Amplified Impact of Climate Change on Fine-Sediment Delivery to a Subsiding Coast, Humboldt Bay, California

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Abstract

In Humboldt Bay, tectonic subsidence exacerbates sea-level rise (SLR). To build surface elevations and to keep pace with SLR, the sediment demand created by subsidence and SLR must be balanced by an adequate sediment supply. This study used an ensemble of plausible future scenarios to predict potential climate change impacts on suspended-sediment discharge (Q_{ss}) from fluvial sources. Streamflow was simulated using a deterministic water-balance model, and Q_{ss} was computed using statistical sediment-transport models. Changes relative to a baseline period (1981–2010) were used to assess climate impacts. For local basins that discharge directly to the bay, the ensemble means projected increases in Q_{ss} of 27% for the mid-century (2040–2069) and 58% for the end-of-century (2070–2099). For the Eel River, a regional sediment source that discharges sediment-laden plumes to the coastal margin, the ensemble means projected increases in Q_{ss} of 53% for the mid-century and 99% for the end-of-century. Climate projections of increased precipitation and streamflow produced amplified increases in the regional sediment supply that may partially or wholly mitigate sediment demand caused by the combined effects of subsidence and SLR. This finding has important implications for coastal resiliency. Coastal regions with an increasing sediment supply may be more resilient to SLR. In a broader context, an increasing sediment supply from fluvial sources has global relevance for communities threatened by SLR that are increasingly building resiliency to SLR using sediment-based solutions that include regional sediment management, beneficial reuse strategies, and marsh restoration.

Keywords Climate change · Suspended-sediment discharge · Subsidence · Sea-level rise · Resiliency · Humboldt Bay

Highlights

- Future projections of increased streamflow produced amplified increases in suspended-sediment discharge.
- Projected increases in suspended-sediment discharge may mitigate sediment demand created by subsidence and sea-level rise.
- Coastal regions with an increasing sediment supply may be more resilient to sea-level rise.

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Introduction

In Humboldt Bay, California, sea-level rise (SLR) includes the combined effect of global SLR and vertical land motion caused by local tectonic subsidence (Clarke and Carver 1992; Valentine et al. 2012). In places like Humboldt Bay, where relative SLR (4.7 ± 1.5 mm/yr) is higher than regional averages due to tectonic subsidence (Russell and Griggs 2012; Montillet et al. 2018), an adequate sediment supply is vital for maintaining surface elevations and keeping pace with SLR.

Although sediment has long been considered a resource (Owens et al. 2008), accelerated rates of sea-level rise (SLR) produced a transition in thinking (Goodrich and Warrick 2015). Maintaining an adequate sediment supply is now considered to be a fundamental strategy for adapting to SLR (Nicholls 2018). Historically, grey infrastructure was used for shoreline protection, but sediment-based solutions (Ganju 2019), which include regional sediment management (Rosati et al. 2004) and beneficial reuse through marsh restoration (Hill 2011; CA-CSMW 2012), are now widely accepted

adaptation strategies for building resiliency in coastal ecosystems threatened by SLR (Powell et al. 2019).

The impact of climate change on sediment yield from fluvial sources is well documented (Langbein and Schumm 1958; Walling and Webb 1996; Coulthard et al. 2012; Li and Fang 2017; Dunn et al. 2019), but evaluating the sustainability of sediment-based solutions within the context of regional sediment budgets (Rosati 2005) represents a critical knowledge gap (Ganju 2019). The conservation of mass principle requires that sediment influx, efflux, and changes in stored sediment must balance across an ecosystem boundary. Without an adequate sediment supply, an increase in sediment demand caused by subsidence, SLR, and tidal prism expansion can produce morphological and ecological responses (Friedrichs and Perry 2001; Ganju and Schoellhamer 2010; Mariotti and Carr 2014; Kirwan et al. 2016; Hopkinson et al. 2018).

In coastal communities threatened by SLR, there is an ongoing need to provide local projections of sediment supply under future climate conditions to guide the implementation of sustainable adaptation strategies to mitigate SLR impacts. Saltmarsh restoration, and associated blue carbon sequestration, is an adaptation strategy that is particularly well-suited for building shoreline protection and resiliency to SLR, while mitigating the impact of extreme events through wave attenuation, shoreline stabilization, and floodwater retention (Shepard et al. 2011; Leonardi et al. 2016; Nicholls 2018). Resiliency in this context is defined as the capacity of salt marshes to accrete sediment, gain elevation, and keep pace with SLR while providing coastal protection and maintaining critical ecological services (Barbier et al. 2011).

Rates of marsh accretion, surface elevation gain, and resiliency to SLR are constrained by the supply of inorganic sediment (Redfield 1972; DeLaune et al. 1983; Thom 1992; Cahoon and Reed 1995; Callaway et al. 1996; Morris et al. 2002; D'Alpaos et al. 2011; Weston 2014; Ganju et al. 2015; Thorne et al. 2016). When marsh migration is not possible, salt marshes keep pace with rising SLR through sediment accretion (Kirwan et al. 2010; Fagherazzi et al. 2012; Thorne et al. 2018). Modeling and field studies agree that sediment-rich marshes are more resilient to SLR, while sediment-limited marshes are less resilient (Patrick and DeLaune 1990; Thom 1992; Stralberg et al. 2011; Kirwan et al. 2016; Baustian and Mendelssohn 2018).

We hypothesized that documented declines in the regional sediment supply (Warrick et al. 2013) may be offset under future climates by increases in suspended-sediment discharge (Q_{ss}) produced by increases in the magnitude and frequency of extreme precipitation events (Trenberth 1999; Dettinger 2016). To test this hypothesis, we investigated the impact of climate change on Q_{ss} using an integrated modeling approach. Implications were explored by assessing the availability of sediment for natural marsh accretion, a sediment-based

solution for building resiliency to SLR. The impact of climate change on marine processes (tidal exchange and wave events) was outside the study scope, but the influx of fine sediment from the coastal margin was assessed on the basis of previous investigations of coastal river plume dynamics.

Study Area

The Humboldt Bay–Eel River study region (Fig. 1) is located in northwestern California. The climate is Mediterranean with dry summers and wet winters. The average annual precipitation is 1585 mm/yr with only 3% occurring between June and September. The strong orographic effects of the Coast Range create a west to east precipitation gradient. Annual precipitation along the coastal margin is greater than 2000 mm/yr but less than 1300 mm/yr in the upper basin of the Eel River. Peak runoff events are typically rainfall driven with snowmelt discharge playing a less significant role. Extreme precipitation events, referred to as atmospheric rivers (Dettinger et al. 2011), produced the largest historic floods (Brown and Ritter 1971; Waananen et al. 1971).

The mountainous rivers that drain the study region have sediment yields that are higher than global averages (Milliman and Syvitski 1992; Milliman and Farnsworth 2011). High yields are caused by the cumulative effects of regional tectonic uplift, erodible lithologies, steep uplands, extreme precipitation, and land use (Brown and Ritter 1971; Kelsey 1980; Nolan and Janda 1995; Milliman and Farnsworth 2011; Warrick et al. 2013). Historically, the upland forests were extensively logged (Leithold et al. 2005; Klein et al. 2012), and low-lying areas adjacent to the bay were diked and disconnected from bay circulation (Schlosser and Eicher 2012).

Humboldt Bay is a tidally forced coastal lagoon (Costa 1982) with rates of relative SLR (Rovere et al. 2016) that are exacerbated by localized tectonic subsidence. The bay is composed of three sub-embayments with limited freshwater inputs during most of the year. The three sub-embayments (North Bay, Entrance Bay, and South Bay) are connected by navigation channels and an entrance channel connects the bay to the open coast. Protected by barrier spits, the bay experiences energetic conditions driven by storm, wave, and wind events. The bay is relatively shallow, with 39 km² of mudflats exposed at mean lower low water (MLLW). The mean tide encompasses 73 km² and the tidal exchange is approximately 114 Mm³/day (NHE 2015).

The conceptual sediment budget for Humboldt Bay (Barnhart et al. 1992) includes local and regional sources of fluvial sediment. Local basins that discharge directly to the bay have a combined contributing area of 442 km². The Eel River discharges to the coastal margin and has a contributing area of 9415 km².

Fig. 1 Map of Humboldt Bay–Eel River (HBER) modeling domain in northwestern California, showing gaged basins with streamflow and suspended-sediment measurements. Basin identifiers for the streamflow gages correspond to descriptions in Table 1, and acronyms for the sediment gages correspond to basin identifiers in Table 3

The coastal sediment budget is dominated by the Eel River (Wheatcroft et al. 1997; Wheatcroft and Borgeld 2000; Warrick 2014). Remarkably, the Eel River is the largest fluvial source of fine-sediment along the coast of California (Farnsworth and Warrick 2007). In December of 1964, a massive regional flood generated the peak of record ($21,240 \text{ m}^3/\text{s}$). Flooding was accompanied by extensive channel aggradation and unprecedented sediment loads (Brown and Ritter 1971; Waananen et al. 1971; Gray et al. 2016), which remained high for several decades before declining (Warrick et al. 2013).

Coastal-river plumes (Homer-Devine et al. 2015) are the primary mechanism for dispersing fine-sediment from fluvial sources along the coastal margin (Hill et al. 2000). The winter

runoff season generally coincides with seasonal downwelling winds that produce northerly coastal currents (Kniskern et al. 2011). The northerly currents transport buoyant plumes of fine sediment from the Eel River along the coastal margin where near-shore turbulence and downwelling lead to retention of fine sediment within the plume (Hill et al. 2007). Plume dynamics enable fine sediment to remain in suspension for multiple days, which allows for northward conveyance and transport into Humboldt Bay during flood tides (Geyer et al. 2000; Hill et al. 2000).

The regular occurrence of coastal-river plumes, along with the large tidal exchange and tidal asymmetry, suggests that the bay may function as a sink for fine sediment in the regional

sediment budget. There are no physical data to directly investigate this assertion; however, there is a depositional center of fine sediment located directly offshore from the entrance of Humboldt Bay (Leithold 1989; Wheatcroft et al. 1997; Wheatcroft and Borgeld 2000), which strongly supports the assertion that the bay is a repository for Q_{ss} from the Eel River.

Methods

A combination of empirical and statistical models was used to assess the impacts of climate change on the delivery of fine-sediment from fluvial sources. A deterministic water-balance model, which models the hydrologic response to climate, was used to simulate a daily time series of streamflow for each basin within the modeling domain (Fig. 1). Sediment-transport models, which describe the statistical relationship between mean daily streamflow and Q_{ss} , were used to compute a daily time series of Q_{ss} for each basin.

The water-balance model was calibrated using daily streamflow measured at twelve unimpaired streamflow gages, and the sediment-transport models were fit using daily values of simulated streamflow and Q_{ss} computed for five sediment gages (Fig. 1). Hereafter, sediment reporting basins that discharge directly to Humboldt Bay (Jacoby Creek, Freshwater Creek, Elk River, and Salmon Creek) are collectively referred to as the bay basins, and the Eel River sediment reporting basin is referred to as the Eel River basin.

Streamflow Simulated Using a Water-Balance Model

Daily streamflow, under historical and future climates, was simulated using the Basin Characterization Model (BCM; Flint et al. 2013). The BCM is a fine-scale (270 m) regional water-balance model that mechanistically simulates the hydrologic response to climate using spatially-gridded data. The BCM data inputs include climate (precipitation and air temperatures) and landscape attributes (topography, soils, and bedrock geology). Energy balance equations are used to partition available water into estimates of local runoff and recharge (Fig. 2). Daily runoff values in each 270-m grid cell are then summed to determine daily streamflow values for each basin. A detailed explanation of the BCM input parameters is provided in ESM 1, and a model archive for the Humboldt Bay-Eel River BCM was published separately (Stern et al. 2020).

For the historical model runs (1960 to 2017), gridded climate data were derived from 94 climate stations distributed across the study region. Historical climate observations were downloaded from the National Weather Service Cooperative Observer Program (COOP, www.ncdc.noaa.gov/), the Remote Automated Weather Stations (RAWS, www.raws.dri.edu/), and the California Irrigation Management

Information System (CIMIS, www.cimis.water.ca.gov/). Climate observations were reviewed, and poor-quality data were identified and removed using a jack-knifing statistical method (Efron and Stein 1981).

Daily climate grids for the historical model were spatially interpolated from the measured observations using Gradient and Inverse Distance Squared (GIDS; Nalder and Wein 1998) weighting. At scales from tens of meters to kilometers, the GIDS method adjusts for local gradients caused by lapse rates, inversions, or rain shadows. This method produces accurate climate grids with sparse data, and data requirements are far less than the requirements for techniques such as kriging (Hughes and Lettenmaier 1981). The daily GIDS grids were then scaled to monthly climate grids downloaded from the PRISM Climate Group (PRISM; <http://prism.oregonstate.edu>; Daly et al. 2008) as a check to ensure that the sum of the daily precipitation and the average of daily air temperatures match the monthly PRISM grids.

The historical model was calibrated (2009 to 2016) and validated (2000 to 2008) using daily streamflow measured at twelve unimpaired streamflow gages (Table 1). The most recent period was selected for calibration to best represent current hydrologic conditions. During calibration, model parameters were iteratively adjusted to match simulated and measured streamflow values and to optimize goodness-of-fit statistics. Because the study objective was to assess the impact of climate change on Q_{ss} , optimization of high flows was prioritized over baseflows during model calibration. The BCM post-processing and calibration procedures are described in ESM 1.

California's climate is uniquely variable in both space and time (Dettinger 2016). To capture this variability, a probabilistic framework of climate projections was developed using a multi-model ensemble of five global climate models (GCMs; Table 2) and two projections for greenhouse gas (GHG) emissions. The five GCMs were selected, from the full ensemble of models used in the Intergovernmental Panel on Climate Change (IPCC) Coupled Model Inter-comparison Project Phase 5 (CMIP5), on the basis of historical performance and the ability to best represent California-specific climate features (CADWR-CCTAG, 2015). The multi-model ensemble captured a range of potential future climate conditions (wetter/drier, warmer/hotter), and the two Representative Concentration Pathways (RCPs) captured mitigated (RCP4.5) and business-as-usual (RCP8.5) GHG atmospheric emissions. The ten climate projections provide a robust framework of plausible future climate change scenarios and capture variability and potential future climate trends that may influence the Q_{ss} projections.

For the future model runs (1960 to 2099), we used the CMIP5 daily climate grids, which were statistically down-scaled and bias-corrected (Pierce et al. 2014) to match historical climate statistics (Livneh et al. 2013) using Localized

Fig. 2 Schematic describing the inputs, outputs, and water balance components of the basin characterization model (BCM), which mechanistically simulates daily streamflow using spatially gridded data. Flint et al. (2013) provide a description of the complete workflow, and a description of the post-processing and calibration procedure is provided in ESM 1

Constructed Analogs (LOCA). The bias-corrected climate grids provided improved precipitation estimates for extreme events, reduced the common downscaling problem of too many light-precipitation days, and greenhouse-gas (GHG) forcings were imposed beginning in 2006. Hereafter, the bias-corrected projections are referred to as the LOCA projections. The LOCA projections were downloaded from Cal-Adapt (<http://cal-adapt.org/data/loca/>) and downscaled to 270 m across the modeling domain for this study using a GIDS method described by Flint and Flint (2012).

As explained above, the historical and future model runs used two different climate datasets to simulate streamflow for the historical period. The historical model used climate grids spatially interpolated from observations within the study region; whereas, the future models used the LOCA projections, which were bias-corrected to observations across California.

Streamflow simulated using the historical model was used to calibrate BCM parameters to local conditions across the modeling domain. Model parameters, calibrated using results from the historical model run, were used to simulate streamflow with the future models. Changes in streamflow and Q_{ss} between the baseline (1981–2010), mid-century (2040–2069), and end-of-century (2070–2099) periods were assessed using the LOCA projections.

Suspended-Sediment Discharge Computed Using Sediment-Transport Models

Sediment-transport models, for each of the five sediment reporting basins (Fig. 1), were defined statistically using simple linear regression and monitoring data with variable periods of record (Table 3). In the bay basins, data collection followed

Table 1 Summary of USGS gages with mean daily streamflow records used to calibrate and validate simulated streamflow for twelve basins in the Humboldt Bay-Eel River study region. Data are available at <https://waterdata.usgs.gov/nwis>. See Fig. 1 for gage locations

Streamflow basin ID	USGS gage ID	USGS gage name	Basin area (km ²)	Period of record	
1	11481000	MAD R NR ARCATA	1256	10/01/1910	- 06/05/2018
2	11481200	LITTLE R NR TRINIDAD	105	10/01/1955	- 06/05/2018
3	11473900	MF EEL R NR DOS RIOS	1930	10/01/1965	- 06/05/2018
4	11478500	VAN DUZEN R NR BRIDGEVILLE	575	10/01/1950	- 06/05/2018
5	11476500	SF EEL R NR MIRANDA	1391	10/01/1939	- 06/05/2018
6	11475800	SF EEL R A LEGGETT	642	10/01/1965	- 06/05/2018
7	11477000	EEL R A SCOTIA	8063	10/01/1910	- 06/05/2018
8	11475000	EEL R A FORT SEWARD	5457	09/01/1955	- 06/05/2018
9	11475560	ELDER C NR BRANSCOMB	17	10/01/1967	- 06/05/2018
10	11468900	MATTOLE R NR ETTERSBURG	184	06/21/2001	- 06/05/2018
11	11469000	MATTOLE R NR PETROLIA	635	10/01/1911	- 06/05/2018
12	11482500	REDWOOD C A ORICK	588	09/01/1911	- 06/05/2018

procedures described by Lewis and Eads (2009). In the Eel River basin, data collection followed procedures described by Edwards et al. (1999) and Turnipseed and Sauer (2010). Monitoring data collected at three of the sediment gages (HHB, KRW, SFM) were previously published by Lewis (2013). Data collected at the Eel River gage (USGS 11477000; U.S. Geological Survey 2021) are publicly available at <https://waterdata.usgs.gov/nwis>. Unpublished monitoring data collected at the JBW gage, along with additional datasets used to compute Q_{ss} for the five sediment reporting basins, are available in the Electronic Supplemental Material (ESM). Hereafter, we use the following terminology, sediment-rating curves were used to compute SSC from continuous measurements of turbidity (bay basins) or streamflow (Eel River). Sediment-transport models were used to compute Q_{ss} from streamflow simulated by the historical and future model runs.

For the bay basin gages, continuous turbidity values were used as a surrogate measurement to compute 10-min SSC values. ESM 1 contains a detailed explanation of the

monitoring data and the methods used to convert turbidity to SSC using sediment-rating curves. Sediment-rating curves were previously published for HHB, KRW, and SFM (Lewis 2013). Synchronous measurements (stage and streamflow, turbidity, and SSC) for the JBW gage and the regression analyses used to compute 10-min values of streamflow and SSC are provided in ESM 2. The suspended-sediment load in the bay basins is predominantly composed of fine-grained sediment (diameter <63 μ m), the channels are relatively small, and SSC is well-mixed at the cross-sections where sediment is measured. The influence of grain size on the statistical relationship between turbidity and SSC for the bay basins was previously assessed (Lewis 2013). For the bay basins, no corrections to adjust SSC values for grain size were applied and the 10-min values of streamflow and SSC (ESM 3) were averaged to compute the mean daily values (ESM 4) of Q_{ss} for the period of record for each basin (Table 3).

For the Eel River gage, continuous streamflow values were used as a surrogate measurement to compute 15-min SSC

Table 2 Summary of global climate models used to simulate streamflow and estimated sediment supply under historical and future climates for the Humboldt Bay-Eel River study region. See Taylor et al. 2012 for detailed model descriptions

Model name	Institute ID	Modeling center or group	References
CanESM2	CCCMA	Canadian Centre for Climate Modeling and Analysis	Arora et al. 2011; Von Salzen et al. 2013
CCSM4	NCAR	National Center for Atmospheric Research, United States of America	Gent et al. 2011
CNRM-CM5	CNRM-CERFACS	Centre National de Recherches Météorologiques (CNRM) / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique (CERFACS), France	Voldoire et al. 2013
HadGEM2-ES	MOHC	Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais), UK	Collins et al. 2011; Martin et al. 2011
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	Watanabe et al. 2010

Table 3 Summary of continuous turbidity and streamflow measurements and discrete suspended-sediment concentration (SSC) samples used to develop sediment-transport models (Eq. 1) for five sediment gages in the Humboldt Bay-Eel River study region. Discrete SSC samples and streamflow (15-min) data for the Eel River gage are available at <https://waterdata.usgs.gov/nwis>. Turbidity and streamflow (10-min) data for the bay basin gages are provided in ESM 3. See Fig. 1 for gage locations

Gage ID	Gage name	Drainage area (km ²)	Period of record used in this study
Eel	USGS Eel River	8034	Discrete SSC samples 10/17/1980–03/02/1998 15-min streamflow 09/17/1988–02/28/2017
JBW	Jacoby Creek	35.9	11/02/2003–09/30/2017
HHB	Freshwater Creek	71.8	11/26/2004–05/04/2011
KRW	North Fork Elk River	50.0	11/18/2002–04/17/2013
SFM	South Fork Elk River	57.5	11/16/2002–04/08/2013

values. The synchronous measurements of streamflow and SSC and regression analyses used to compute 15-min values of SSC for the Eel River gage are provided in ESM 2. A minimum flow threshold was defined at 10 m³/s for the low flow regression to mitigate a low flow sampling bias identified in a previous study (Warrick 2014). Data collected before the baseline historical period (1981–2010) were excluded from the regression analysis to mitigate the impact of time-dependent trends and SSC values were corrected for the percentage of fine-sediment (<63 µm) to exclude the sand-sized fraction. The 15-min values of streamflow and SSC (ESM 3) were averaged to compute mean daily values (ESM 4) of Q_{ss} for the period of record (Table 3).

Sediment-transport models for each of the five sediment reporting basins were defined using linear regression and log-transformed variables

$$\text{Log}_{10} Q_{ss} = \text{Log}_{10} a + b (\text{Log}_{10} Q_w) \quad (1)$$

where Q_{ss} is suspended-sediment discharge (metric tons/day), Q_w is streamflow (m³/s), and a and b are regression coefficients. The sediment-transport models (Eq. 1) were fit using daily values of Q_{ss} (ESM 4) paired with streamflow values simulated using the calibrated historical model (ESM 5). Estimates of Q_{ss} for the Eel River were corrected for fines, but the estimates of Q_{ss} for the bay basins did not require a correction.

A group-average method (Glysson 1987; Curtis et al. 2006) was used to define low and high flow regression models for each of the five sediment reporting basins. The group average method is appropriate when a large number of low to moderate data values create a sampling bias that strongly influences the slope of the regression models and is useful for improving the sediment-transport predictions for high flows. This is an extremely important consideration because slight errors in the slope of a regression model can generate large errors in predicted transport. Daily values of simulated streamflow and Q_{ss} from 1981 to 2017

were log₁₀-transformed, binned, and group-averages determined. Streamflow bin sizes, which ranged from 0.07 to 0.11 in log₁₀ units, were scaled to basin size.

Curvature and retransformation bias are two common problems associated with regression models that are fit to log-transformed data (Helsel and Hirsch, 2002). Separate regression models were defined for low flows and high flows to mitigate curvature. Thresholds used to separate low and high flows were determined iteratively by optimizing regression statistics and testing for linearity and equal variance in the residuals. Retransformation bias causes underprediction of sediment transport and was corrected for using a non-parametric “smearing estimator” (Duan 1983), which is insensitive to non-normality in the regression residuals.

Sediment-transport models, defined using historical data, were used to predict changes in Q_{ss} on the basis of streamflow simulated for future climates. To mitigate the problem of non-stationarity (Milly et al. 2008), we followed the approach of Warrick (2014). The computational period, for estimating Q_{ss} under historical conditions, began in 1981 after the lingering effects of the massive 1964 flood had declined. Although we addressed non-stationarity in the development of the sediment-transport models, we assumed no time-dependent trends in the statistical relationship between streamflow and Q_{ss} under future climates. The sediment-transport models are stationary, and the impact of climate change assessed solely on the basis of streamflow response.

Accuracy and prediction errors for simulated historical streamflow were assessed for each calibration basin by comparing measured and simulated streamflow using standard statistical metrics (Legates and McCabe 1999). Goodness-of-fit was assessed using the coefficient of determination (r^2) and the Nash-Sutcliffe efficiency metric (NSE, Nash and Sutcliffe 1970). Values of r^2 describe the proportion of total variance in the measured data described by the simulated data and can range from 0 to 1. NSE is less sensitive to the differences in the mean and the variance in the measured and simulated data. The NSE, which can range from negative infinity to 1, is calculated as the ratio of one minus the mean square error divided by the variance. Larger r^2 and NSE values indicate better agreement between measured and simulated streamflow.

Errors in streamflow, simulated using the historical model, were assessed using the mean percent error (MPE), and an overall mean absolute error (MAE) was defined for the study region. The MPE, calculated as the sum of the differences between the measured and simulated values divided by the total number of values, is negative when simulated streamflow is underestimated and positive when simulated streamflow is overestimated. The overall MAE was calculated as the absolute value of the MPE values averaged across the calibration basins.

The accuracy of the Q_{ss} estimates, computed from streamflow simulated with the historical model, was assessed by comparison with Q_{ss} computed from measured streamflow.

For the bay basins, Q_{ss} results were validated against turbidity-derived Q_{ss} (ESM 4). For the Eel River, the Q_{ss} results for the baseline historical period (1981–2010) were validated against previously published estimates for a 90-yr period (1911–2000; Warrick 2014).

Prediction errors for the turbidity-derived Q_{ss} were assumed to be equal to the sum of individual errors reported by Wright and Schoellhamer (2005). Four sources of error were considered by Wright and Schoellhamer (2005): error of the relation between turbidity and SSC (26%), laboratory error of SSC (8.8%), error of measured and actual SSC (15.2%), and error of the streamflow estimates (1.4%). Wright and Schoellhamer (2005) combined the errors with quadrature, a standard method for propagating random measurement errors, to define a mean error of 31.5%. In this study, we assumed a mean error of 31.5% for the turbidity-derived Q_{ss} for the bay basins.

Prediction errors for Q_{ss} , computed using the sediment-transport models (eq. 1), were computed using the standard error of the prediction (RMSE%), which captures error due to uncertainty in the regression coefficients. The RMSE%, calculated as the square root of the sum of the squared differences divided by the number of values used to fit the regression, considers variance and mean error with smaller values indicating higher accuracy. This method only accounts for errors associated with fitting the regression models and does not account for systematic errors associated with measurements of SSC or streamflow.

The “sum of the individual errors” is commonly used in sediment budget studies to provide some information about the error associated with Q_{ss} , but there is no standardized method and no way to translate these errors with certainty to the future climate results. A 30-year window was used to assess climate change impacts across the ten climate scenarios, which has been proposed as the shortest time period necessary to capture climate variability (Schindler et al. 2015). Changes were determined as the relative percent difference between ensemble means calculated for the historical baseline (1981–2010), mid-century (2040–2069), and end-of-century (2070–2099) periods. Uncertainty was determined using the standard deviation of the 30-year means across the ten climate scenarios.

Results

Water-Balance Model Performance

Calibration and validation results for the 12 calibration basins showed good agreement between simulated streamflow and measured streamflow (Table 4). During the calibration period, the r^2 and NSE values for daily streamflow were ≥ 0.65 for 11 out of 12 basins. During the validation period, the r^2 values were ≥ 0.65 for 11 basins, and the NSE values were ≥ 0.65 for

8 basins. The mean percent errors showed that simulated mean daily streamflow was overestimated during the calibration period and underestimated during the validation period, and the mean absolute error for the calibration period was higher than for the validation period.

The majority of fine-sediment transport occurs during peak flows in the mountainous basins that drain the study region, and for this reason, peak flow results are of particular interest. A comparison of simulated and measured streamflow for the Eel River gage (USGS 11477000, Fig. 3) showed that peak flow magnitudes were underestimated during the validation period. The implications associated with underestimating peak flows will be revisited in the discussion.

Sediment-Transport Model Performance

The regression statistics for the five sediment-transport models (Table 5) showed that variance in the data was well-fit by the regression models (Fig. 4). Fitting separate low-flow and high-flow models using the group-average method improved the statistical fit and resulted in r^2 values that were all greater than 0.81. The prediction errors (RMSE%) for the high-flow models were 25% less than for the low-flow model errors, which is a positive result. Again, the majority of fine-sediment transport occurs during higher flows, and lower prediction errors for the high-flow models improved the Q_{ss} projections.

Validation of the Q_{ss} results (Table 6) showed that the sediment-transport models underestimated Q_{ss} by up to 47%. Because Q_{ss} is often not in phase with streamflow, and statistical models that use streamflow as a predictor variable commonly underestimate Q_{ss} (Horowitz 2003). Although high flows were prioritized over low flows during the calibration of the historical model, underestimation of peak magnitudes (Fig. 3) contributed to the underprediction of Q_{ss} .

Climate Change Impacts

The future climate projections for the study region showed a high probability of a warmer and more variable climate with increased annual precipitation (Fig. 5). For both the mid-century and end-of-century, the CanESM2 RCP8.5 scenario projected the greatest warming. The CNRM-CM5 is a warmer-wetter GCM, and the CNRM-CM5 RCP8.5 scenario projected the largest increase in precipitation for both the mid-century and end-of-century. In comparison, the HadGEM2-ES is a hotter-drier GCM, which projected potential declines in precipitation for the mid-century (RCP4.5 and RCP8.5) and end-of-century (RCP4.5). Six scenarios projected increases in mean precipitation for the mid-century, but nine scenarios projected increases in precipitation for the end-of-century. The climate change results showed that mean annual precipitation and the magnitude and frequency of extremes,

Table 4 Daily and monthly statistical metrics, for twelve gaged basins in the Humboldt Bay - Eel River study region, used to calibrate and validate streamflow simulated using the Basin Characterization Model(Flint et al. 2013). See Fig. 1 for gage locations. [r^2 = coefficient of determination, NSE Nash Sutcliffe Efficiency, MPE mean percent error]

Basin ID	USGS gage ID	USGS gage name	Calibration period						Validation period					
			2009–2016						2000–2008					
			Daily			Monthly			Daily			Monthly		
			r^2	NSE	MPE	r^2	NSE	MPE	r^2	NSE	MPE	r^2	NSE	MPE
1	11481000	Mad R Arcata	0.78	0.78	19.3	0.92	0.92	16.5	0.74	0.73	−13.0	0.89	0.89	−14.2
2	11481200	Little R Trinidad	0.75	0.75	22.9	0.91	0.90	22.5	0.75	0.74	7.3	0.92	0.92	8.6
3	11473900	MF Eel Dos Rios	0.67	0.66	2.4	0.86	0.86	7.6	0.71	0.65	−0.2	0.91	0.91	6.7
4	11478500	Van Duzen	0.74	0.74	19.0	0.95	0.95	17.9	0.68	0.67	−5.9	0.94	0.94	−5.0
5	11476500	SF Eel Miranda	0.76	0.75	−22.9	0.95	0.95	−5.2	0.72	0.41	−3.3	0.94	0.94	8.4
6	11475800	SF Eel Leggett	0.81	0.80	24.8	0.94	0.90	25.0	0.86	0.86	9.3	0.81	0.65	8.4
7	11477000	Eel Scotia	0.65	0.65	−13.9	0.92	0.88	17.8	0.70	0.55	0.5	0.89	0.87	28.2
8	11475000	Eel R Ft Seward	0.82	0.82	5.3	0.91	0.91	11.1	0.81	0.79	−0.2	0.93	0.92	4.2
9	11475560	Elder C Nr Branscomb	0.71	0.70	15.2	0.90	0.90	11.0	0.67	0.60	−21.7	0.90	0.89	−22.0
10	11468900	Mattole Ettersburg	0.80	0.79	−5.8	0.92	0.90	−1.2	0.85	0.72	1.1	0.96	0.89	3.9
11	11469000	Mattole Petrolia	0.75	0.69	−0.2	0.86	0.80	−4.4	0.70	0.64	19.6	0.94	0.76	18.6
12	11482500	Redwood C	0.56	0.54	−2.1	0.9	0.90	14	0.56	0.49	−13.1	0.89	0.89	5.0
		Mean	0.73	0.72	5.3	0.91	0.90	11.1	0.73	0.65	−1.6	0.91	0.87	4.2
		Mean Absolute Error (MAE) in Percent			12.8			12.9			7.9			11.1

interpreted as precipitation variability, are likely to increase under future climates.

One of the study objectives was to explore the availability of sediment for natural marsh accretion, a sediment-based solution for building resiliency to SLR. Hereafter, we focus on comparing study results for the historical baseline and mid-century periods, because this comparison period represents a realistic time frame for implementing adaptation strategies. A complete summary of climate change impacts on streamflow and Q_{ss} is provided in ESM 1.

Mid-century increases in precipitation were translated into increased streamflow. For the bay basins, seven scenarios projected increases in mean annual streamflow, peak flows, and the number of peak flow days. For the Eel River, seven scenarios projected increases in mean annual streamflow, eight scenarios projected increases in peak flows, and nine scenarios projected increases in the number of peak flow days. The streamflow results showed that mean annual flows and the magnitude and frequency of peak flows are likely to increase under future climates.

The timing of peak flow days is relevant to changes in the seasonality of Q_{ss} (Fig. 6). The RCP4.5 scenarios projected the largest increase in the number of peak flow days in January, and the RCP8.5 scenarios projected the largest increases in peak flow days in December. The RCP8.5 scenario for the hotter-drier HadGEM2-ES model projected a shift in the occurrence of peak flows to February. The MIROC5

model projected a warmer climate with relatively small changes in precipitation and a shift in peak flow days to March.

A shift in the winter runoff season could impact the delivery of fine-sediment to Humboldt Bay. Coastal-river plumes discharged from the Eel River must coincide with winter upwelling events. These upwelling events produce the northerly currents that convey sediment northward along the coastal margin allowing flood tides to transport sediment entrained within the plumes into the bay. The occurrence of peak runoff events during periods dominated by southerly coastal currents would decrease the delivery of fine sediment to the bay.

Increases in mid-century streamflow produced amplified increases in Q_{ss} . The warmer-wetter CNRM-CM5 RCP8.5 scenario projected the largest increase in Q_{ss} for both the bay basins and the Eel River (Table 7). The hotter-drier MIROC5 RCP4.5 scenario projected the largest decline in Q_{ss} for the bay basins, and the HadGEM2-ES 8.5 scenario projected the largest decline for the Eel River. Six scenarios projected increases in Q_{ss} for the bay basins and seven scenarios projected increases for the Eel River. A comparison of exceedance curves for the Eel River for the baseline and mid-century periods (Fig. 7) showed climate impacts across the complete probability distribution. For the ten mid-century scenarios, Q_{ss} is consistently higher than the baseline period over the full range distribution with the one exception being the hotter-drier HadGEM2-ES RCP8.5 scenario. The Q_{ss} results showed

Fig. 3 Simulated and measured mean daily streamflow for the Eel River at the Scotia gage (USGS 11477000) during calibration and validation periods. The timing of streamflow simulated with the basin

characterization model (BCM) generally match measured values; however, peaks during the validation period were underestimated. See Table 4 for the goodness-of-fit statistics

Table 5 Regression parameters, statistical metrics, and bias correction factors for sediment-transport models developed for five basins in the Humboldt Bay-Eel River study region. See Fig. 1 for gage locations.

Sediment basin ID	Gage name	Corrected for fines (<63 µm)	Regression model thresholds	Intercept (log10)	Slope (log10)	Sample Size	r^2	RMSE (log10)	Prediction RMSE (%)	p value	Bias correction factor
Eel	Eel R at Scotia	Y	Qlog10< 3.0	-2.08	2.15	17	0.98	0.18	42	< 0.0001	1.08
JBW	Jacoby Creek	Y	Qlog10> 3.0	-5.18	3.12	9	0.98	0.13	31	< 0.0001	1.04
		N	Qlog10< 0.25	0.22	1.15	25	0.90	0.22	55	< 0.0001	1.13
HHB	Freshwater Creek	N	Qlog10> 0.25	-0.54	2.87	11	0.96	0.16	37	< 0.0001	1.06
		N	Qlog10< 0.5	-0.06	1.55	19	0.87	0.26	65	< 0.0001	1.15
KRW	North Fork Elk River	N	Qlog10> 0.5	-1.14	3.12	13	0.94	0.22	55	< 0.0001	1.12
		N	Qlog10< 0.3	0.82	1.26	24	0.93	0.21	51	< 0.0001	1.11
SFM	South Fork Elk River	N	Qlog10> 0.3	-0.04	2.50	14	0.99	0.10	24	< 0.0001	1.02
		N	Qlog10< 0.2	0.97	1.39	23	0.81	0.36	98	< 0.0001	1.29
		N	Qlog10> 0.2	0.15	2.60	16	0.97	0.17	40	< 0.0001	1.07

Q streamflow, r^2 coefficient of determination, $RMSE$ root mean squared error, p value calculated probability

that the regional fine-sediment supply is likely to increase under future climates.

Results for the end-of-century showed larger climate change impacts on streamflow and Q_{ss} (ESM 1) are likely to occur. For the bay basins, nine scenarios projected increases in mean annual streamflow and the number of peak flow days, ten scenarios projected increases in peak flows, and nine scenarios project increases in Q_{ss} . For the Eel River, eight scenarios projected increases in mean annual streamflow and peak flows, ten scenarios projected increases in the number of peak flow days, and ten scenarios projected increases for the Eel River.

The study region is underlain by erodible lithologies and basins that discharge to the coastal margin have sediment yields that are higher than global averages. In these high yield basins, the wetter climate scenarios produced amplified increases in Q_{ss} . As envisioned by Coulthard et al. (2012), these high yield basins act as “geomorphic multipliers.” When the signal of increased precipitation is translated to runoff, streamflow, and Q_{ss} , the climate change impacts are amplified. For the bay basins, the ensemble means projected changes in Q_{ss} of 27% for the mid-century (Table 7) and 58% for the end-of-century (ESM 1). For the Eel River, the ensemble means projected changes in Q_{ss} of 53% (Table 7), and 99% for the end-of-century (ESM 1).

Discussion

Quantifying the impacts of climate change on fine-sediment delivery involves considerable uncertainty. The largest uncertainties are associated with the climate projections, emissions scenarios, and downscaling methods, and smaller uncertainties are related to the water-balance model, sediment transport models, and observational data (Vetter et al. 2017).

The limitations of simulating streamflow using the BCM are discussed at length by Flint et al. (2013). Errors were minimized through rigorous calibration of the historical model, but peak flows were underestimated during the validation period. Additional uncertainty was introduced by using model parameters, calibrated for the gaged basins, to simulate streamflow in the ungaged basins. Given the small range of values for the calibration parameters, this approach provided better estimates than a simple scaling approach, such as the ratio of ungaged to gaged areas.

The limitations of computing Q_{ss} using statistical sediment-transport models are well documented (Walling and Webb 1981; Rieger and Olive 1984; Glysson 1987; Asselman 2000; Lewis and Eads 2009; Warrick et al. 2013; Gray 2018). These models tend to underpredict sediment transport

Fig. 4 Separate low flow and high flow sediment-transport models (Eq. 1) fit using mean daily fine-sediment discharge paired with simulated streamflow for the five sediment reporting basins in the Humboldt Bay-

Eel River study region. See ESM 4 and ESM 5 for raw data, Fig. 1 for gage locations, Table 3 for a summary of gage data, and Table 5 for model parameters and regression statistics

for high flows (Horowitz 2003). The accuracy of sediment transport predictions depends upon the range of values used to define the model, the statistical fit, whether conditions during the computational period are representative, and whether

the variations in sediment transport are well explained by streamflow (Porterfield 1972; Gray and Simões 2008).

The group-average method used to define the sediment-transport models alleviated low-flow sampling biases, and

Table 6 Validation of mean annual suspended-sediment discharge results. Q_{ss} estimated using simulated streamflow from the historical water-balance model are compared to Q_{ss} estimated using measured streamflow

for the bay basins (ESM 4) and the Eel River (Warrick 2014). See Fig. 1 for sediment gage locations.

Sediment basin ID	Gage name	Basin area (km ²)	Period of record (Water years)	Years of record	Q_{ss} estimated using simulated flow (Mt/yr)	Q_{ss} estimated using measured flow (Mt/yr)	Percent difference (%)
Eel	Eel R at Scotia	8,063	1981–2010	30	10.3±3.2	11.9±1.3	–13
JBW	Jacoby Creek	35.9	2004–2016	12	0.002±0.001	0.004±0.001	–47
HHB	Freshwater Creek	71.8	2005–2008, 11	5	0.004±0.002	0.007±0.002	–36
KRW	North Fork Elk River	50.0	2003–2008, 11, 13	8	0.007±0.002	0.012±0.004	–38
SFM	South Fork Elk River	57.5	2003–2008, 11, 13	8	0.011±0.005	0.014±0.004	–18

 Q streamflow, Q_{ss} suspended-sediment discharge, Mt/yr million metric tons per year

the use of separate low-flow and high-flow models improved prediction errors. The validation results indicate that Q_{ss} at the gaged locations may be underestimated by up to 47% (Table 6). Predictions errors (RMSE%) for the high flow models (Table 5) were 24 to 55%, which is similar to errors (30 to 50%) reported in previous studies (Meade et al. 1990; Glysson et al. 2001; Horowitz 2003; Farnsworth and Warrick 2007; Gray and Simões 2008; Gray 2018).

Although we recognize that Q_{ss} is often out of phase with streamflow, we assumed that Q_{ss} varied non-linearly with streamflow. Non-stationarity (Milly et al. 2008) and the influence of time-dependent trends (Warrick et al. 2013; Gray 2018) on the statistical relationship between streamflow and Q_{ss} were minimized by excluding data collected before the historical baseline period (1981–2010). Although we addressed non-stationarity in the development of the sediment-transport models, we assumed no time-dependent trends in the statistical relationship between streamflow and Q_{ss} under future climates. The use of stationary sediment-transport models, fit to short-term historical data, added additional uncertainty.

Changes in land use or land cover were not investigated, although we recognize that the additive effect vegetation or land cover changes could substantially alter the magnitude and timing of streamflow and the statistical relationship between streamflow and Q_{ss} . Dynamic sediment-transport models (Ahn and Steinschneider 2018), which allow regression parameters to change over time to account for persistent impacts such as large floods (Gray 2018) or changes in land use and land cover (Bussi et al. 2014), would be useful for further investigating time-dependent trends.

We did not address dynamic floodplain deposition, but we recognize low-lying areas at the bay interface as sinks for fine-sediment. Historically, former tidelands were diked, drained, and subsequently experienced local subsidence (Schlosser and Eicher 2012). Overbank flooding in these low-lying areas occurs during wet years and excessive floodplain sedimentation has been documented in the lower reaches of Freshwater Creek and Elk River (Lewis 2013). We assumed that fine

sediment transported past the sediment gages was delivered to the tidal reaches at the bay interface.

Validation results showed that the water-balance model underestimated peak flows, and the statistical models underestimated Q_{ss} . For these reasons, the Q_{ss} estimates for historical and future climates are considered to be conservative. Poor model performance in simulating peak flow magnitudes is particularly important because the effective discharge for suspended-sediment transport in the study region is known to follow the small mountain-river paradigm (Milliman and Syvitski 1992). This paradigm, which states that Q_{ss} in small mountain basins is strongly correlated to peak flows, has been confirmed by numerous studies (Tropeano 1991; Coppus and Imeson 2002; Grodek et al. 2012; Lewis 2013; Warrick et al. 2015).

Assessing uncertainty for the GCM outputs is challenging (Tebaldi and Knutti 2007), but ensemble averaging (Knutti et al. 2010) reduced uncertainty for the future climate projections. Selecting a subset of CMIP5 models that are most representative of California-specific climate features (CADWR-CCTAG 2015) further reduced uncertainty, and the use of multiple RCPs incorporated emissions uncertainty. A comparison of 30-year means among the different GCMs and RCPs for the historical, mid-century, and end-of-century periods showed the potential variability of streamflow and Q_{ss} under future climates. Presentation of the results in terms of the percent change, relative to the historical baseline, provided the best metric for assessing differences among the scenarios and between different time periods. The ensemble means and standard deviations provided a single metric that captured multiple sources of variability and uncertainty.

We hypothesized that documented declines in the regional fine-sediment supply (Warrick et al. 2013) under current conditions might be offset under future climates by projected increases in Q_{ss} produced by increases in the magnitude and frequency of extreme precipitation events. Study results indicate that Q_{ss} responded strongly to climate change. The ensemble means for the mid-century projected increases in Q_{ss}

Fig. 5 Summary of ten climate projections, shown as 30-year means, derived for the Humboldt Bay-Eel River study region from five global climate models (GCM) and two representative concentration pathways (RCP). Precipitation projections, shown as percent change, and air temperature projections, shown as change in degrees, were calculated as the difference between mean annual values for the historical baseline (1981–2010), mid-century (2040–2069), and end-of-century (2070–2099) periods. Standard deviation bars are used to show inter-annual variability

of 27% for the bay basins and 53% for the Eel River (Table 7). These results contrast sharply with a recent study of sediment yield to the world's major deltas that determined climate change was responsible for increases in sediment yield of only 6 to 9% (Dunn et al. 2019). The strong contrast can be explained by mountainous physiography, highly erodible geology, a lack of flow regulation and reservoir entrapment, and the high sediment yields that characterize the study region.

The ensemble of five GCMs and two RCPs provided a probabilistic framework for exploring the impacts of climate change on streamflow and Q_{ss} . The ten scenarios used in this study captured plausible future climates (hotter-drier to warmer-wetter) and predicted a range of potential future sediment

supply conditions. Despite large uncertainties, the study results provide useful projections to aid resource and land managers as they plan for future sediment supply scenarios, respond to potential vulnerabilities, and develop adaptation strategies for improving resiliency to SLR. The sediment supply projections can be used to guide adaptation strategies and to assess the availability of sediment for implementing sediment-based solutions to build resiliency to SLR.

Salt marshes, which respond dynamically to SLR and changes in sediment supply, provide shoreline protection and bolster resiliency to SLR. Recent work has shown that SLR impacts in salt marshes may be ameliorated by natural sedimentation events (Baustian and Mendelssohn 2018). In Humboldt Bay, the remaining salt marshes cover 3.6 km². Direct measurements of marsh accretion indicate short-term accretion rates of 2.19 ± 1.36 mm/yr (Curtis et al. 2019) and marsh cores indicate historical accretion rates of 3.5 to 5.7 mm/yr (Thorne et al. 2016). The annual supply of inorganic sediment required to balance rates of short-term accretion is 0.002 to 0.010 Mt/yr. This represents 4 to 19% of the Q_{ss} (0.057 ± 0.23 Mt/yr) computed for the bay basins using the historical model (Table 7). In comparison, the annual input

Fig. 6 Number of peak flow days per decade (> 95%-ile) during the historical baseline (1981–2010) and mid-century (2040–2069) periods for ten climate scenarios derived from five global climate models (Table 2) and two representative concentration pathways (RCP)

Table 7 Climate change impacts on streamflow and suspended-sediment discharge summarized for the bay basins and the Eel River for baseline historical (1981–2010) and mid-century (2040–2069) periods. See ESM 1 for a summary of the end-of-century results

		Mean streamflow (million m ³ /year)		Peak streamflow (million m ³ /year)		Number of days exceeding peak flows		Suspended-Sediment Discharge (million metric tons/year)	
		Bay Basins	Eel River	Bay Basins	Eel River	Bay basins	Eel River	Bay Basins	Eel River
1981-2010 Historical Model		0.631	22.5	4.77	237	18	18	0.057±0.023	10.3±3.19
1981-2010 LOCA HSY HST	CanESM2	0.581	25.2	4.78	262	18	18	0.040	10.9
	CCSM4	0.574	24.5	4.40	244	18	18	0.035	10.2
	CNRM-CM5	0.505	22.3	4.23	246	18	18	0.032	11.2
	HadGEM2-ES	0.532	23.7	4.16	239	18	18	0.033	12.8
	MIROC5	0.513	22.9	4.02	240	18	18	0.032	11.5
Ensemble Mean ± StdDev		0.541±0.035	23.7±1.16	4.32±0.29	246±9.27	18±0	18±0	0.034±0.003	11.3±0.94
Mid-century									
2040-2069 LOCA RCP 4.5	CanESM2	0.628	28.4	4.75	269	23	24	0.051	16.3
	CCSM4	0.581	25.7	4.56	265	20	21	0.042	17.0
	CNRM-CM5	0.628	28.8	4.46	263	26	27	0.053	23.1
	HadGEM2-ES	0.505	21.9	4.36	241	16	19	0.030	12.4
	MIROC5	0.503	21.7	3.92	228	18	20	0.026	10.0
2040-2069 LOCA RCP 8.5	CanESM2	0.642	29.8	4.64	277	23	26	0.050	23.6
	CCSM4	0.633	27.9	5.05	276	20	23	0.057	19.8
	CNRM-CM5	0.682	29.9	4.67	268	26	27	0.065	25.8
	HadGEM2-ES	0.499	20.9	4.40	231	15	19	0.032	9.12
	MIROC5	0.525	23.6	4.04	241	19	21	0.031	12.7
Ten Scenarios Ensemble Mean ± StdDev		0.583±0.069	25.9±3.56	4.49±0.33	256±18.7	21±3.8	23±3.2	0.044±0.013	17.0±5.94
Percent difference in mid-century results relative to LOCA HST									
2040-2069 LOCA RCP 4.5	CanESM2	8%	13%	-1%	3%	24%	33%	29%	49%
	CCSM4	1%	5%	4%	9%	9%	16%	20%	67%
	CNRM-CM5	24%	29%	5%	7%	44%	48%	63%	105%
	HadGEM2-ES	-5%	-8%	5%	1%	-13%	4%	-9%	-3%
	MIROC5	-2%	-5%	-2%	-5%	0%	9%	-19%	-12%
2040-2069 LOCA RCP 8.5	CanESM2	11%	18%	-3%	6%	27%	43%	25%	116%
	CCSM4	10%	14%	15%	13%	10%	25%	64%	94%
	CNRM-CM5	35%	34%	10%	9%	45%	45%	101%	129%
	HadGEM2-ES	-6%	-12%	6%	-3%	-18%	2%	-2%	-29%
	MIROC5	2%	3%	1%	0%	7%	17%	-3%	10%
Ten Scenarios Ensemble Mean		8%	9%	4%	4%	14%	26%	27%	53%

of inorganic sediment required to balance historical marsh accretion rates is 0.010 to 0.016 Mt/yr, which represents 19 to 30% of the total annual Q_{ss} computed for the bay basins.

Historically, sediment delivery from the local bay basins was sufficient to support natural marsh accretion, which increased surface elevations allowing the marshes to keep pace with SLR, and provided a remainder of additional sediment to fill subsided areas. The

conceptual mass-balance calculations for the potential contribution of fluvial sediment for marsh accretion highlight the importance of understanding the balance between sediment supply and sediment demand. Under future climates, increased sediment demand, caused by the combined impacts of subsidence and SLR, may be partially or wholly balanced by projected increases in Q_{ss} .

Fig. 7 Exceedance curves for the Eel River for a historical baseline (1981–2010) and ten mid-century (2040–2069) scenarios derived from five global climate models (Table 2) and two representative concentration pathways (RCP). Inset figure magnifies the upper portion of the curves and shows that suspended-sediment discharge (Q_{ss}) increased under all but one of the scenarios for the largest magnitude events

In this case study for Humboldt Bay, fine-sediment delivery from fluvial sources was estimated but the internal sediment budget remains undefined. Studies of marsh accretion and sediment supply are continuing, and new marsh loss studies are underway.

Conclusions

This study presents a robust modeling approach and a probabilistic framework for assessing the impacts of climate change on the fine-sediment delivery from fluvial sources in a coastal region experiencing localized tectonic subsidence. In Humboldt Bay, sediment demand created by subsidence, SLR, and tidal prism expansion may be partially or wholly offset under future climates by projected increases in precipitation and streamflow that produce amplified increases in the

regional sediment supply. Subsiding coastlines require a larger sediment supply to keep pace with SLR, and coastal regions with a higher sediment supply may be more resilient to SLR.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s12237-021-00938-x>.

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