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Temporal downscaling of decadal sediment load estimates to a daily interval for use in hindcast simulations

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Summary In this study we used hydrologic proxies to develop a daily sediment load time-series, which agrees with decadal sediment load estimates, when integrated. Hindcast simulations of bathymetric change in estuaries require daily sediment loads from major tributary rivers, to capture the episodic delivery of sediment during multi-day freshwater flow pulses. Two independent decadal sediment load estimates are available for the Sacramento/San Joaquin River Delta, California prior to 1959, but they must be downscaled to a daily interval for use in hindcast models. Daily flow and sediment load data to the Delta are available after 1930 and 1959, respectively, but bathymetric change simulations for San Francisco Bay prior to this require a method to generate daily sediment load estimates into the Delta. We used two historical proxies, monthly rainfall and unimpaired flow magnitudes, to generate monthly unimpaired flows to the Sacramento/San Joaquin Delta for the 1851–1929 period. This step generated the shape of the monthly hydrograph. These historical monthly flows were compared to unimpaired monthly flows from the modern era (1967–1987), and a least-squares metric selected a modern water year analogue for each historical water year. The daily hydrograph for the modern analogue was then assigned to the historical year and scaled to match the flow volume estimated by dendrochronology methods, providing the correct total flow for the year. We applied a sediment rating curve to this time-series of daily flows, to generate daily sediment loads for 1851–1958. The rating curve was calibrated with the two independent decadal sediment load estimates, over two distinct periods. This novel technique retained the timing and magnitude of freshwater flows and sediment loads, without damping variability or net sediment loads to San Francisco Bay. The time-series represents the hydraulic mining

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period with sustained periods of increased sediment loads, and a dramatic decrease after 1910, corresponding to a reduction in available mining debris. The analogue selection procedure also permits exploration of the morphological hydrograph concept, where a limited set of hydrographs is used to simulate the same bathymetric change as the actual set of hydrographs. The final daily sediment load time-series and morphological hydrograph concept will be applied as landward boundary conditions for hindcasting simulations of bathymetric change in San Francisco Bay.

Introduction

Calibration and validation of numerical models require sufficient data to adjust parameters and evaluate forcing functions. Tidal-timescale models of estuarine geomorphology are best calibrated to sediment flux data and bathymetric change (Ganju and Schoellhamer, 2007), and are usually forced at the landward boundary with a daily time-series of freshwater flow and sediment load. Daily time-series are needed in systems with episodic freshwater flow events, which last several days. In many cases the calibration data and forcing data do not overlap temporally. Therefore it is necessary to estimate forcing data in a robust manner. Daily sediment loads can be estimated with rating curves, assuming that daily freshwater flow data are available. If these data are not available, proxies for daily freshwater flow must be identified.

Other researchers have estimated historical flows using proxies such as coral reef banding (Smith et al., 1989; Isdale et al., 1998), dendrochronology (Smith and Stockton, 1981; Clevealand and Stahle, 1989; Meko et al., 2001), and benthic stratigraphic analyses (Goman and Wells, 2000). These proxies, however, are typically annual and cannot be resolved at finer temporal scales. Stochastic hydrology methods (e.g. Tarboton et al., 1998; Salas et al., 2006) use statistical models to generate monthly to weekly streamflows with annual flow data; these models may not take into account other available historical data, such as rainfall. Stochastic models, by definition, capture the statistical quantities of measured data. However, in systems where recent water storage and release are affected by dam operations, the statistical quantities in the modern era may differ from the historical era, when human intervention was minimal.

Historical estimates of sediment load are possible with proxies such as total basin deposition (Gilbert, 1917; Duck and McManus, 1994), heavy metal geochronologies (Sommerfield and Nittrouer, 1999), coupled climate-watershed-sediment yield models (Syvitski and Morehead, 1999), and rating curves (Porterfield, 1980). Temporal resolution is again limited to the timescale of the proxy. However, with a freshwater flow record of any temporal resolution, a sediment load record of the same resolution can be constructed using rating curves. The most widely used form of these curves are presented by Muller and Forstner (1968) as

$$Q_s = aQ^{b+1} \quad (1)$$

where Q_s is the sediment load, a and b are site-specific parameters, and Q is the freshwater flow. The parameter a represents the sediment supply present within the stream and watershed, while b represents the erosive power of the stream. Parameter a can vary over several orders of magnitude, while b varies from 0 to less than 3 (Muller and Forstner, 1968), and both must be determined for each watershed/stream system independently. These parameters may vary over time as well, due to changes in land use, stream hydraulics, and climate.

The Sacramento and San Joaquin Rivers supply the majority of water and sediment to San Francisco Bay, drained from the Central Valley of California and transported through the Delta (Fig. 1). The hydraulic gold mining period, 1852–1884, released large quantities of sediment from the Sierra Nevada, and resulted in increased deposition in river channels and the Bay (Gilbert, 1917). Following the cessation of hydraulic mining, the sediment pulse reduced, leading to erosion within the Bay (Jaffe et al., 2007). Construction of reservoirs in the 20th century led to increased trapping of sediment and a further reduction of sediment supply to the Bay (Wright and Schoellhamer, 2004). In light of regional climate change and land use practices, future sediment supply (and therefore estuarine geomorphology) may continue to be in disequilibrium. We are currently developing methods to evaluate future scenarios of geomorphic change within San Francisco Bay; hindcasting the historical bathymetric change is a critical calibration step which requires historical freshwater flow and sediment load data at a daily interval. Daily time-series are needed to properly represent the multi-day flow events that are typical in San Francisco Bay; McKee et al. (2006) estimate that almost 10% of the yearly sediment load can be delivered in one day, and over 40% within seven days for an extremely wet year.

Daily freshwater flow data into the Delta are available back to 1930 (Sacramento River, San Joaquin River, and east-side streams), while daily sediment load data for the Sacramento and San Joaquin Rivers were collected starting in 1957 and 1959, respectively. Simulations of estuarine geomorphology, which we are performing for San Francisco Bay, require daily flow and load data back to 1853, in order to hindcast measured bathymetric change (Jaffe et al., 1998; Cappiella et al., 1999). Gilbert (1917) and Porterfield (1980) provide decadal sediment load estimates over two periods using two different methods, which we must downscale to a daily interval. A method to construct the daily freshwater flow and load time-series is presented here, through the use of rainfall proxies, an analogue selection procedure, and sediment load rating curves. This novel technique retains the timing and magnitude of monthly and yearly freshwater flows and sediment loads, and appropriately downscales the record into daily intervals for use in hindcast models.

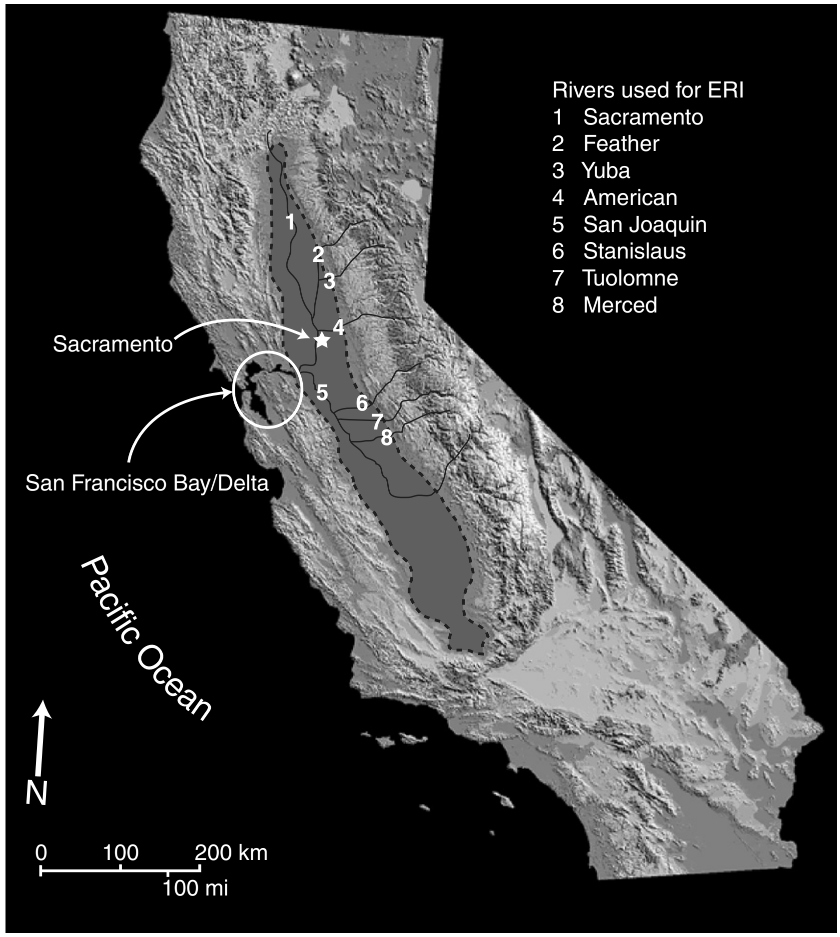

Figure 1 Map of California, with Central Valley outlined by dashed line. The eight rivers used for the ERI drain the Central Valley through San Francisco Bay, to the Pacific Ocean.

Methods and results

Downscaling decadal sediment load estimates to a daily interval requires identification of available proxies, and generation of appropriate relationships between those proxies. Temporal coverage of available proxies varies, but there are enough proxies with which to make reasonable estimates of daily sediment loads (Fig. 2).

Monthly rainfall

Monthly rainfall totals for Sacramento are available from the Global Historical Climatology Network of the National Climatic Data Center. These data, available at http://www.ncdc.noaa.gov/, are composed of monthly surface station measurements, and span back to January, 1850 for the Sacramento location. The record shows the expected Mediterranean pattern: maximum rainfall between December and January, tapering to minimum rainfall by September. Late autumn, winter, and early spring rainfall events at Sacramento typically indicate snowfall at higher elevations in the Sierra Nevada, and therefore may be stored as snowpack. Higher elevation snowpack is typically released as flow during the spring snowmelt period. Discretizing this annual cycle with water years that begin in October rather than calendar years is ideal given California's Mediterranean climate. The rainfall record can be used for monthly rainfall totals starting in water year 1851 (October 1, 1850).

Monthly unimpaired flow 1906-present

The California Department of Water Resources publishes a measure of unimpaired river flow, known as the Eight-River Index (ERI), spanning from 1906-present (California Department of Water Resources, available at http://cdec.water.ca.gov/). This index combines the total flows into the Sacramento and San Joaquin Rivers, which includes the Feather, Yuba, American, Stanislaus, Tuolomne, and Merced Rivers (Fig. 1). This index negates the effect of diversions, storage, export, or import (though it neglects runoff from the valley floor). Individual monthly totals are available for December—May, while combined totals are available for June/July, August/September, and October/November. The averaged record from 1906 to 1929 shows that flow increases from December to May, which exhibits the largest monthly unimpaired flow totals. This lag between peak rainfall and peak flows is largely due to delayed snowmelt from the Sierra Nevada, which peaks in the early spring. This trend has changed during the 20th century, due to increased late-fall precipitation, decreased late-spring precipitation,

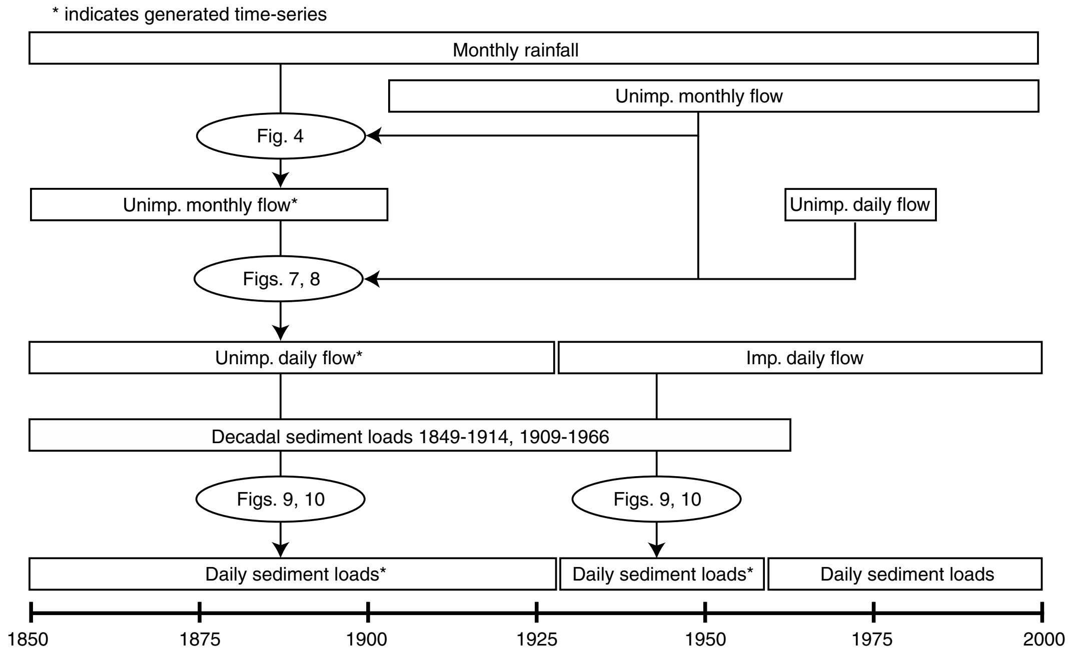

Figure 2 Temporal coverage of proxy data and generated time-series. Unimpaired daily flows are ultimately scaled to annual flow estimates of Meko et al. (2001, 2002).

and increased spring temperatures (Roos, 1991; Aguado et al., 1992), which are increasing the fractional amount of winter streamflow, and reducing the fractional amount of spring streamflow.

Reconstructed monthly unimpaired flows 1851—1905

Reconstructed monthly unimpaired flows for 1851—1905 are estimated by regressing monthly rainfall totals with measured monthly unimpaired flow totals (Fig. 2). Regressions may vary with time due to increased reservoir capacity and water management (Fig. 3), therefore we limit the regression period to 1906—1929. Because much of the spring runoff is a result of previous precipitation (in the form of snow), a lagged regression may be optimal; May flows, for example, may be modeled as a function of total rainfall from October—May. Once a relationship is developed for monthly unimpaired flows as a function of rainfall, the relationship can be applied to the rainfall time-series of 1851—1905 to estimate monthly unimpaired flows, assuming the relationship is stationary.

Regressions of cumulative monthly rainfall totals versus monthly unimpaired flows from 1906 to 1929 gave relationships with an r^2 range of 0.34—0.74, and RMS errors of

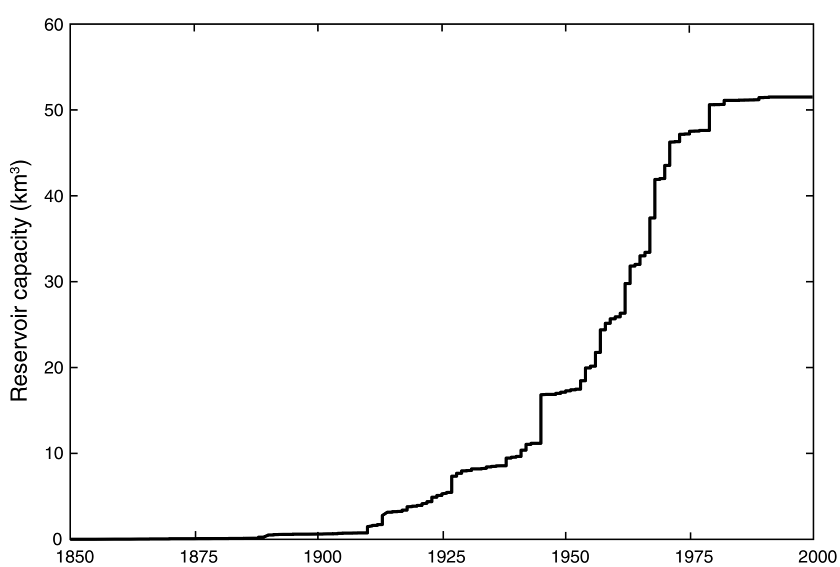

Figure 3 Reservoir capacity in California.

0.11—1.80 million acre-feet (Fig. 4). Including antecedent rainfall conditions during the water year improved regressions in all cases. Applying these relationships to the 1851—1905 rainfall data yielded monthly flows for 1851—1905 (Fig. 5). When averaged over all years, the average reconstructed 1851—1905 hydrograph is similar in shape to the average measured 1906—1929 hydrograph (Fig. 6), with peak flow in May, suggesting that the regression procedure did not skew seasonal patterns of flow. Interannual variability of precipitation did not begin to change significantly until the mid-20th century (Aguado et al., 1992), therefore the similar shapes are appropriate. This step provided the shape of the monthly hydrograph.

Reconstructed daily flows 1851—1929

A monthly hydrograph does not satisfy the needs for hindcasting simulations, as daily time-series are needed to accurately represent ephemeral freshwater flows. Therefore a method to assign daily variability of flow must be developed. An analogue selection procedure developed here assigns a modern daily hydrograph to a historical year, based on similar monthly hydrographs between the modern and historical year. Though the number, timing, and duration of peak events may be variable, the nature of a monthly hydrograph may suggest the relative influence of rainfall versus snowmelt for a given water year, and therefore

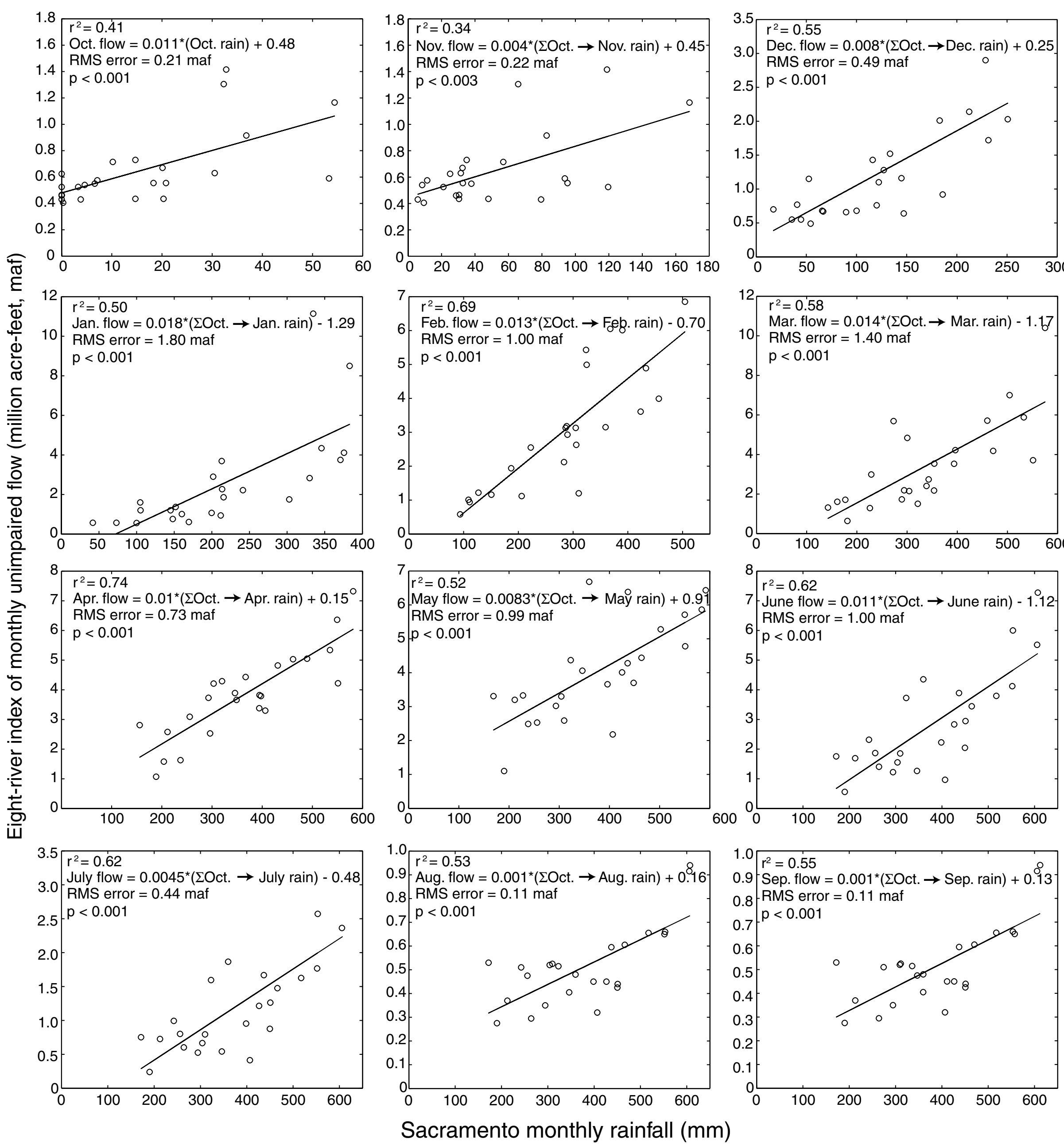

Figure 4 Regressions of cumulative monthly rainfall at Sacramento vs. monthly unimpaired flow (ERI), over the 1906—1929 period.

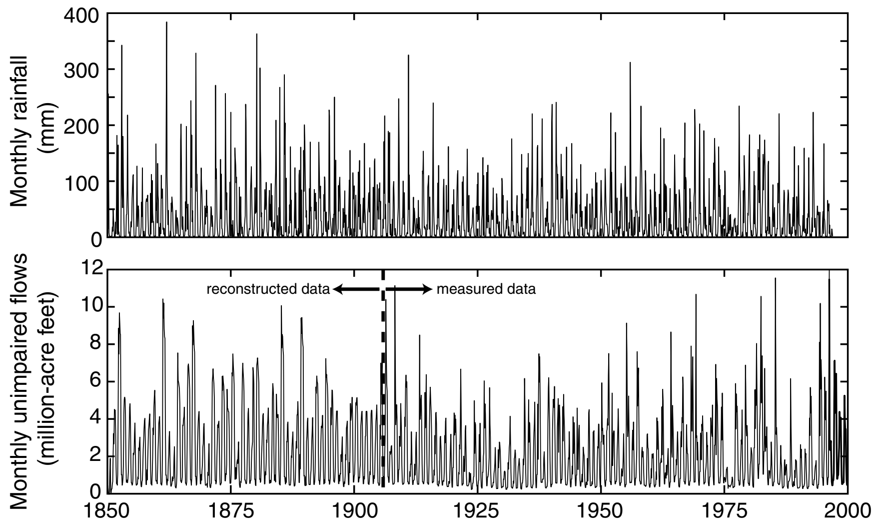

Figure 5 Monthly rainfall and unimpaired flows; flows prior to 1906 were generated using regressions shown in Fig. 4.

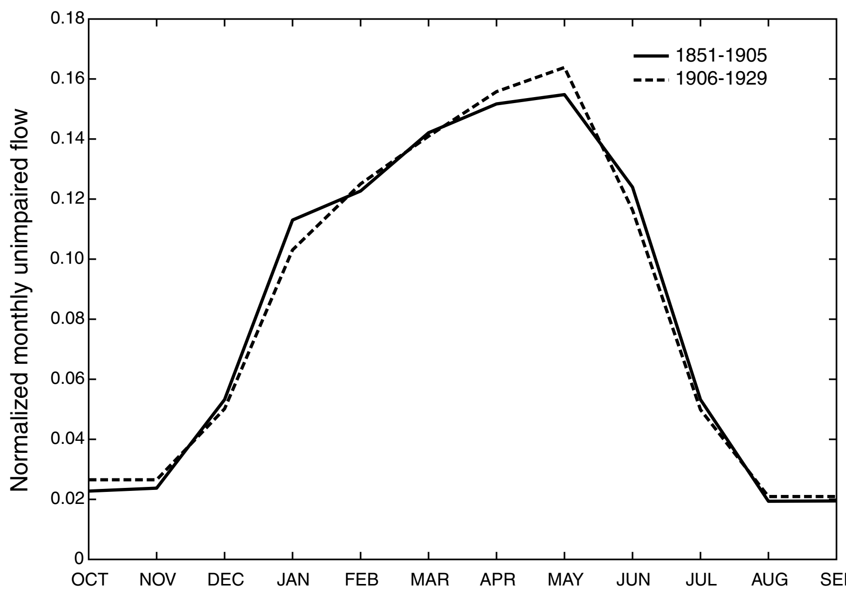

Figure 6 Comparison of 1851—1905 mean reconstructed hydrograph and 1906—1929 mean measured hydrograph. Values are normalized by the average yearly total flow.

capture some crucial elements of the hydrograph (e.g., duration of high flow season).

One confounding factor is the management signal present in modern daily hydrographs. Retention of snowmelt in reservoirs has attenuated the typical snowmelt signal in runoff, and therefore the modern daily hydrographs are not a suitable set for representing historical hydrographs, when reservoirs were not present. A set of estimated unimpaired daily hydrographs for water years 1967—1987 was used here to circumvent this complication. These estimates were derived by incorporating estimates of unimpaired flows below major reservoirs throughout the watershed, obtained from the California—Nevada River Forecast Center, along with estimates of freshwater exports from the Delta region, to reconstruct daily unimpaired outflow from the Delta. Knowles (2002) provides further details of this derivation. For the present study, these daily data were scaled such that their monthly totals matched those of the ERI to ensure consistency across time periods. For each historical monthly hydrograph (1851—1929), the closest analogue from the modern unimpaired monthly hydrographs (1967—1987) was determined using a least-squares metric. October, November, and June—September flows are removed from the selection procedure due to the greater watershed sediment-transport influence during December—May.

Once a suitable analogue was found for the historical monthly hydrograph, it was assumed that the year shares the corresponding daily unimpaired hydrograph as well. The daily hydrograph for the water year was then scaled to match the total flow volume estimated by Meko et al. (2001, 2002), whose dendrochronology study provides total yearly flows for the Sacramento and San Joaquin Rivers that are applied for the 1851—1929 period. We used the dendrochronology results for scaling because they are an independent measure of the total flow, and incorporate data from several sites in the watershed.

For each historical water year prior to measurement of daily flows (1851—1929), the modern (1967—1987) monthly unimpaired hydrograph with the smallest mean squared error relative to the historical year was determined (Fig. 7). The analogue selection procedure successfully represents the timing of flows; for example, the reconstructed water year 1871 monthly hydrograph is matched best with modern year 1985, which has a major late flow signal, while modern year 1983, with a large, earlier flow signal is the worst analogue (Fig. 8). Because the magnitude of total flow

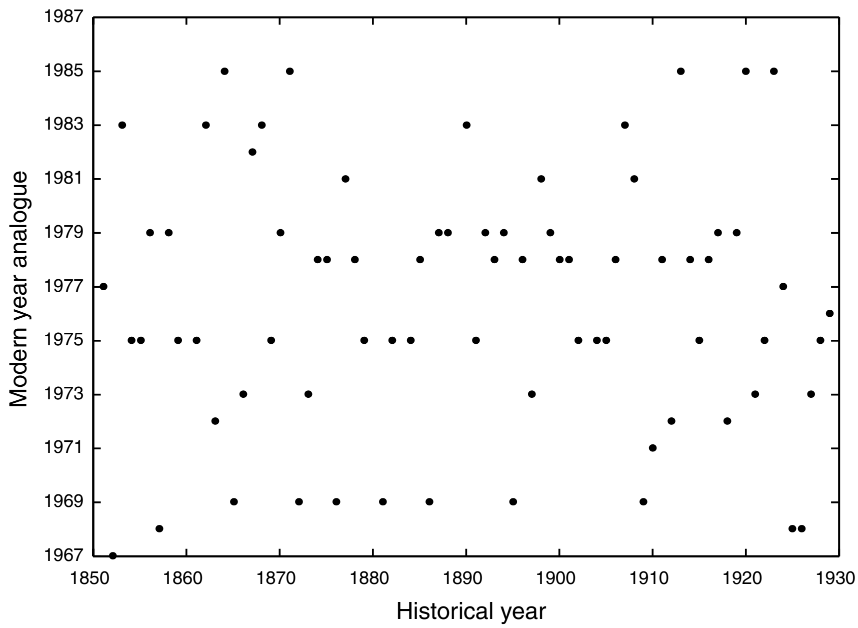

Figure 7 Results of the analogue selection procedure; each reconstructed historical monthly hydrograph from 1851 to 1929 was compared with unimpaired modern monthly hydrographs from 1967 to 1987, and the closest analogue by a least-squares metric is shown.

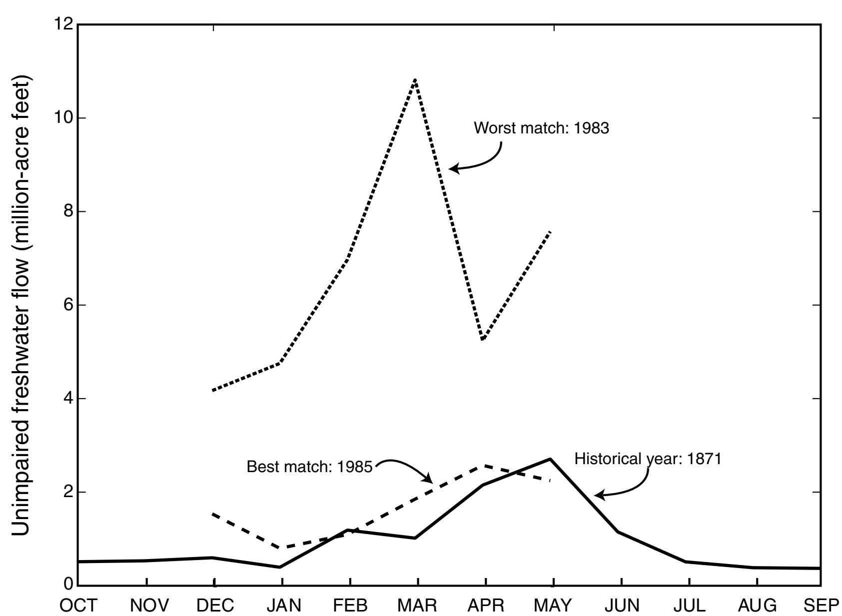

Figure 8 Example of analogue selection results for the reconstructed monthly hydrograph for 1871; the best analogue was 1985, which had peak flow in the late spring, while the worst analogue was 1983, with peak flow in March. October, November, and June—September flows are removed from the selection procedure due to the greater watershed sediment-transport influence during December—May.

in 1985 does not match 1871, the modern daily hydrograph was scaled to agree with the yearly historical flow estimates of Meko et al. (2001, 2002). Each historical year (1851–1929) was assigned the scaled daily hydrograph from the modern year match, thereby yielding a continuous daily time-series of unimpaired flow (Fig. 9). Daily impaired flows, 1930-present, are available through the DAYFLOW program (Christopher Enright, pers. comm.; California Department of Water Resources, 2007).

Sediment rating curves

Once a continuous daily time-series of unimpaired flow was generated, a sediment rating curve was applied to estimate daily sediment loads (Fig. 2). The parameter b (Eq. (1)), represents the erosive power of the stream, which is modulated by changes in stream/floodplain morphology. Ogden Beeman and Associates (1992) determined b = 0.1 for the Sacramento and San Joaquin Rivers for the period 1955–1990; an analysis

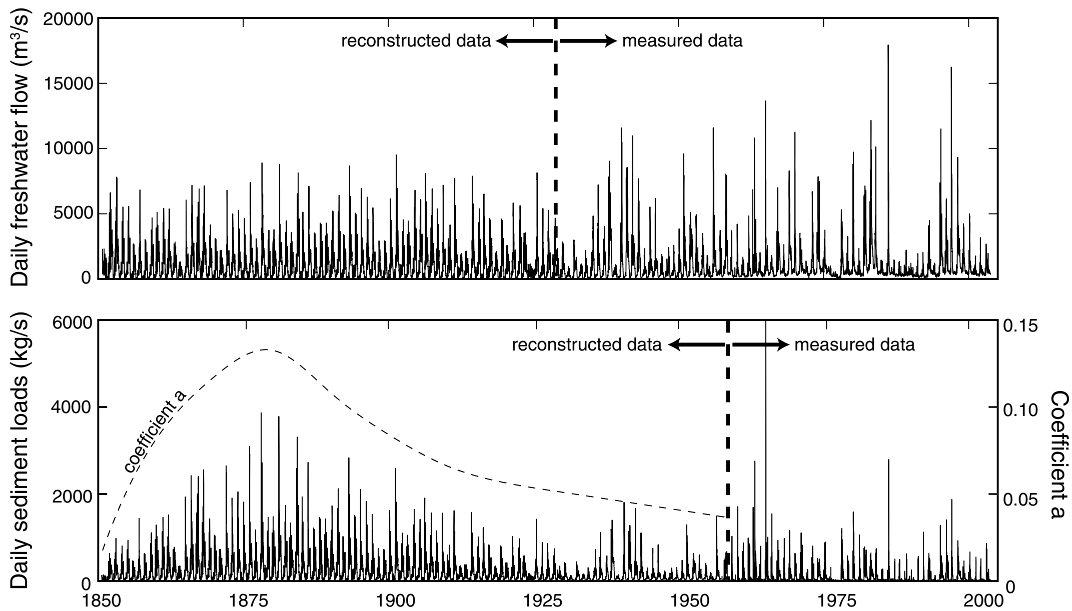

Figure 9 Daily freshwater flow; sediment loads (Eq. (1)), and variation of parameter a (Eq. (1)).

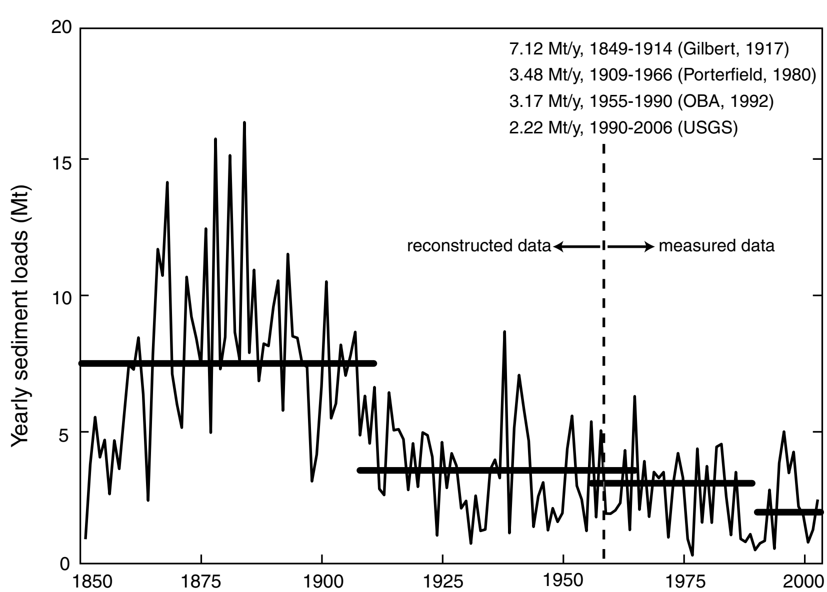

Figure 10 Total yearly reconstructed loads, and two bulk estimates of sediment load by Gilbert (1917) and Porterfield (1980), for the span 1849–1914 and 1909–1966, respectively. Measured sediment loads by Ogden Beeman and Associates (1992) and the US Geological Survey (www.usgs.gov/nwis) also shown. The reconstructed time-series matches the 1849–1966 period loads, by adjusting parameter a.

of recent water years (2000–2003) yields $b = 0.13$. The value 0.13 was used for this reconstruction. Historical information on stream/floodplain morphology is limited and not comprehensive enough to warrant varying b. The more variable parameter in this watershed is a, which represents sediment supply. This parameter will vary with time, in accordance with watershed activities such as hydraulic mining, urbanization, and retention of sediment behind dams. Calibration of a for 1851–1958 was accomplished with the two decadal sediment load estimates to San Francisco Bay from Gilbert (1917) and Porterfield (1980). Using bathymetric change data, Gilbert (1917) estimated a total load of 876 million m^3 during the 1849–1914 period (13.5 million m^3/y); Porterfield (1980) used rating curves for individual tributaries to San Francisco Bay over limited periods, extrapolated for 1909–1966, to estimate yearly loads of 6.6 million m^3/y between 1909 and 1966. Using bulk density estimates (529 kg/m^3, Schultz, 1965; Krone, 1979), this yields mass loadings of 7.12 Mt/y (1849–1914) and 3.48 Mt/y (1909–1966). The unknown errors associated with these estimates may be large, but they provide reasonable bounds to calibrate the parameters for historic loading estimates. While Gilbert did not provide rating curve parameters, we can place constraints on a using his load estimates. These constraints on coefficient a are (1) the value before hydraulic mining began in 1852 is 1/9 of the maximum value (Gilbert, 1917); (2) the maximum value occurs in 1884 when hydraulic mining stopped (Gilbert, 1917); and (3) the slope of a in 1959 is equal to the observed rate of sediment load decrease from 1957 to 2001 (Wright and Schoellhamer, 2004). The shape of parameter a was determined using these caveats, and a spline interpolation was performed to fill in intervals.

A continuous daily time-series of sediment load was developed using the sediment rating curve. Eq. (1) was applied to the daily time-series of freshwater flow, with a constant b of 0.13 and a variable a, to generate a daily time-series of sediment load (Fig. 9). Again, the shape of a was modulated to satisfy the criterion specified in Section 2.5. While peak daily loads in the modern era exceed peak loads in the reconstructed era (Fig. 9), the peak yearly load in the reconstructed era is double the peak yearly load in the modern era (Fig. 10 and Table 1). The eleven largest yearly loads were observed prior to 1900, while twelve of the 13 lowest yearly loads were all after 1924.

Table 1 Decadal sediment loads from the Sacramento and San Joaquin Rivers, at Freeport and Vernalis, respectively

Decade	Average yearly sediment load (Mt)	Source
1850–1860	3.87	This study
1860–1870	8.27	This study
1870–1880	8.79	This study
1880–1890	9.83	This study
1890–1900	7.53	This study
1900–1910	7.19	This study
1910–1920	4.43	This study
1920–1930	3.40	This study
1930–1940	2.80	This study
1940–1950	3.41	This study
1950–1960	3.20	This study/USGS
1960–1970	2.88	USGS
1970–1980	2.47	USGS
1980–1990	2.36	USGS
1990–2000	2.36	USGS

Values prior to 1957 are from this study, values after 1957 are from the US Geological Survey (waterdata.usgs.gov/nwis).

Discussion

Errors in the reconstructed hydrograph

We are able to estimate errors in the flow reconstruction procedure from two sources: (1) regression of unimpaired flow on rainfall and (2) scaling of the total flow. The regressions of unimpaired flow on rainfall (Fig. 4), when averaged over all months, generate a relative error of 35%. The scaling of the total flow is performed using the results of Meko et al. (2001, 2002), which is based on dendrochronology reconstructions. Meko et al. (2001), for the Sacramento River reconstruction, show an RMS error in the 1630–1905 interval of 1.21 million acre-feet, which corresponds to 6% of the average flow from 1850 to 1906. The errors involved in the selection procedure are not readily estimated.

Errors due to sediment rating curve

The sediment rating curve was calibrated with two decadal estimates of sediment loads, from Gilbert (1917) and Porterfield (1980). Gilbert (1917) used measurements of total basin deposition to estimate an average yearly load, while Porterfield (1980) using rating curves for individual tributaries of the Bay/Delta system. Our use of Gilbert's deposition estimates neglects sediment-transport past the Golden Gate and into the Pacific Ocean, but there are no reliable estimates of exchange at the ocean–estuary boundary. Porterfield's rating curves suffer from the same flaws of all rating curves: possible hysteresis (time-dependent rating curve within a single flow event), and a non-stationary system on the decadal timescale. In addition, Porterfield's rating curves were developed using data over a limited period. Our use of a stationary parameter b assumes that erosive power of the rivers has remained constant; while this may be incorrect, we have chosen to vary the more important parameter a, because there is greater information available on watershed sediment supply than there is on erosive power and stream configuration. Changes in river channel configuration, due to anthropogenic and sediment-transport processes, may also introduce changes in erosive power and trapping efficiency. Limited data precludes estimating these changes.

Usage of these estimates and a rating curve for this study is adequate because the final goal is decadal-scale geomorphology in the estuary. While a rating curve ignores, for instance, the ''first flush'' phenomenon (where more sediment is transported per unit water during the first large flood), the major perturbation of hydraulic mining suggests this is a second-order forcing on estuarine geomorphology. It should be noted that peak sediment loads prior to 1959 may have exceeded the peak load observed in 1964; our method will dampen those peaks due to neglect of the first flush phenomenon. The most critical aspect of the decadal-scale hindcasting is estimating the decadal-scale sediment loads, and resolving them at a daily time step, which we have done in this study.

Temporal variability of daily hydrograph

The daily time-series of flow (Fig. 9) shows substantially lower peak flow values from 1851 to 1929, as compared to 1930–2004. Understating of variance in modeled data sets is a common problem of regression models. The non-linearity of sediment-transport requires that peak flows are adequately represented, and not dampened by the reconstruction procedure. The MOVE1 regression technique (Hirsch, 1982), which retains the variance of the predicted variable, was also used in comparison to standard linear regression, and yielded a mean monthly hydrograph with a markedly different pattern than the measured period (Fig. 6). The largest differences were in months with the greatest variance (January, March, and June), therefore we chose to use standard linear regression.

We also tested the reconstruction procedure by applying the analogue selection method to all water years, including the modern era. The entire record of monthly ERI data, 1906–2004, was used as the historical data set, while the modern 1967–1987 data were again used as the set of possible analogues. The fully reconstructed record (Fig. 11) shows similar variance (in terms of standard deviation) to the combined reconstructed/measured record, suggesting that the procedure is adequate for representing peak flows and standard deviation of flows. Visually, the reduction of variability at the intersection of reconstructed and measured flows raises concern. However, the measured rainfall record shows a corresponding reduction in variance, during the prolonged drought of the early 1930's. The relationship between rainfall variance and flow variance is not expected to be stationary however, due to changes in rain/snow patterns (Roos, 1991; Aguado et al., 1992) and flow management.

Reconstructing flows in an altered system

The modification of California's watershed in the 20th century, with the addition of reservoir storage and water management, creates an ''impaired'' condition, whereby the natural flow of water from mountains to estuary to ocean is altered to satisfy various societal and environmental needs. Prior to the construction of major dams, snowmelt carried a large amount of runoff down to the estuary, but now snowmelt is retained in reservoirs to meet needs later in the year, when rainfall and runoff are at a minimum. The daily flow data available at the head of the Sacramento/San Joaquin Delta is impaired, and represents the influence of

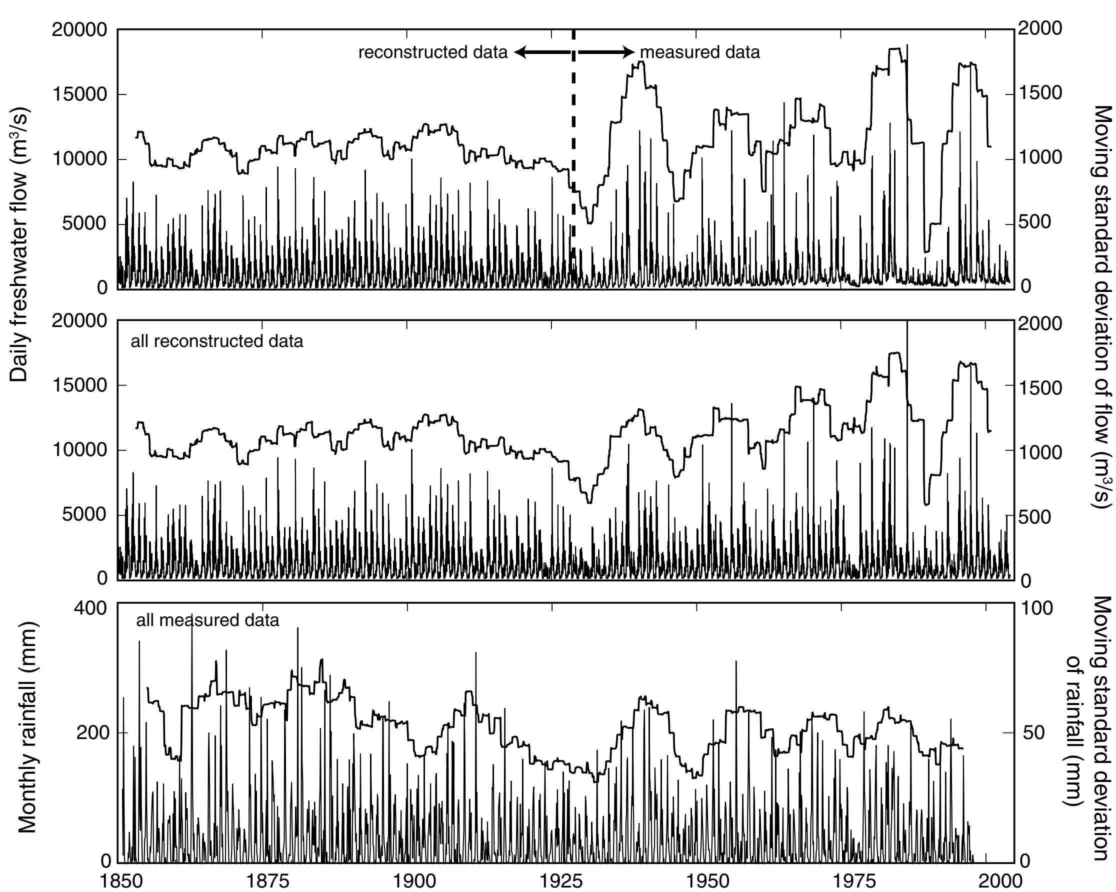

Figure 11 Combined reconstructed/measured freshwater flow record, entirely reconstructed record for 1851–2004, and entire measured rainfall record. Six-year moving standard deviation for each record is also shown.

reservoirs and water management. For hindcasting efforts prior to this influence, it is necessary to use a proper set of comparison data, as the system has been fundamentally changed. Reconstructed unimpaired flow data (Knowles, 2002) are critical to the matching procedure here, to avoid the erroneous comparison of impaired and unimpaired hydrographs.

Development of boundary conditions for decadal-scale hindcast models: morphological hydrograph

In any hindcasting endeavor, there are difficulties in estimating historical boundary conditions, when high-resolution data were not collected. The importance of these boundary forcings can be evaluated by quantifying their variability on the timescale of interest. For decadal-scale modeling of tidal basins and coastlines, the concept of the morphological tide (Latteux, 1995) has been applied in systems where freshwater flow and watershed sediment load are minor forcings. The morphological tide is a reduced set of boundary tidal stage and velocity that gives the same geomorphic change as the actual boundary tidal stage and velocity. This enables short-term (<1 y) simulations to be scaled up to the decadal timescale, thereby increasing computational efficiency and reducing data needs.

Models of estuarine geomorphology in San Francisco Bay require a similar concept, applied instead to freshwater flow and watershed sediment load. Over the decadal timescale, neither tidal forcing nor salinity conditions varied as much as sediment loading from hydraulic mining and sediment trapping behind dams. In a system with order-of-magnitude anthropogenic perturbations in sediment load, accurate representation of the perturbed sediment load is needed to hindcast geomorphic change. We intend to use the analogue selection procedure to explore the use of a morphological hydrograph. Because the procedure chooses from a limited set of hydrographs, frequently selected hydrographs (along with the appropriate sediment rating curve coefficients) may be modeled repeatedly to give the same bathymetric change as the actual set of hydrographs. A limited set of hydrographs can be selected to represent modes of runoff variability in the system, i.e. rainfall-dominated, snowmelt-dominated, mixed, or drought.

General approach to developing daily sediment load time-series

Developing a daily sediment load time-series during historical periods first requires identifying a proxy that covers the longest period of time, and can be related to a sediment-transport relevant variable: rainfall for unimpaired flow, in this case. Once the relationship during the concurrent period is established, the relationship is extended to all periods where only the proxy variable is available (assuming the relationship is stationary). In non-stationary systems, where sediment supply and water management have altered proxy relationships, suitable modifications must be made: these include variable rating curves (validated with historical data) and use of an appropriate set of modern data that eliminates anthropogenic effects. These reconstructed data, still at a coarse temporal scale, must then be downscaled using more frequent data, which are modern data in this case. The resulting daily sediment load time-series is constrained by the proxy data, the relation of the proxy to sediment load, and corrections for non-stationarity. Although applied to sediment load in this study, the method can be applied to other constituents as well.

Conclusion

The scarcity of daily flow data prior to the 20th century confounds estimating daily sediment loads. In cases where decadal sediment load estimates are available, a temporal downscaling method can be used to generate daily sediment load estimates. We reconstructed combined daily flows from the eight major rivers that drain the Central Valley of California, and calibrated a sediment rating curve using decadal estimates of sediment load. We first reconstructed monthly flows using monthly rainfall as a proxy. The monthly hydrographs from the historical era (1851—1929) were then compared with monthly hydrographs from the modern era (1967—1987, when daily unimpaired hydrographs are available), using a least-squares metric. The historical year was then assigned the daily hydrograph of the matched modern year, and the total flow was scaled to match independent dendrochronology-based reconstructions of total flow. The daily time-series of flow, along with the sediment rating curve, provide a daily time-series of sediment load, which, along with the concept of the morphological hydrograph, can be used as boundary conditions for hindcast simulations.

In addition to the utility for hindcast simulations, these time-series can be coupled with studies of contaminant deposition, marsh accretion, and climate change. The mass of sediment-associated contaminants exported from the watershed may be estimated, if a contaminant concentration is assigned to the sediment load estimates. Observations of marsh accretion, over decadal timescales, can be used in combination with these sediment load estimates to calculate potential trapping efficiencies of estuarine embayments and adjacent marshes. In view of future scenarios of climate and land use change, reconstructed time-series such as this provide a bounds on historical conditions in watershed—estuary systems.

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