater geomorphic thresholds to transport sediment. A post-settlement sediment yield equilibrium was suggested to be established in the future as the watershed response to anthropogenic and natural disturbances diminishes with time (Wright & Schoellhamer, 2004). The model presented here was developed for quantifying sediment supply from the Sacramento River Basin to the Bay-Delta based on projected climate in the 21st century and enhancing the conceptual model of future sediment transport for this region. Additionally, results from this model will be directly input to the CASCaDE II series of hydrodynamic models to study sediment processes in the tidal Bay-Delta ecosystem. Projected water and sediment supply trends for the next 100 years will help resource and land managers prepare for the effects of climate change in a complex and highly managed estuarine system.

2. Methods

A calibrated watershed and sediment transport model of the Sacramento River basin using Hydrologic Simulation Program—FORTRAN (HSPF) (Stern et al., 2016) was used to quantify hydrologic and sediment trends for the next century using 20 future climate projections. The semidistributed HSPF model requires meteorological inputs including precipitation, air temperature, and potential evapotranspiration. HSPF is a temporally continuous model that employs lumped segments for parameterization and calibration.

2.1. Watershed Model

The Sacramento River basin HSPF model was run at a daily timestep and calibrated and validated using historical climate for the period 1958–2008, as described in Stern et al. (2016). The model domain was divided into 97 subwatersheds based on geology, elevation, soils, and other physical properties that were further divided by land use type for parameterization (Stern et al., 2016). The model was calibrated and validated using 27 streamflow gages downloaded from the National Water Information System (NWIS, www.waterdata.usgs.gov), with eight of those located on the Sacramento River. Suspended sediment concentrations (SSC) and suspended sediment loads were calibrated at six different locations along the Sacramento River and 13 gages along major tributaries. A decreasing trend of historical suspended sediment loads from the Sacramento River was shown and validated by the observed sediment record trend (Wright & Schoellhamer, 2004). The calibrated model was run using downscaled climate scenarios and future reservoir outflows described in the following sections. Because the CASCaDE II project is focused on the Bay-Delta, the primary model output variables analyzed for trends were located on the Sacramento River at Freeport (watershed outlet/upstream extent of the Bay-Delta; Sacramento R A Freeport Ca; Figure 1) and included streamflow, sediment load, and suspended sediment concentration. Although improvements to climate data, hydraulic function tables, and the spatial distribution of physical properties during parameterization were employed to reduce uncertainty, many potential sources of error are inherent to watershed modeling. As a semidistributed model, parameterization of HSPF requires subwatersheds to be considered homogeneous, which could cause over-generalization and reduces the representation of heterogeneity across the landscape. A lack of calibration data for sediment, snow, and managed water sources like agricultural use and groundwater pumping also induced errors into the model. Results for streamflow calibration and validation were excellent for gages on the Sacramento River, with average daily Nash-Sutcliffe (NSE; Nash & Sutcliffe, 1970) values of 0.90, R^2 of 0.92, and mean error percent of −7% (Stern et al., 2016). Mean error percent of suspended sediment loads and SSC at the Sacramento River at Freeport gage were 10% and 7%, respectively.

2.2. Future Climate Projections

Global climate models (GCMs) are not predictions, instead they are projections that simulate many aspects of the Earth under possible future scenarios. GCMs account for the conservation of energy, mass, and momentum and how these are exchanged among different components of the climate system (Hayhoe et al., 2017). Modern GCMs can simulate many important aspects of Earth's climate including large-scale patterns of temperature and precipitation, general characteristics of storm tracks like atmospheric rivers and extratropical cyclones, and observed changes in global mean temperature and ocean heat content as a result of human emissions (Flato et al., 2013). These models are at a coarse resolution (2 degrees or roughly 220-km) and generally do not represent local fine-scale physical processes especially in variable and mountainous terrain or in areas close to the ocean.

To assess potential future trends in streamflow and sediment supply, the calibrated HSPF model was run using 20 future climate projections (scenarios) with varying air temperature and precipitation. These 20 scenarios consist of 10 GCMs; each run using two representative (greenhouse gas) concentration pathways (RCPs), RCP 4.5 and RCP 8.5. The 10 Global Climate Models (GCMs) were selected from the full CMIP5 ensemble (DWR-CCTAG, 2015) based on historical performance in simulating quantities relevant to California water resource planning (Table 1). Of the two RCPs used, RCP 8.5 represents a future with very high global population, slow economic growth and a technological change, and a high dependence on fossil fuels (Riahi et al., 2011), and RCP 4.5 represents a future in which greenhouse gas emissions are partially mitigated through technological advances and policy changes (Thomson et al., 2011).

Table 1
Ten Global Climate Models Chosen, With Modeling Center Information

Model name	Institute ID	Modeling center or group
ACCESS1.0	CSIRO-BOM	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia
CanESM2	CCCMA	Canadian Centre for Climate Modeling and Analysis
CCSM4	NCAR	National Center for Atmospheric Research, United States of America
CESM1-BGC	NSF-DOE-NCAR	National Science Foundation (NSF), Department of Energy (DOE), and National Center for Atmospheric Research (NCAR), USA; Community Earth System Model
CMCC-CMS	CMCC	Centro Euro-Mediterraneo per I Cambiamenti Climatici
CNRM-CM5	CNRM-CERFACS	Centre National de Recherches Météorologiques (CNRM) /Centre Européen de Recherche et Formation Avancée en Calcul Scientifique (CERFACS), France
GFDL-CM3	NOAA GFDL	National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory (GFDL), United States of America
HadGEM2-CC	MOHC	Met Office Hadley Centre, United Kingdom
HadGEM2-ES	MOHC	Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais), United Kingdom
MIROC5	MIROC	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology

These 20 climate scenarios were statistically downscaled using the localized constructed analog (LOCA) method described in Pierce et al. (2014) from 2 degrees (approximately 222-km) to 6-km resolution. A historical baseline climate data set from water years (WY) 1950 to 2005 (Livneh et al., 2013) was used as a training data set, and bias correction was done to correct the modeled data set of each LOCA scenario to match the statistics of the historical modeled period to the historical data for that time period (Pierce et al., 2014). The LOCA method has been shown to produce better estimates of extreme events and reduces the common downscaling problem of too many light-precipitation days (Pierce et al., 2014).

The GCM scenarios provide air temperature and precipitation, but not potential evapotranspiration (PET), which is required as an HSPF model input. Daily PET was developed using the Priestley-Taylor equation (Priestley & Taylor, 1972) and LOCA air temperature from each scenario, consistent with the PET calculations for the historical model development (Stern et al., 2016).

2.3. Watershed Model Boundary Conditions

Daily streamflow boundary conditions below each dam (Figure 1) for the historical HSPF model run were compiled and input directly to the model (Stern et al., 2016). To develop future time series of outflow for each reservoir site, a combination of models was applied to simulate future managed flows that reflected the influences of reservoir operational rules, diversions, and groundwater pumping (Knowles & Cronkite-Ratcliff, 2018). This process was three-fold. First the same GCMs used in this paper (Table 1) were downscaled using the LOCA method and were input to the Variable Infiltration Capacity Routing (RVIC) watershed model to create unimpaired streamflow estimates for the contributing watershed of each dam (Knowles & Cronkite-Ratcliff, 2018; Lohmann et al., 1996). Secondly, to calculate management operations, these unimpaired flows were routed through a modified CalSim model (C2-CalSim; Knowles & Cronkite-Ratcliff, 2018), producing monthly managed flows for each of the dam boundary conditions. Finally, to produce the necessary daily flows for HSPF, a machine learning algorithm called CRESPI (Cascade RESamPlIng; Knowles & Cronkite-Ratcliff, 2018) was implemented using flow outputs from the RVIC and C2-CalSim to produce daily managed flow estimates that were scaled to match multidecadal variability represented in the C2-CalSim outputs. A detailed explanation of each model and associated methodology can be found in Knowles and Cronkite-Ratcliff (2018). These time series outputs from the combined RVIC, C2-CalSim, and CRESPI method were input directly as daily, managed boundary conditions for each reservoir site for each future scenario and for the historical baseline. To stay consistent with the historical HSPF model (Stern et al., 2016), all dams were considered a zero-sediment boundary.

2.4. Uncertainty

Assessing uncertainty in studies that make use of GCM outputs is challenging (e.g., Knutti & Sedláček, 2013). The performance of the HSPF model used here was assessed in Stern et al. (2016). However, Hattermann et al. (2018) found that "climate model related uncertainty is so large that it obscures the

sensitivity of the hydrological system." The selection of the subset of CMIP5 models that perform best in the system under study (DWR-CCTAG, 2015) may serve to reduce this dominant uncertainty. In this paper, we present results corresponding to individual GCM runs to portray the spread and variability among the GCMs. We also present ensemble averages for the two RCPs evaluated, which provides an opportunity to assess the relative effects of the different emissions scenarios. Ensemble averaging in this manner may also further reduce uncertainty (Knutti et al., 2010).

3. Results

3.1. Changes in Temperature and Precipitation

Comparisons between each scenario's historical period (WY1980–2009) and the end-of-century 30-year period (WY2070–2099) were analyzed to quantify projected changes in climate. Figure 2 shows the change in air temperature, in degrees Celsius (C), and percent change in precipitation on the vertical axis for each of the 20 scenarios, with error bars that indicate the spatial standard deviation over the model domain. The ensemble mean in Figure 2 represents the average of all scenarios, and the ensemble means for RCP 4.5 and 8.5 are shown for visual reference. Air temperature in the Sacramento River Basin is projected to increase between 1.6- and 5.3-degrees C by end-of-century (Figure 2). The 20 climate scenarios showed consistent increases in temperature, with greater increases of air temperature under RCP 8.5. The RCP 4.5 scenarios showed an average temperature increase of 2.5 degrees C and ranged between 1.6 to 3.2 degrees C, whereas the RCP 8.5 scenarios showed an average increase of 4.3 degrees C and ranged between 3.6 degrees and 5.3 degrees C.

Average precipitation differences from each model's historical period (WY1980–2009) to the end-of-century (WY2070–2099) period for the Sacramento River Basin ranged from −10% to +30% (Figure 2). Although eight of the 20 scenarios showed decreases in precipitation by end-of-century, only two of the 20 showed decreases in annual precipitation variability calculated from the annual standard deviation. On average, RCP 4.5 scenarios showed a precipitation increase of 6.1%, whereas average RCP 8.5 scenarios increased by 7.9% by end-of-century. In addition, and notably, peak precipitation days (>95th percentile threshold calculated from the historical baseline) increased by end-of-century or stayed the same for 19 out of 20 scenarios (Figure 3). Four out the 20 scenarios showed increases in peak precipitation by over 100% by end-of-century. RCP 4.5 peak precipitation days increased on average by 51% and RCP 8.5 increased by 64% by end-of-century.
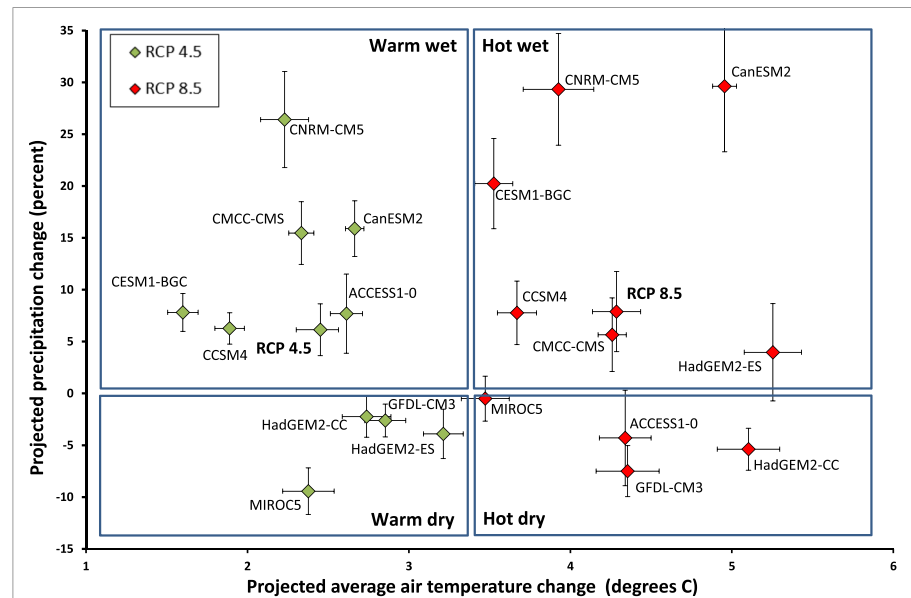

Figure 2. Projected air temperature (degrees Celsius) and precipitation (percent) changes from the historical period 1980–2009 to the end-of-century 2070–2099 period for the 20 scenarios. Runs using the two representative concentration pathways (RCP) and their ensemble averages are shown as green diamonds for RCP 4.5 and red diamonds for RCP 8.5.
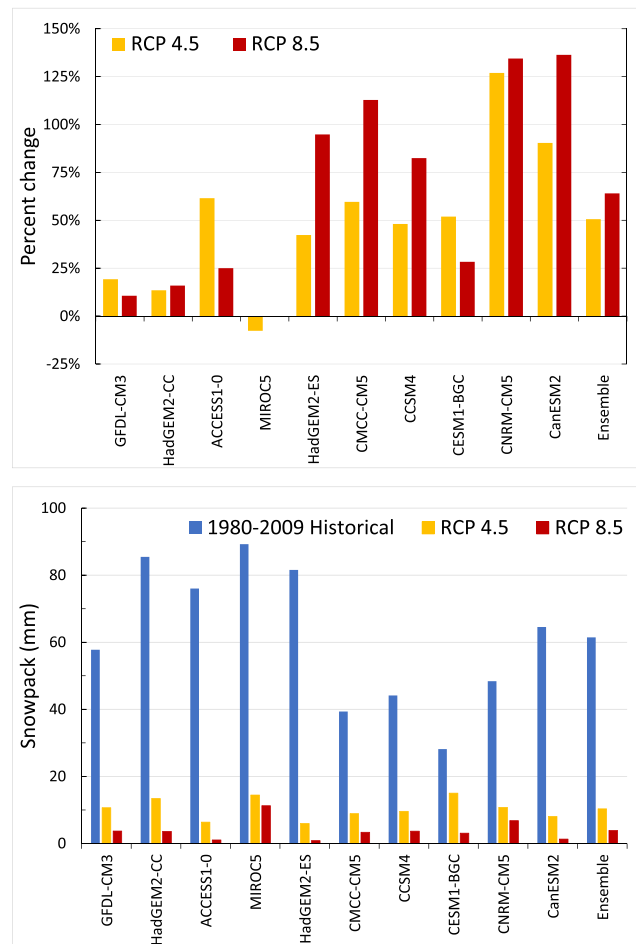
Figure 3. Percent change in peak precipitation days (>95th percentile) (top panel), April 1st snow water equivalent (mm) by end-of-century (2070–2099) (bottom panel) compared to historical baseline (1980–2009) for 10 models for representative concentration pathways (RCP) 4.5 and 8.5, and ensemble averages.

In California, snow is the primary source of surface water storage, and the April 1st snowpack measurement is a vital metric of the potential water resources available through the dry summer months. In our model domain, which is below the major reservoirs, modeled April 1st snow water equivalent (SWE) in the Sacramento River basin decreased dramatically across all future scenarios by end-of-century (Figure 3) and is consistent with other studies assessing changes in snowpack in the Sierra Nevada (Gergel et al., 2017; Rhoades et al., 2018; Thorne et al., 2015). Compared to the historical baseline for each scenario, monthly April 1st SWE by end-of-century decreased from −86% to −100% for RCP 8.5 scenarios. The number of peak streamflow days increased by 51% and 64% for RCP 4.5 and 8.5, respectively. Each scenario's historical period is from WY1980–2009, and the GCM models are bias-corrected to WY1950–2013 Livneh et al. (2013) data; therefore, the historical periods of each scenario are not identical (Figure 3, blue bars). Even with the known differences in historical SWE, the relative changes in snowpack by the end-of-century are drastic. In all cases, RCP 4.5 scenarios had the smallest increases in temperature and thus the highest amount of snowpack by the end-of-century. Changes in snowpack varied seasonally and the largest decreases in SWE were found from January through April in general, although decreases of −99% to −100% occurred frequently from July through November due to lower initial SWE values.

3.2. Changes in Streamflow

Projected precipitation changes were the main driving mechanism for changes in the magnitude of modeled streamflow. To a lesser extent, air temperature influenced streamflow by increasing evapotranspiration,

decreasing SWE, and changing the timing of snowmelt. Percent change in streamflow, peak streamflow, and sediment changes for the Sacramento River at Freeport location for mid-century (WY2040–2069) and end-of-century (WY2070–2099) compared to the historical baseline (WY1980–2009) for each scenario are shown in Table 2. Bold values indicate an overall statistically significant trend calculated using the nonparametric Spearman's Rho and Kendall Tau tests ($p < .05$) of WY1980–2099 for that constituent. On average, streamflow increased from the historical baseline to end-of-century by 4% for RCP 4.5 scenarios and 5% for RCP 8.5 scenarios. Streamflow changes varied between scenarios but generally followed projected changes in precipitation.

Current climate projections indicate increases in precipitation frequency and intensity for the Sacramento River Basin, which leads to increased peak streamflow. Figure 4 shows the RCP 8.5 monthly total number of peak streamflow days for the water year for the historical period, mid-century, and end-of-century. The historical threshold was calculated from the top 5% of flows in the historical baseline. Seasonal changes in streamflow by end-of-century from the historical baseline are evident across all scenarios, which affects the timing of water resources, water quality, and water temperature through the end of the warm season. RCP 4.5 and 8.5 scenarios showed average increases in peak streamflows of 62% and 96%, respectively. The monthly hydrologic timing varied between scenarios, but on average, peak streamflows increased in all months compared to the historical period of each scenario, and the RCP 8.5 ensemble showed more peak streamflow days than the RCP 4.5 ensemble (Figure 4). RCP 4.5 scenarios showed variable shifts in hydrologic timing, and several scenarios showed increases in December and May whereas only one RCP 8.5 scenario showed an increase in May. Most scenarios showed increases of peak streamflows in February and March and almost no increases in April. By the end-of-century, mean streamflow decreased in eight out of the 20 scenarios; yet, only one out of 20 scenarios showed a decrease in peak streamflow, commensurate with an increase in precipitation variability (Table 2).

Table 2
Percent Change From Historical Baseline for 10 Models With Two Representative Concentration Pathways (RCP) Each and Ensemble Averages for Streamflow, Peak Streamflow (>95th Percentile), Sediment Load, and Suspended Sediment Concentration (SSC)

		Percent change from historical baseline							
		RCP 4.5				RCP 8.5			
		Streamflow	Peak streamflow	Sediment load	SSC	Streamflow	Peak streamflow	Sediment load	SSC
GFDL-CM3	Mid	1	46	4	−2	8	71	16	5
	End	−1	22	−2	−4	−5	38	1	−8
HadGEM2-CC	Mid	9	95	48	9	1	**43**	16	1
	End	−1	39	26	−1	−6	**70**	27	−9
ACCESS 1–0	Mid	12	**199**	62	13	−8	40	7	−9
	End	6	**141**	44	7	−10	29	−13	−13
MIROC5	Mid	0.2	−11	8	2	−7	−32	−12	−7
	End	−9	−29	−23	−11	0.5	11	10	1
HadGEM2-ES	Mid	**−10**	18	0.3	**−12**	−12	13	−10	−15
	End	**−10**	35	4	**−13**	−4	79	46	−3
CMCC-CMS	Mid	−4	−11	−2	−5	10	76	47	12
	End	10	61	50	11	4	90	53	4
CCSM4	Mid	−0.5	42	26	−2	8	**120**	49	6
	End	5	76	33	2	8	**148**	72	6
CESM1-BGC	Mid	1	13	13	1	**5**	**29**	**19**	**5**
	End	7	46	48	9	**19**	**106**	**94**	**24**
CNRM-CM5	Mid	**17**	**105**	**119**	**23**	**25**	**174**	**124**	**28**
	End	**22**	**129**	**133**	**30**	**27**	**233**	**194**	**35**
CanESM2	Mid	**11**	**88**	**55**	**13**	**20**	**125**	**129**	**27**
	End	**12**	**99**	**76**	**15**	**18**	**159**	**201**	**29**
Ensemble	Mid	4	**58**	**33**	4	5	**66**	**38**	5
	End	4	**62**	**39**	5	5	**96**	**69**	7

Note. Mid = water years 2040–2069, End = water years 2070–2099. Highlighted and bold values indicate significant (p < .05) increasing or decreasing annual trends from water years 1980–2099.
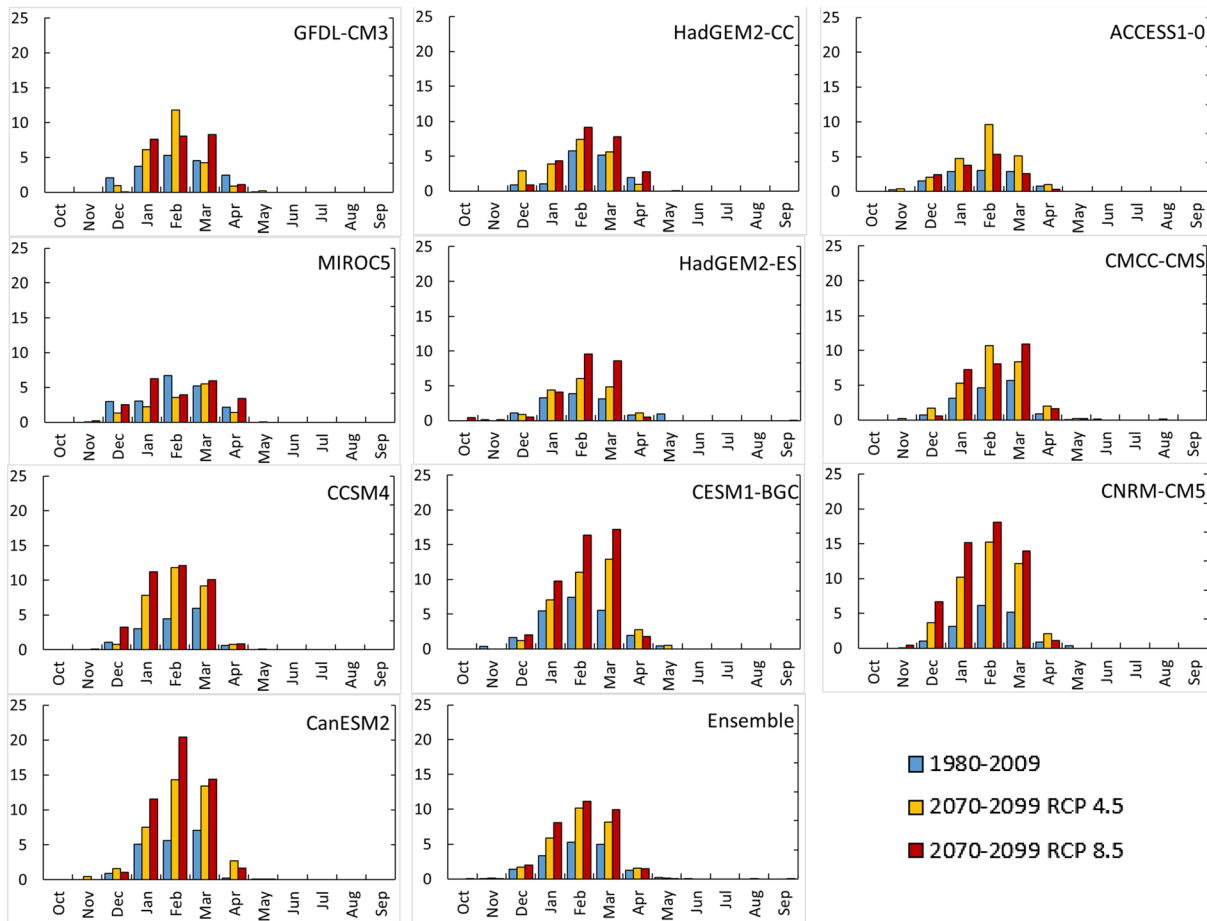
Figure 4. Average number of peak streamflow days (>95th percentile) per month for the 2070–2099 30-year period compared to the historical baseline, for each scenario, and for ensemble averages.

3.3. Changes in Sediment Discharge and Suspended Sediment Concentrations

The changes in precipitation and air temperature had varying effects on flow, sediment, and suspended sediment concentration (SSC); however, mean sediment loads were more sensitive to changes in climate than mean streamflow and SSC. Increases in sediment loads were on the same order of magnitude as changes in peak streamflow, whereas increases in streamflow and SSC were much lower. The average results from the RCP 4.5 and 8.5 scenarios indicated a +39% and +69% increase in sediment load by the end-of-century compared to the historical baseline, respectively. SSC varied by scenario but increased on average by +5% and +7% for RCP 4.5 and 8.5 scenarios, respectively. Across the individual scenarios, SSC changes ranged from −13 to +35%. To assess trends of sediment supply to the Bay-Delta, streamflow and sediment were tested for trends using Spearman's R and Kendall's Tau tests over the WY1980–2099 period. The RCP 4.5 and 8.5 ensembles and five out of 20 individual scenarios had statistically significant increases in sediment loads ($p < .05$, Table 2). The RCP 4.5 and 8.5 ensemble averages showed statistically significant increasing sediment load without a corresponding increasing trend in average streamflow (Table 2), likely due to increases in peak streamflow. One out of 20 scenarios showed a statistically decreasing trend of SSC and a decreasing trend of mean streamflow.

Although there is interannual variability within each scenario and variability between scenarios, RCP 4.5 and 8.5 ensemble averages both showed that changes in precipitation and precipitation variability lead to changes in sediment transport. Figure 5 shows the annual sediment load time series from WY1980–2099 for the individual RCP 4.5 (top panel) and RCP 8.5 (bottom panel) scenarios, with a 30-year running average in blue (RCP 4.5 ensemble) or red (RCP 8.5 ensemble). Ensemble averages showed statistically significant increasing trends in sediment transport and increases of peak streamflow ($p < .05$), indicating an
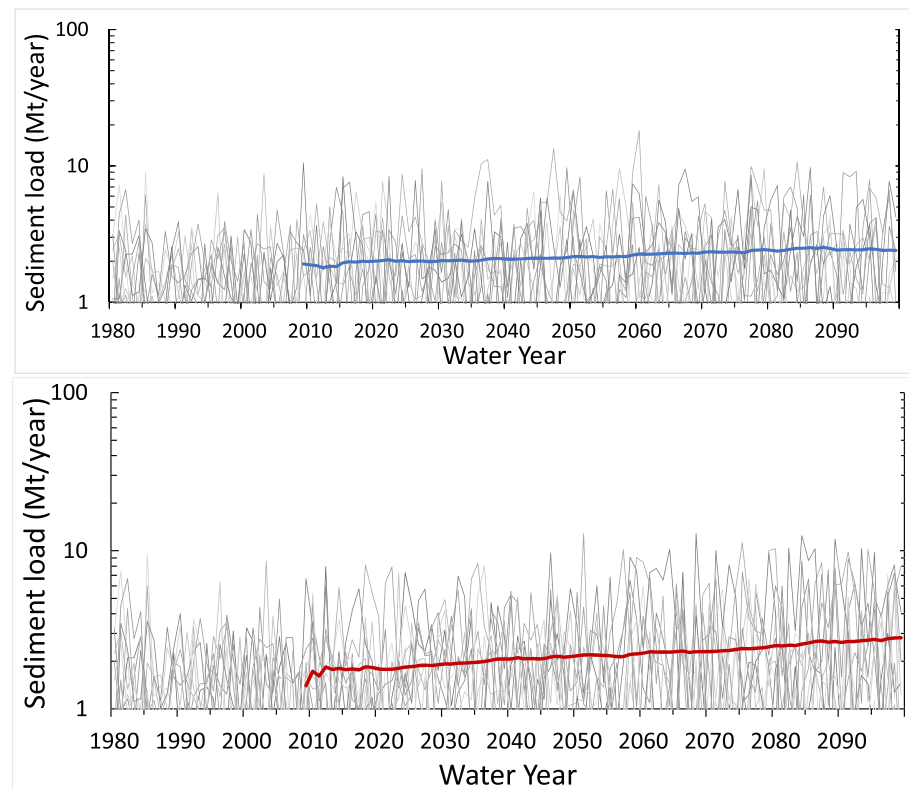
Figure 5. Total annual sediment load (million metric tons, Mt) for the Sacramento River at Freeport location, for representative concentration pathway (RCP) 4.5 scenarios (gray lines) with 30-year running average for RCP 4.5 ensemble in blue (top panel) and RCP 8.5 scenarios (gray lines) and 30-year running average for RCP 8.5 ensemble in red (bottom panel).

increased range of future streamflow conditions and sediment loads and higher peak discharges of flow and sediment.

To assess the probability of larger magnitude sediment events by the end-of-century, sediment exceedance curves were calculated for the end-of-century period for each of the RCP 4.5 and 8.5 scenarios and are shown with the historical baseline (WY1980–2009) for visual reference in Figure 6. RCP 4.5 and 8.5 ensembles are shown in blue and red, respectively. Exceedance curves describe the probability of an event for a certain threshold and show a shift in future sediment events. The larger, less frequent sediment events are projected to become more common and higher magnitude in all 20 scenarios, even in the drier scenarios (Figure 6). The increases of the largest sediment events (top 1st–2nd percentile) result in most cases in much higher sediment transport magnitudes than have occurred historically, in some cases two to three times higher, which could lead to physical and ecological implications for resource managers. Six of the wettest scenarios showed a dramatic shift in sediment supply for nearly all event frequencies, although most of the scenarios were lower than the historical baseline for the lower frequency (~4th–20th percentile) events. The RCP 4.5 ensemble was higher in sediment transport for most exceedances and diverged from the historical baseline at the less frequent, larger events. The 8.5 ensemble showed larger sediment transport events than the historical average, for all event frequencies. Notably, the drier scenarios showed less sediment transport in the middle of the curve (medium frequency events) and indicated more sediment being transported during small and less frequent events, increasing the variability of sediment transport depending on the exceedance event type.

4. Discussion and Conclusions

The global climate model (GCM) results for the Sacramento River Basin indicate that 60% of scenarios projected increases in average precipitation, with a general model consensus of increased peak precipitation,
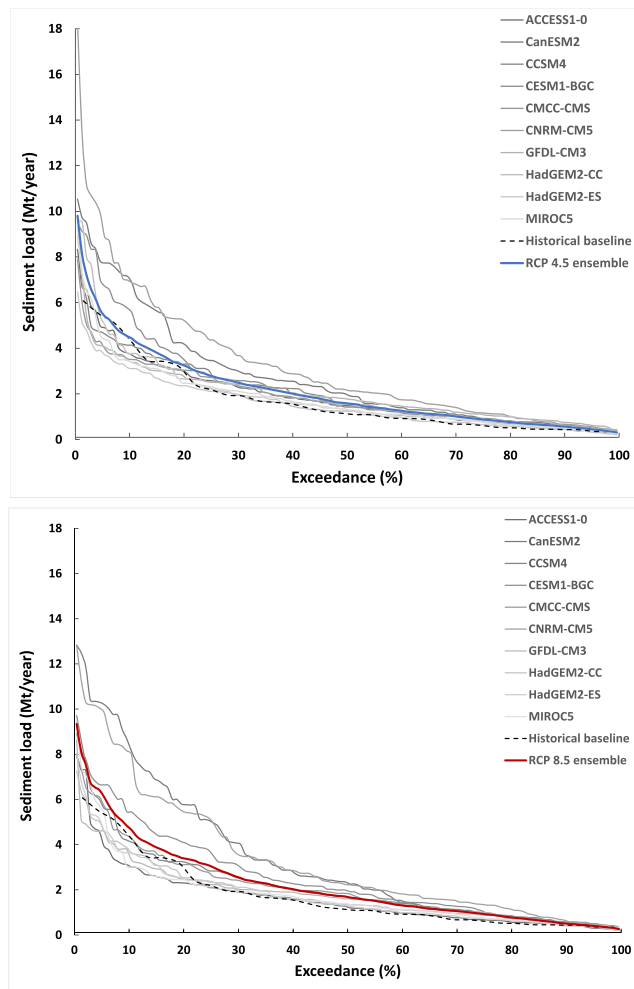
Figure 6. Sediment load exceedance curves (Mt, million metric tons/year) for the 10 models for representative concentration pathway (RCP) 4.5 (top panel) and RCP 8.5 (bottom panel) from water years 1980–2099 and the historical baseline (water years 1980–2009, black dashed line) for visual reference.

and an all model consensus of increased temperatures, with varying magnitudes that broadly depend on representative concentration pathway (RCP). At the Sacramento River at Freeport location, the primary source of freshwater and sediment to the Bay-Delta, model results indicated significant and surprising changes to projected streamflow and sediment transport. Although snow is a small component of the water balance within the model boundary due to the low average elevation, the snow water equivalent decreased dramatically in all scenarios, indicating a potential shift of hydrologic timing to less flow in the summer months and more peak streamflows in January through March. Streamflow, sediment loads, and suspended sediment concentrations (SSCs) increased on average across all scenarios but varied greatly depending on the scenario. The RCP 4.5 and 8.5 scenarios showed average increases of +4% and +5% for streamflow, +62% and +96% for peak streamflow, +5% and +7% for SSC, and +39% and +69% for sediment loads, respectively, by end-of-century compared to the historical baseline. Five scenarios had statistically significant increasing trends for sediment and SSC. Peak streamflow had statistically significant increases for eight out of the 20 scenarios by end-of-century whereas mean streamflow increased in six of the 20 scenarios. RCP 4.5 and 8.5 ensemble averages showed statistically significant increases in sediment load and peak streamflow but not in average streamflow or SSC.

Increases in peak precipitation days for 18 out of 20 scenarios indicate the likelihood of more high flow events than historically, even in the drier scenarios where the high flow events may occur between an

increasing number of dry days. These peak precipitation events can generally be classified as landfalling atmospheric rivers, the source of the largest storms and floods on the West Coast. Atmospheric river magnitude and frequencies are projected to increase in the next century for the majority of the ten GCMs, which further increases the role of these large storms to determine the occurrence of extended wet periods or prolonged droughts (Dettinger, 2016). An increase in the number of peak precipitation days increased the number of peak streamflow days (>95th percentile) for most scenarios by the end of the century, which led to increases in sediment loads. Several scenarios produced decreases in mean streamflow; however, these scenarios had increases in sediment loads due to the increase in peak streamflow days. The potential projected changes in sediment loads to the Bay-Delta are consistent with a recent study (Schoellhamer et al., 2018) that provided several possible explanations for increasing sediment supply by the end-of-century. One such explanation is that HSPF is not able to model changes in reservoir trapping efficiency and post-hydraulic mining geomorphic adjustments. However, the model can assess changes due to climate variability such as precipitation falling as snow and intensity of storms. Stern et al. (2016) found that sediment supply is sensitive to changes in climate and SWE. In this study we found an increase of sediment loads and SSC to the Bay-Delta by end-of-century for most of the scenarios and statistically significant increases in five out of the 20 scenarios and both RCP ensemble averages.

Significant consequences arise from either too much or too little sediment. Although we found statistically significant increases in five of the 20 scenarios and the RCP 4.5 and 8.5 ensembles, the nonsignificant trends of a leveling off or decline of sediment are also plausible outcomes. A leveling off or continued decline of sediment could significantly deteriorate the health and resiliency of the Bay-Delta as the climate continues to change. Increases in the most intense and frequent storms and atmospheric rivers projected in most scenarios would generate an increased amount of runoff and sediment transport. Temperature increases lead to earlier snow melt and therefore create larger magnitude floods earlier in the wet season and thus higher sediment loads than previously experienced in the watershed. The risk of increased intense flooding imposes additional failure risk to the Bay-Delta levees, dams, and other infrastructure components that are already in need of reinforcing and repair. Water quality may become an increased concern with higher sediment loads since sediment can transport contaminants such as pesticides, herbicides, nutrients, and mercury.

The projections of increased sediment supply to the Bay-Delta indicated by our results would help bolster the resilience of marshes against sea level rise by aiding in marsh accretion. Maintaining marshes longer into the century sustains the habitat of many native fish and bird species that could otherwise be lost. Tidal flats and beaches in the San Francisco Bay rely on a constant sediment supply to be sustained, and the threshold rate of sea level rise resistance is typically dependent on sediment availability (Kirwan & Megonigal, 2013). Some fish species depend on turbid waters to reduce the risk of predation, as well as potential increased deposition of spawning gravels with very high flow events. Excessive fine-grained sediment can clog spawning gravels for salmon. Too much sediment increases light attenuation and could have adverse effects on benthic organisms and thus the rest of the food web in the Bay-Delta.

There are many sources of uncertainty and limitations of this study, including the future climate scenarios (as discussed in section 2.4), the model input data, the HSPF model parameterization, and the observed calibration data. The main sources of error pertaining to the historical HSPF model are described in Stern et al. (2016) and include model input data uncertainties, model assumptions, parameter uncertainty, and a lack of calibration data including diversions and groundwater pumping. One model assumption was to keep the same parameters used in the historical run for future runs except to ensure negative sediment discharge values did not occur, which can happen if too much scour is modeled in a stream segment. This could lead to an overestimation of sediment load in some of the future scenarios; however, the HSPF model also cannot account for levee failure, dam overtopping, increased sediment transport from wildfires, and other large-scale mass sediment events. These events are infrequent but could become more commonplace in the future due to increased climate variability and increased peak streamflows coupled with an aging flood protection system. These events can potentially contribute large amounts of sediment that would counteract any apparent bias to an overestimation of modeled sediment loads and SSC in the future. Stationarity is a concern for this type of modeling, and no land use changes were considered for this study due to a lack of data projecting future changes. To help mitigate stationarity of model inflows from dam releases, a model to assess changes in reservoir management was developed using the best possible data and the current

rules for each dam. Uncertainty analyses regarding climate scenarios and future boundary conditions are detailed in Pierce et al. (2014) and Knowles and Cronkite-Ratcliff (2018).

Even with the many caveats and assumptions of the combined modeling approach described here, results of the scenarios can be useful to managers who need to plan for the middle- and long-term time scales. Projected increases in peak flows and sediment suggest a number of possible management actions, including floodplain restoration to capture sediment during peak events, increasing groundwater recharge to manage peak flows and prepare for droughts, and bolstering flood control structures.

Ultimately, as a connecting mechanism between various parts of the ecosystem through the hydrological cycle, increased peak flows and sediment transport would impact tidal and sediment dynamics in the Bay-Delta in various positive and negative ways. However, the HSPF model is one-dimensional and cannot directly assess questions about a complex tidal environment related to sea-level rise, contaminant transport, nutrient cycling, fish habitat, and marsh accretion. The ability to answer these questions relies on future climate, streamflow, and sediment supply to the Bay-Delta. Results from this model are used as inputs to a hydrodynamic model (Martyr-Koller et al., 2017) to assess tidal sediment dynamics in the Bay-Delta. The hydrodynamic results will aid in modeling the effects of climate change on the ecosystem and food web for the next century. Issues facing the Bay-Delta are relevant to other vulnerable deltaic environments around the word like the Mississippi River delta, mangroves in the Pacific, the Nile River delta, and the Parnaiba River delta. Extensive coastal development, urbanization, climate change, and sea level rise threaten diverse deltaic ecosystems around the world. Understanding geomorphic function of these deltaic systems under potential future climate conditions can help resource managers decide on effective measures to support and promote ecologic and sediment processes into the next century.

References

Achete, F., Van der Wegen, M., Roelvink, J. A., & Jaffe, B. (2017). How can climate change and engineered water conveyance affect sediment dynamics in the San Francisco Bay-Delta system? *Climatic Change*, *142*(3–4), 375–389. https://doi.org/10.1007/s10584-017-1954-8

Apitz, S. E. (2011). Conceptualizing the role of sediment in sustaining ecosystem services: Sediment-ecosystem regional assessment (SEcoRA). *Science of the Total Environment*, *415*, 9–30.

Blum, M. D., & Roberts, H. H. (2009). Drowning of the Mississippi Delta due to insufficient sediment supply & global sea-level rise. *Nature Geoscience*, *2*(7), 488–491. https://doi.org/10.1038/ngeo553

Cloern, J. E., Knowles, N., Brown, L. R., Cayan, D., Dettinger, M. D., Morgan, T. L., et al. (2011). Projected evolution of California's San Francisco Bay-Delta-River system in a century of climate change. *PLoS ONE*, *6*(9), e24465. https://doi.org/10.1371/journal.pone.0024465

Crooks, S., Herr, D., Tamelander, J., Laffoley, D., & Vandever, J. (2011). *Mitigating climate change through restoration and management of coastal wetlands and near-shore marine ecosystems: Challenges and opportunities (Environment Department Paper 121)*. Washington, DC: World Bank.

Dettinger, M. (2016). Historical and future relations between large storms and droughts in California. *San Francisco Estuary and Watershed Science*, *14*(2). https://doi.org/10.15447/sfews.2016v14iss2art1

DWR-CCTAG: California Department of Water Resources-Climate Change Technical Advisory Group (2015). Perspectives and Guidance for Climate Change Analysis. California Department of Water Resources Technical Information Record, 142 p.

Faraco, L. F. D., Andriguetto-Filho, J. M., & Lana, P. C. (2010). A methodology for assessing the vulnerability of mangroves and fisherfolk to climate change. *Pan-American Journal of Aquatic Sciences*, *5*, 205–223.

Fisher, T. R., Carlson, P. R., & Barber, R. T. (1982). Sediment nutrient regeneration in three North Carolina estuaries. *Estuarine, Coastal and Shelf Science*, *14*(1), 101–116. https://doi.org/10.1016/S0302-3524(82)80069-8

Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S. C., Collins, W., et al. (2013). In K. M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P. M. Midgley (Eds.), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK, and New York, NY: Cambridge University Press.

Gergel, D. R., Nijssen, B., Abatzoglou, J. T., Lettenmaier, D. P., & Stumbaugh, M. R. (2017). Effects of climate change on snowpack and fire potential in the western USA. *Climatic Change*, *141*(2), 287–299. https://doi.org/10.1007/s10584-017-1899-y

Gilman, E., Ellison, J. C., Duke, N. C., Field, C., & Fortuna, S. (2008). Threats to mangroves from climate change and adaptation options: A review. *Aquatic Botany*, *89*(2), 237–250. https://doi.org/10.1016/j.aquabot.2007.12.009

Giosan, L., Syvitski, J., Constantinescu, S., & Day, J. (2014). Climate change: Protect the world's deltas. *Nature News*, *516*(7529), 31–33. https://doi.org/10.1038/516031a

Hattermann, F. F., Vetter, T., Breuer, L., Su, B., Daggupati, P., Donnelly, C., et al. (2018). Sources of uncertainty in hydrological climate impact assessment: A cross-scale study. *Environmental Research Letters*, *13*(1). https://doi.org/10.1088/1748-9326/aa9938

Hayhoe, K., Edmonds, J., Kopp, R., LeGrande, A., Sanderson, B., Wehner, M., & Wuebbles, D. (2017). Climate models, scenarios, and projections, Publications, Agencies and Staff of the U.S. Department of Commerce. 589. In D. J. Wuebbles et al., (Eds.), *Climate science special report: A sustained assessment activity of the U.S. Global Change Research Program* (pp. 186–227). Washington, DC: U.S. Global Change Research Program. https://digitalcommons.unl.edu/usdeptcommercepub/589

Healey, M. C., Dettinger, M. D., & Norgaard, R. B. (2008). *The state of Bay-Delta Science, 2008* (pp. 174). Sacramento, CA: CALFED Science Program.

Kirwan, M. L., & Megonigal, J. P. (2013). Tidal wetland stability in the face of human impacts and sea-level rise. *Nature*, *504*(7478), 53–60. https://doi.org/10.1038/nature12856

Knowles, N. & Cronkite-Ratcliff, C. (2018). Modeling Managed Flows in the Sacramento/San Joaquin Watershed under Scenarios of Future Change for CASCaDE. *US Geological Survey Open File Report* No 2018–1101, https://doi.org/10.3133/ofr20181101

Knutti, R., Furrer, R., Tebaldi, C., Cermak, J., & Meehl, G. H. (2010). Challenges in combining projections from multiple climate models. *Journal of Climate*, *23*, 2739–2758. https://doi.org/10.1175/2009JCLI3361.1

Knutti, R., & Sedláček, J. (2013). Robustness and uncertainties in the new CMIP5 climate model projections. *Nature Climate Change*, *3*(4), 369. https://doi.org/10.1038/nclimate1716

Krauss, K. W., McKee, K. L., Lovelock, C. E., Cahoon, D. R., Saintilan, N., Reef, R., & Chen, L. (2014). How mangrove forests adjust to rising sea level. *New Phytologist*, *202*(1), 19–34. https://doi.org/10.1111/nph.12605

Livneh, B., Rosenberg, E. A., Lin, C., Mishra, V., Andreadis, K., Maurer, E. P., & Lettenmaier, D. P. (2013). A long-term hydrologically based dataset of land surface fluxes and states for the conterminous U.S.: Update and extensions. *Journal of Climate*, *26*(23), 9384–9392. https://doi.org/10.1175/JCLI-D-12-00508.1

Lohmann, D., Nolte-Holube, R., & Raschke, E. (1996). A large-scale horizontal routing model to be coupled to land surface parametrization schemes. *Tellus*, *48*(5), 708–721. https://doi.org/10.1034/j.1600-0870.1996.t01-3-00009.x

Luoma, S. N., Dahm, C. N., Healey, M., & Moore, J. N. (2015). Challenges facing the Sacramento–San Joaquin Delta: Complex, chaotic, or simply cantankerous? *San Francisco Estuary and Watershed Science*, *13*(3). https://doi.org/10.15447/sfews.2015v13iss3art7

Martyr-Koller, R. C., Kernkamp, H., van Dam, A., van der Wegen, M., Lucas, L. V., Knowles, N., et al. (2017). Application of an unstructured 3D finite-volume numerical model for hydrodynamic and water-quality transport in the San Francisco Bay-Delta System. *Estuarine, Coastal and Shelf Science*, *192*, 86–107. https://doi.org/10.1016/j.ecss.2017.04.024

MES (2005). *Ecosystems and human well-being: General synthesis. Millennium Ecosystem Assessment* (pp. 160). Washing, DC: Island Press.

Milligan, B., & Holmes, R. (2017). Sediment is critical infrastructure for the future of California's Bay-Delta. *Shore & Beach*, *85*(2).

Mitsch, W. J., & Hernandez, M. E. (2013). Landscape and climate change threats to wetlands of north and Central America. *Aquatic Sciences*, *75*(1), 133–149. https://doi.org/10.1007/s00027-012-0262-7

Nash, J. E., & Sutcliffe, J. V. (1970). River flow forecasting through conceptual models, I. A discussion of principles. *Journal of Hydrology*, *10*, 282–290.

Orr, M. K., Crooks, S., & Williams, P. B. (2003). Will restored tidal marshes be sustainable? *San Francisco Estuary and Watershed Science*, *1*(1). https://doi.org/10.15447/sfews.2003v1iss1art5

Pierce, D. W., Cayan, D. R., & Thrasher, B. L. (2014). Statistical downscaling using LOcalized Constructed Analogs (LOCA). *Journal of Hydrometeorology*, *15*(6), 2558–2585. https://doi.org/10.1175/JHM-D-14-0082.1

Porterfield, G. (1980). Sediment transport of streams tributary to San Francisco, San Pablo, and Suisun Bays, California, 1909–66. *U.S. Geological Survey Water-Resources Investigations Report*, *80*(64), 92.

Priestley, C. H. B., & Taylor, R. J. (1972). On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Review*, *100*, 81–92. https://doi.org/10.1175/1520-0493(1972)100<0081:OTAOSH>2.3.CO;2

Rhoades, A. M., Jones, A. D., & Ullrich, P. A. (2018). The changing character of the California Sierra Nevada as a natural reservoir. *Geophysical Research Letters*, *45*, 13,008–13,019. https://doi.org/10.1029/2018GL080308

Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., et al. (2011). RCP 8.5—A scenario of comparatively high greenhouse gas emissions. *Climatic change*, *109*(1–2), 33. https://doi.org/10.1007/s10584-011-0149-y

Robinson, A., Richey, A., Cloern, J. E., Boyer, K. E., Burau, J., Canuel, E., et al. (2016). Primary production in the Sacramento-San Joaquin Delta: A science strategy to quantify change and identify future potential. *Prepared with funding from the U.S. Geological Survey and the Delta science program*. A report of SFEI-ASC's resilient landscapes program, publication #781, Richmond, CA: San Francisco Estuary Institute-Aquatic Science Center.

Sankey, J. B., Kreitler, J. T., Hawbaker, J., McVay, J. L., Miller, M. E., Mueller, E. R., et al. (2017). Climate, wildfire, and erosion ensemble foretells more sediment in western USA watersheds. *Geophysical Research Letters*, *44*, 8884–8892. https://doi.org/10.1002/2017GL073979

Schoellhamer, D., McKee, L., Pearce, S., Kauhanen, P., Salomon, M., Dusterhoff, S., et al. (2018). *Sediment Supply to San Francisco Bay (SFEI Contribution No. 842)*. Richmond, CA: San Francisco Estuary Institute.

Schoellhamer, D. H. (2011). Sudden clearing of estuarine waters upon crossing the threshold from transport to supply regulation of sediment transport as an erodible sediment pool is depleted: San Francisco Bay, 1999. *Estuaries and Coasts*, *34*(5), 885–899. https://doi.org/10.1007/s12237-011-9382-x

Schoellhamer, D. H., Wright, S. A., & Drexler, J. Z. (2012). A Conceptual Model of Sedimentation in the Sacramento-San Joaquin Delta. *San Francisco Estuary and Watershed Science*, *10*(3), 1–25. https://doi.org/10.15447/sfews.2012v10iss3art3

Schoellhamer, D. H., Wright, S. A., & Drexler, J. Z. (2013). Adjustment of the San Francisco estuary and watershed to decreasing sediment supply in the 20th century. *Marine Geology*, *345*, 63–71. https://doi.org/10.1016/j.margeo.2013.04.007

Schoellhamer, D. H., Wright, S. A., Monismith, S. G., & Bergamaschi, B. A. (2016). Recent advances in understanding flow dynamics and transport of water-quality constituents in the Sacramento–San Joaquin River Delta. *San Francisco Estuary and Watershed Science*, *14*(4). https://doi.org/10.15447/sfews.2016v14iss4art1

Stern, M. A., Flint, L. E., Minear, J., Flint, A. L., & Wright, S. A. (2016). Characterizing changes in streamflow and sediment supply in the Sacramento River basin, California, using hydrological simulation program—FORTRAN (HSPF). *Water*, *8*(10) 432 p, 432. https://doi.org/10.3390/w8100432

Stralberg, D., Brennan, M., Callaway, J. C., Wood, J. K., Schille, L. M., Jongsomjit, D., et al. (2011). Evaluating tidal marsh sustainability in the face of sea-level rise: A hybrid modeling approach applied to San Francisco Bay. *PLoS ONE*, *6*(11), e27388. https://doi.org/10.1371/journal.pone.0027388

Swanson, K. M., Drexler, J. Z., Schoellhamer, D. H., Thorne, K. M., Casazza, M. L., Overton, C. T., et al. (2014). Wetland Accretion Rate Model of Ecosystem Resilience (WARMER) and its application to habitat sustainability for endangered species in the San Francisco Estuary. *Estuaries and Coasts*, *37*(2), 476–492. https://doi.org/10.1007/s12237-013-9694-0

Syvitski, J. P. M., Kettner, A. J., Overeem, I., Hutton, E. W., Hannon, M. T., Brakenridge, G. R., et al. (2009). Sinking deltas due to human activities. *Nature Geoscience*, *2*(10), 681–686. https://doi.org/10.1038/ngeo629

Thomson, A. M., Calvin, K. V., Smith, S. J., Kyle, G. P., Volke, A., Patel, P., et al. (2011). RCP4. 5: A pathway for stabilization of radiative forcing by 2100. *Climatic change*, *109*(1-2), 77. https://doi.org/10.1007/s10584-011-0151-4

Thorne, J. H., Boynton, R. M., Flint, L. E., & Flint, A. L. (2015). The magnitude and spatial patterns of historical and future hydrologic change in California's watersheds. *Ecosphere*, *6*(2), 1–30.

UNEP (2006). Marine and coastal ecosystems and human well-being: A synthesis report based on the findings of the Millennium Ecosystem Assessment. UNEP. 76 p.

Ward, R. D., Friess, D. A., Day, R. H., & MacKenzie, R. A. (2016). Impacts of climate change on mangrove ecosystems: A region by region overview. *Ecosystem Health and Sustainability*, *2*(4).

Wright, S. A., & Schoellhamer, D. H. (2004). Trends in the sediment yield of the Sacramento River, California, 1957–2001. *San Francisco Estuary and Watershed Science*, *2*(2). https://doi.org/10.15447/sfews.2004v2iss2art2

Wright, S. A., & Schoellhamer, D. H. (2005). Estimating sediment budgets at the interface between rivers and estuaries with application to the Sacramento-San Joaquin River Delta. *Water Resources Research*, *41*, W09428. https://doi.org/10.1029/2004WR003753

Yang, S. L., Belkin, I. M., Belkina, A. I., Zhao, Q. Y., Zhu, J., & Ding, P. X. (2003). Delta response to decline in sediment supply from the Yangtze River: Evidence of the recent four decades and expectations for the next half-century. Estuarine. *Coastal and Shelf Science*, *57*(4), 689–699. https://doi.org/10.1016/S0272-7714(02)00409-2