Estimating reservoir sedimentation rates at large spatial and temporal scales: A case study of California

J. Toby Minear[1] and G. Matt Kondolf[1]

Received 27 November 2007; revised 8 June 2009; accepted 27 July 2009; published 25 December 2009.

[1] Previous reservoir sedimentation models have ignored two key factors for large spatial and temporal modeling of multiple reservoirs: trapping by upstream dams and decreasing sediment trapping as reservoirs fill. We developed a spreadsheet-based model that incorporates both factors. Using California as a case study, we used measured sedimentation rates to estimate sediment yields for distinct geomorphic regions and applied those rates to unmeasured reservoirs by region. Statewide reservoirs have likely filled with 2.1 billion m^3 of sediment to date, decreasing total reservoir capacity by 4.5%. About 200 reservoirs have likely lost more than half their initial capacity to sedimentation.

Citation: Minear, J. T., and G. M. Kondolf (2009), Estimating reservoir sedimentation rates at large spatial and temporal scales: A case study of California, *Water Resour. Res.*, *45*, W12502, doi:10.1029/2007WR006703.

1. Introduction

[2] Reservoir sedimentation is a serious problem in many regions with high sediment yield, particularly in, geologically active regions such as California. Small-capacity reservoirs in rapidly eroding mountain regions are most vulnerable to sedimentation problems. The costs of dealing with accumulated sediments can be prohibitively expensive and, for some dam removals, have been the greatest component of dam decommissioning costs [e.g., *U.S. Bureau of Reclamation*, 2006]. Even before reservoirs fill completely with sediment, sediment within the reservoir can reduce usable capacity, interfere with outlet works, damage turbines, and cause backwater flooding upstream [*Morris and Fan*, 1998]. Reservoirs filled with sediment may be at greater risk during earthquakes because accumulated sediment deposits are denser than water and may exert greater force against the dam during seismic shaking [*Chen and Hung*, 1993]. Reservoir sediments are also a significant global sink for carbon and other important nutrients [*Vorosmarty et al.*, 2003; *Stallard*, 1998]. In addition, the trapped sediment is not available for downstream economic and ecological benefits, such as beach replenishment [*Willis and Griggs*, 2003] or salmonid habitat, and release of sediment-starved water commonly causes bed incision in the downstream channel, which can result in downstream stream bank erosion, infrastructure damage, and drawdown of the alluvial water table [*Williams and Wolman*, 1984; *Kondolf*, 1997].

[3] In the design and maintenance of most reservoirs, little thought has been given to sustaining reservoir functions as capacity is progressively lost to sedimentation. Loss of reservoir capacity from sedimentation is difficult to offset with construction of new reservoirs because reservoirs have already been constructed at most viable sites in the developed world [*Morris and Fan*, 1998]. Maintaining reservoir capacity into the future will require that we address capacity losses from sedimentation, which requires tools to predict sedimentation rates and to identify reservoirs vulnerable to rapid sedimentation.

[4] Existing reservoir sedimentation models are not able to model large temporal or spatial scale patterns of sedimentation, primarily due to the extensive data requirements of the models. Current sedimentation models include process-based models that operate at small temporal and spatial scales and require data such as yearly or daily hydrologic records, detailed reservoir bathymetry, and sediment grain size distributions [e.g., *Ackers and Thompson*, 1987; *Sundborg*, 1992; *Lajczak*, 1996; *Tarela and Menendez*, 1999; *Rowan et al.*, 2000]. Similarly, geographic information system (GIS) based large spatial scale models estimate sedimentation on the basis of land use and/or hydrologic data [*Verstraeten et al.*, 2003; *Vorosmarty et al.*, 2003], which are lacking for most areas, particularly for historical periods. In addition, applying these process-based models without calibration can result in modeled sediment yields diverging from measured sediment yield rates by orders of magnitude [*Trimble*, 1999].

[5] Most importantly, existing reservoir sedimentation models do not account for two important factors: the effects of trapping by upstream reservoirs and changes in the rate of sediment retention, known as the trap efficiency, over time as reservoirs fill. As upstream reservoirs are built, they can reduce sediment yield to downstream reservoirs. This effect is particularly important in areas with numerous reservoirs within the same watershed, as exemplified by the 57 reservoirs on the American River and tributaries upstream of Folsom Reservoir, California (California Division of Safety of Dams (CDSD), Electronic database of dams and reservoirs in California, 2005, available at http://www.water.ca.gov/damsafety/).

[6] Temporally variable trap efficiency, the percentage of the incoming sediment trapped by a reservoir, is an important factor to include in sedimentation models when the time

[1]Department of Landscape Architecture and Environmental Planning, University of California, Berkeley, California, USA.

0043-1397/09/2007WR006703$09.00

Table 1. Reservoirs and Reservoir Sediment Yields by Geomorphic Region in California[a]

Geomorphic Region	Abbreviation	Number of Reservoirs: Total	Number of Reservoirs: Surveyed Reservoirs	Sediment Yield ($m^3\ km^{-2}\ yr^{-1}$): Median	25% of Median	75% of Median	Minimum	Maximum	Mean	Standard Error	Median Denudation Rate ($mm\ yr^{-1}$)
Coastal	C	370	23	262	160	406	19	3,419	417	142	
Central Valley	CV	18	4	89	36	234	24	277	120	55	0.032
Siskiyou	Sis	94	2	531	351	711	351	711	531	180	0.192
Peninsular	P	425	6	130	50	505	21	905	270	137	0.047
Sierra Nevada	SN	166	19	97	73	369	8	1,257	219	67	0.035
Transverse	T	127	12	519	304	986	93	5,085	919	389	0.188

Regions Without Sedimentation Data	Abbreviation	Number of Reservoirs: Total	Number of Reservoirs: Surveyed Reservoirs	Estimated Sediment Yield ($m^3\ km^{-2}\ yr^{-1}$)
Modoc	M	107	ND	531
Mojave Desert	MD	11	ND	97
Cascade	Cas	41	ND	531
Basin and Range	BR	17	ND	97
Colorado Desert	CD	3	ND	130
Colorado River	CR	3	ND	not used

[a]Capacity data from individual reservoirs used to determine sedimentation rates available at http://www.lib.berkeley.edu/WRCA/. We excluded the Colorado River geomorphic unit from this study because the river originates outside California and only a small portion of the state drains to the Colorado. ND indicates no reservoir sedimentation data used (either none reported or none meeting minimum standards for use in study). Estimated sediment yields are for regions with no data interpolated from nearby regions.

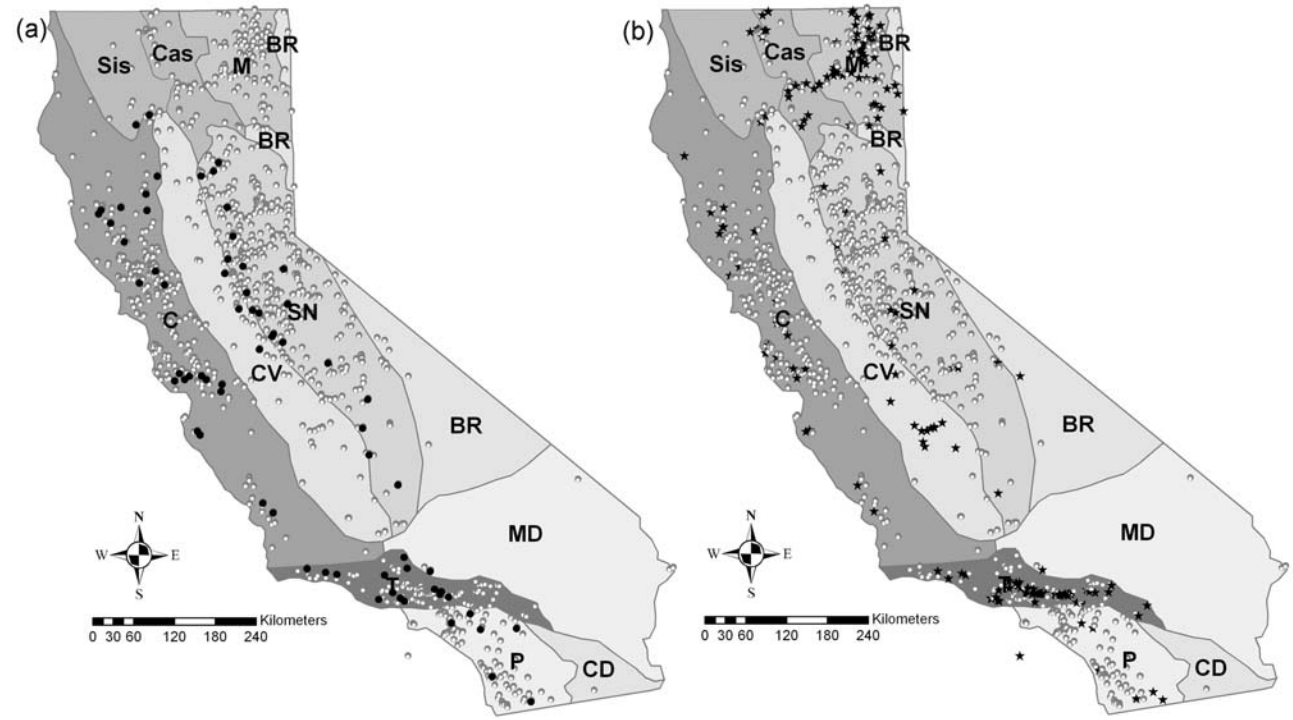

Figure 1. Reservoirs and geomorphic regions of California. (a) Reservoirs with measured sedimentation rates used in this study are shown with solid circles; others are shown with open circles. Geomorphic regions [from *CGS*, 2002] with higher median sediment yields are shown in darker shades; lower yield areas are shown in lighter shades. (b) Reservoir sedimentation predicted by the 3W model: open circles, >50% of capacity remaining; solid stars, <50% capacity due to sedimentation. The extent of the state extends from 32.50°N to 42.00°N and from 114.13°W to 124.40°W.

scale of the model is approaching the time scales at which appreciable changes occur in reservoir capacity because of reservoir sedimentation. For bed load sediment, trap efficiency is 100% (except in very small diversion or low-head navigation dams) but for suspended sediment trap efficiency varies roughly with the ratio of reservoir capacity to river inflow: large reservoirs typically approach 100% and small reservoirs are less efficient, with trap efficiency decreasing over time as sedimentation reduces capacity [*Brune*, 1953]. Previous reservoir sedimentation models have either not incorporated trap efficiency [*Dendy et al.*, 1973], thereby implicitly assuming 100% trap efficiency, or have used constant trap efficiency less than 100% [*Taylor*, 1983; *Renwick et al.*, 2005; *Vorosmarty et al.*, 2003].

[7] We developed a spreadsheet-based model that iteratively calculates sediment yield, accounting for trapping by upstream reservoirs and changing trap efficiency with time. As a case study, we applied the model to California, where a large number of the state's 1391 dams are in areas of high sediment yield. Dozens of small reservoirs in the state have already experienced significant capacity loss, and the population of reservoirs is aging: more than half are more than 50 years old, and at least 170 are more than a century old.

2. Methods

[8] Our approach consists of two parts: (1) a determination of sediment yield by geomorphic region from measured reservoir sedimentation rates and (2) the application of this sediment yield rate to unmeasured reservoirs in each region.

2.1. Determining Sediment Yield by Geomorphic Region

[9] To capture the pronounced regional variations in sediment yield, we used the geomorphic regions defined by the *California Geological Survey* (*CGS*) [2002] on the basis of similar climate, relief, geology, and vegetation (Table 1 and Figure 1a). To determine sediment yield by region, we compiled reservoir sedimentation data from *Dendy and Champion* [1973, 1978], *Federal Interagency Sedimentation Committee* (*FISC*) [1992], *Willis and Griggs* [2003], *Kondolf and Matthews* [1993], and unpublished data of B. Greimann, U.S. Bureau of Reclamation (personal communication, 2005). Remarkably few reservoirs in California have been subject to sedimentation surveys, with the number of surveys declining since the mid-20th century (Figure 2). We excluded three reservoirs (Matilija, San Clemente, and Englebright) that have been proposed for removal and have good sedimentation data to use to test our model.

[10] To locate the reservoirs, we initially assessed the Reservoir Sedimentation Information System (RESIS) [*Steffen*, 1996], which organized data from *Dendy and Champion* [1973, 1978] and *FISC* [1992] into a computerized database, later updated (as RESIS-II) with an automated location program that attempted to match coordinate data from each of the reservoirs, with approximately 75% success [*Stallard et al.*, 2001]. The RESIS-II database had inconsistencies in reported drainage areas and spelling of reservoir names [*Stallard et al.*, 2001], errors in reservoir location, and duplicate entries with conflicting data. We instead chose

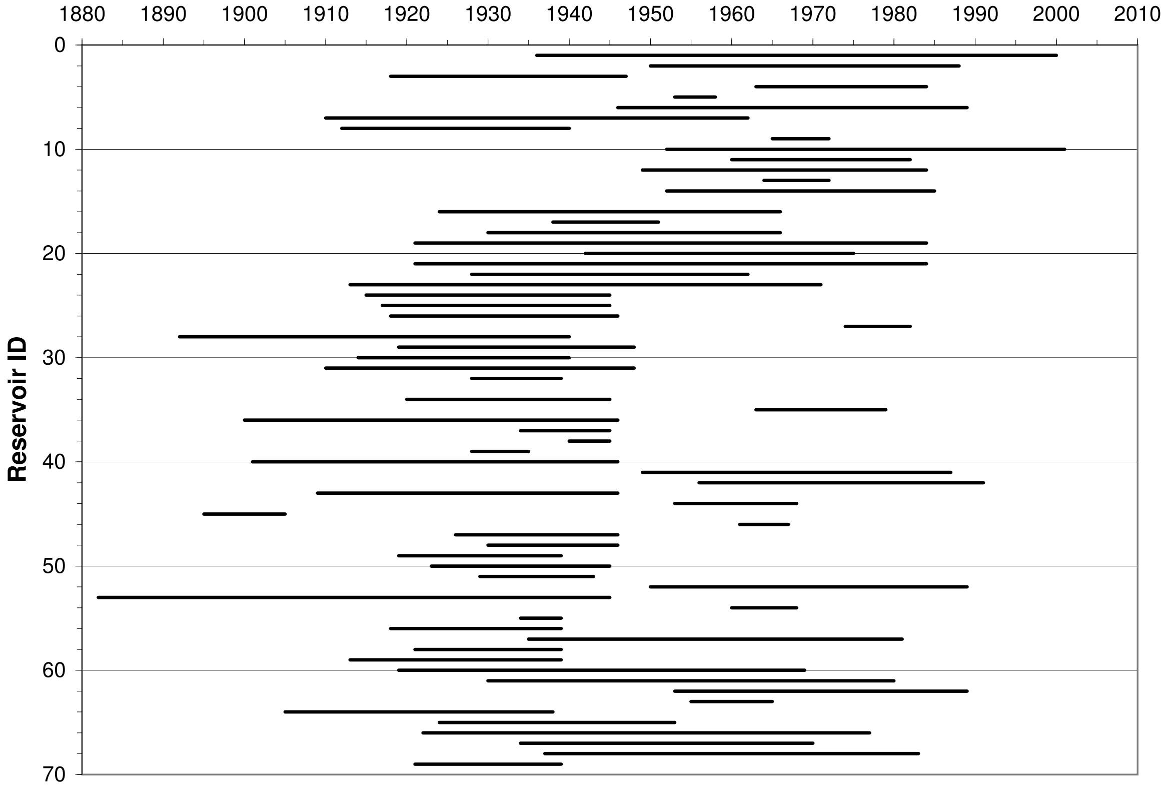

Figure 2. Period of reservoir sedimentation surveys in California. Note the sparseness of data for the latter part of the 20th century. Numbers on the *y* axis correspond to the reservoir identification numbers held on file at the University of California, Berkeley, Water Resources Center Archives.

to match the reservoir sedimentation records to the database of the CDSD, which regulates the 1391 dams in the state that exceed a threshold size of 7.7 m high and 18,500 m^3 storage capacity or 1.8 m high and 61,700 m^3 storage capacity. We initially identified 214 reservoirs with sedimentation records, from which we removed records for debris basins (89) and dry flood-control-only reservoirs (19) because they are dry most of the year and would have different trap efficiencies. We also excluded diversion dams (1) and reservoirs that lacked essential data, such as age or size (2). This left 103 reservoirs, for which we determined locations of 69 by matching the name, stream, size, and construction date to the CDSD database. The remaining 34 reservoirs were not used because we could not confidently determine their location.

[11] Using universal transverse Mercator (UTM) coordinates in the CDSD database, we plotted locations of all dams (measured and unmeasured) on a GIS map of California and compiled dendritic diagrams relating reservoirs to others upstream and downstream. Superimposing geomorphic regions of California [from *CGS*, 2002] onto the larger GIS map, we assigned each reservoir to one of the regions on the basis of its catchment's dominant geomorphic region. We deleted from our data set 189 dams in the CDSD database lacking drainage area, year completed, or UTM coordinates, leaving 1202 dams. Overlaid on a GIS layer of reservoirs and lakes, the CDSD dams typically plotted within tens of meters of where the hydrography data set displayed the appropriate lake or reservoir. There were significant differences between the CDSD and the National Inventory of Dams (NID) databases, despite the fact that the California entries in the NID were supposedly compiled from CDSD data. Hundreds of dams appeared in one but not the other database. The source of this discrepancy was not obvious.

2.2. Estimating Sediment Yield Rates by Geomorphic Region

[12] We used the following equation from *Brown* [1944] to calculate trap efficiency:

$$C_{a,t} = 1 - 1/\left[1 + (0.00021 \times K_{a,t-1}/W_a)\right], \qquad (1)$$

where $C_{a,t}$ is trap efficiency (expressed as a decimal percent) of reservoir a at time step t; $K_{a,t-1}$ is reservoir capacity (m^3) of reservoir a at time step $t-1$, calculated by equation (5); and W_a is drainage area (km^2) of reservoir a. We used the Brown equation instead of the better known Brune curve [*Brune*, 1953] because the Brune relation requires water inflow data, which were available for only about 20% of the reservoirs.

[13] To calculate the sediment yield from a basin with a reservoir that has a sedimentation record, we constructed a coupled worksheet model to calculate the weighted watershed area (adjusted for upstream construction of reservoirs and trapping effects) for a reservoir of interest, while taking into account trap efficiency for all reservoirs in the basin and construction of upstream reservoirs. For the first worksheet, we created a set of formulas, three versions of which are shown here for each time step (a year in this case),

taking into account trap efficiency as well as upstream reservoirs:

$$A'_{a,t} = \{C_{a,t}[A_a - (A'_b + A'_c + \ldots)]\}, \quad (2)$$

$$A'_{b,t} = \{C_{b,t}[A_b - A']\}, \quad (3)$$

$$A'_{c,t} = \{C_{c,t}A_c\}. \quad (4)$$

This set of equations represents the weighted watershed area (A') for a single time step for a set of reservoirs along a single mainstream. In the equation, A' is the weighted watershed area (km^2) during the time step; C is trap efficiency (decimal), calculated from *Brown*'s [1944] equation (1); A is the drainage area (not sediment contributing area) (km^2); subscripts a, b, and c denote different reservoirs: in this case reservoir a is farthest downstream and c is upstream of b; and subscript t denotes current time step (yearly in our case). If reservoirs b and c were on separate streams and not in line with each other, the formula to use for reservoir b would be equation (4).

[14] For the first part of the study, to determine the sediment yield rates for reservoirs with measured sedimentation rates, we differentiated between two populations of reservoirs: measured and unmeasured. Since the infill rates and sediment yield are not known a priori for the unmeasured reservoirs, we used the initial trap efficiency as the single value for unmeasured reservoirs upstream of the measured reservoir of interest. For the measured reservoirs, since we had both initial and final trap efficiency, we linearly interpolated between them to determine trap efficiency for the intervening years. For the second part of the study, when we applied the sediment yield rates to calculate reservoir sedimentation in unmeasured reservoirs, we calculated trap efficiency from the *Brown* [1944] curve on a yearly basis as described in equation (1).

[15] We used the following equation to determine the volumetric sediment yield for a single measured reservoir:

$$Y = X_a / \mathrm{sum}_{(t\ \mathrm{start\ to}\ t\ \mathrm{finish})}(A'_a) \quad (5)$$

where Y is the sediment yield of the basin (m^3 km^{-2} per time step), X_a is the amount of sediment accumulated in reservoir a (m^3), sum$_{(t\ \mathrm{start\ to}\ t\ \mathrm{finish})}$ is the sum over the years of the sedimentation survey from which X_a is derived, and A' is calculated from equations (2), (3), and (4) above. Here Y is a volumetric sediment yield, not sediment yield by weight, since it has not been corrected for the density of the sediment in the reservoirs.

2.3. Estimating Reservoir Sedimentation in Unmeasured Reservoirs

[16] For the second part of the study, estimating reservoir sedimentation in unmeasured reservoirs, we used the calculated volumetric sediment yield values for each geomorphic region from the first part of the study, applying the median sediment yield as well as the 25th and 75th quartiles (Table 1). For geomorphic regions lacking measured reservoirs (Modoc, Cascade, Basin and Range, and Mojave Desert), we assigned yields from nearby regions.

[17] We constructed a coupled three-worksheet (3W) model, similar to the model for estimating sediment yield, linking yearly time steps of varying trap efficiency, reservoir capacity, and reservoir sedimentation rate. For the first worksheet of the 3W model, we created a set of formulas, three of which are shown here, to calculate reservoir sedimentation in a given reservoir for each time step (a year in this case), taking into account trap efficiency as well as upstream reservoirs:

$$R_{a,t} = \{C_{a,t-1}[A_aY - (R_b + R_c + \ldots)]\}, \quad (6)$$

$$R_{b,t} = \{C_{b,t-1}[A_bY - (R_c)]\}, \quad (7)$$

$$R_{c,t} = \{C_{c,t-1}[A_cY]\}. \quad (8)$$

This set of equations represents the reservoir sedimentation R for a single time step for a set of reservoirs along a single mainstream. In the equation, R is the amount of sediment (m^3) trapped during the time step; C is trap efficiency (decimal), in this case calculated in the second worksheet from *Brown*'s [1944] equation (1); A is the reservoir's drainage area (not just the area below upstream dams) (km^2); Y is sediment yield (m^3 km^{-2} per time step); subscripts a, b, and c denote different reservoirs: in this case reservoir a is farthest downstream and c is upstream of b; and subscript t denotes current time step (yearly in our case), while subscript $t - 1$ represents the previous time step. If reservoirs b and c were on separate streams and not in line with each other, the formula to use for reservoir b would be equation (8). To determine the total amount of sediment deposited, R was summed for the period of interest.

[18] In the second worksheet, we calculated trap efficiency for each reservoir using the *Brown* [1944] curve, equation (1) in section 2.2, with the capacity term, K, calculated in the third worksheet. The third worksheet calculates the reservoir capacity to reflect the amount of sediment deposited in the reservoir during the previous time step:

$$K_t = K_{t-1} - R_t, \quad (9)$$

where K is reservoir capacity (m^3), t and $t - 1$ denote the current and previous time step, and R (m^3) is the calculated value from equations (6), (7), and (8) above.

[19] We assumed that reservoir sediments had a density of 960 kg m^{-3}, the median value from *Dendy and Champion* [1973, 1978] and *FISC* [1992], after comparing reported values of density among geomorphic regions and comparing the 3W model estimates of median yield with bedrock denudation studies using a rock density of 2650 kg m^{-3}. The linked 3W worksheets used to determine both steps of this study (estimating sediment yield from measured reservoirs and estimating reservoir sedimentation in unmeasured reservoirs) can be found in the auxiliary material for this paper.[1]

[1]Auxiliary materials are available at ftp://ftp.agu.org/apend/wr/2007wr006703.

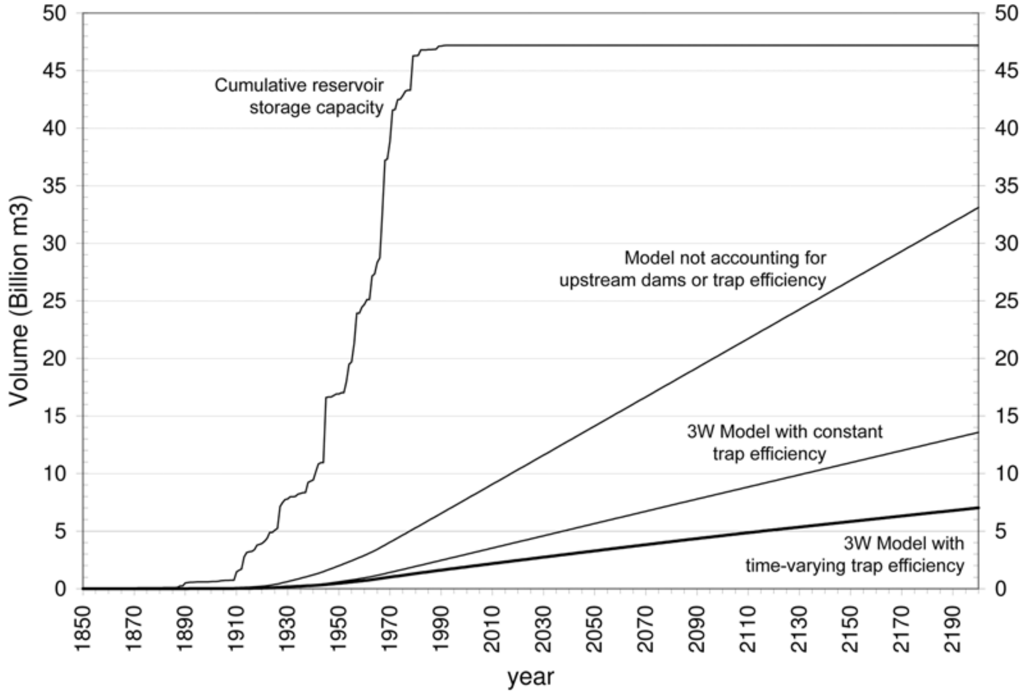

Figure 3. Cumulative reservoir capacity and estimates of reservoir sedimentation. Shown are long-term reservoir sedimentation accumulation predicted by the 3W model and predictions by simplified sedimentation models that do not account for multiple upstream dams or temporally variable trap efficiencies.

2.4. Uncertainty and Limitations of the Model

[20] Many variables influence sediment deposition within a reservoir, including flow, relative pool height, sediment supply from upstream, and sediment size and distribution, which vary regionally with geology, geomorphic delivery processes, land use history, fires, and climatic cycles. Our approach assumed that similar processes occur within geomorphic regions and that these processes are constant through time, which is a simplification necessary for computation. Thus, this model is appropriate for detecting regional trends and highlighting reservoirs potentially at risk of sedimentation but would not give accurate estimates of sedimentation within individual reservoirs.

[21] For our study, we assumed that the surface sediment samples from *Dendy and Champion* [1973, 1978] and *FISC* [1992] were representative of the sediment density found throughout each individual reservoir, but in reality sediment density can vary in a single reservoir with sample location and depth and how composite sediment density is calculated for the reservoir [e.g., *Snyder et al.*, 2006]. For the 3W model, we applied the median sediment density of 960 kg m^{-3} from *Dendy and Champion* [1973, 1978] and *FISC* [1992] (taken primarily from grab samples at the top layer of sediment) to all geomorphic regions in the study since there was little statistical evidence to support using a different value, but densities could vary among and within regions.

3. Results

[22] The median sediment yield in the state is 180 m^3 km^{-2} yr^{-1}, with the highest yield (520 m^3 km^{-2} yr^{-1}) in the Transverse Ranges and the lowest (89 m^3 km^{-2} yr^{-1}) in the Central Valley. Although compilations of sediment yield data typically show smaller yields from larger basins [*Walling*, 1983], no such trend was apparent in our small data set. Total annual sediment accumulated in California reservoirs through the year 2008 is estimated to be 2.1 billion m^3, representing a decrease of 4.5% of the state's total reservoir storage capacity of 47.2 billion m^3. Extrapolated to year 2200, the cumulative sedimentation is predicted to reach 7.1 billion m^3 (15% of statewide capacity) (Figure 3).

[23] The 3W model predicted that at present, over 120 reservoirs have capacities reduced to less than 25% of original capacity and almost 190 reservoirs have less than 50% of original capacity remaining (Figure 1b). These include not only small diversion dams and debris basins but also several moderate-sized reservoirs with well-known sedimentation problems, including San Clemente, Searsville, Jameson, Gibraltar, Matilija, and Century reservoirs.

[24] Comparing the 3W model results against sedimentation data for three well-studied reservoirs exposed some discrepancies, as should be expected when using median sediment yield. San Clemente Reservoir on the Carmel River decreased in reservoir capacity from 1.76 million m^3 in 1921 to 154,000 m^3 in 2000 [*Coastal Conservancy*, 2007], a difference of 1.62 million m^3. The 3W model predicted 1.65 million m^3 of sediment, close to the measured loss of capacity. Englebright Dam on the Yuba River was built in 1941 with an initial reservoir capacity of 86 million m^3. The 3W model estimated that Englebright

Reservoir should have 5.6 million m^3 of sediment on the basis of regional trends, but *Childs et al.* [2003] estimated the volume of sediment in the reservoir at 21.9 million m^3. This discrepancy may be explained by the fact that Englebright Dam was built as a debris basin to trap sediment from hydraulic mining upstream and much of the hydraulic mining sediment remains in tributaries continuing to move down into Englebright Reservoir [*James*, 2005]. As such, the catchment sediment yield of the Yuba River is likely much higher than elsewhere in the Sierra Nevada. Matilija Dam on Matilija Creek (Ventura River) was built in 1949 with a capacity of 8.66 million m^3, which decreased to 5.45 million m^3 in 1967 when the dam was lowered out of safety concerns arising from structural deterioration [*U.S. Bureau of Reclamation*, 2006]. Matilija Dam had approximately 615,000 m^3 (500 ac ft) of storage remaining in 1999, with the reservoir nearly full of 4.5 million m^3 of sediment trapped [*U.S. Bureau of Reclamation*, 2006]. The 3W model estimated 3.2 million m^3 of deposited sediment, or approximately 70% of the observed reservoir sedimentation.

4. Discussion

[25] When creating reservoir sedimentation models, it is important to take into account trapping by upstream reservoirs and incorporating variable trap efficiency in areas with numerous dams in the same watershed. Without taking into account upstream reservoirs, the total drainage area impounded by dams in California would appear to be 906,000 km^2 (over 2 times the area of the state). However, after correcting for reservoirs in upstream watersheds using the 3W model, the impounded drainage area drops to 186,000 km^2 (46% of the state). We compared the results of the 3W model against two simple reservoir sedimentation models, both of which did not account for trapping by upstream reservoirs and assumed either perfect trap efficiency or set trap efficiency to the static initial value. The two simpler models overpredicted reservoir sedimentation rates compared to the 3W model by 416% and 161%, respectively, up to the year 2008 (Figure 3). Without accounting for upstream dams or trap efficiency, total sedimentation in the year 2200 would be projected to be 33.1 billion m^3, or two thirds of the state's reservoir capacity, much higher than the volume projected by the 3W model (7.1 billion m^3).

[26] The 3W model as well as future reservoir sedimentation models could be improved by a statistical analysis of the *Brown* [1944] and *Brune* [1953] sediment trapping data since these curves are still recommended in standard reservoir engineering textbooks [*Vanoni*, 2006]. The Brown and Brune equations were derived by fitting the data by eye and, as such, no meaningful statistical information can be gleaned from them. We performed a brief statistical analysis during the course of this current study and found that compared to the original data, both Brown and Brune's equations produce residuals that have a trend and are not homoschedastic. An improvement of generalized trap efficiency equations would be a valuable contribution to the field. An expansion or evaluation of the quality of their data set also would be warranted. In California, a welcome addition to the current reservoir sedimentation database would be additional sedimentation surveys, particularly in geomorphic regions that have not been well studied such as the Siskiyou, Mojave Desert, and Modoc Plateau regions.

5. Conclusion

[27] Sediment accumulated in reservoirs creates costly problems for dam operation and ultimate decommissioning. Many of the dams on the landscape can be viewed as future maintenance problems, which will become more urgent as they fill with sediment and lose capacity. In addition, the carbon stored within reservoir sediments has been shown to be a significant sink of terrestrial carbon [*Stallard*, 1998]. Given that most reservoirs have not been surveyed for sedimentation, managers could benefit from a tool with which to identify at a regional level those reservoirs at higher risk of filling in the near future so that problems can be anticipated and countermeasures can be explored and implemented such as installation of upstream sediment traps, sediment pass-through, flushing, or mechanical removal.

[28] The 3W model presented here is the first such model to estimate reservoir sedimentation at a large number of reservoirs while taking into account the effect of reduced sediment input due to trapping by upstream dams, important in rivers with multiple dams. The model serves to identify reservoirs vulnerable to sedimentation problems by virtue of their size and regional sediment yields and which may be likely candidates for either removal or sediment management. Our analysis indicates that sedimentation rates are small relative to overall storage capacity statewide, but some individual reservoirs have been affected because of their small capacities and high sediment yields of their catchments. The model correctly identified several small reservoirs that have been recognized as having filled (or nearly so) with sediment and identified several others that are likely to experience such problems in the near future, which have important implications given the high costs of dredging or decommissioning such structures. While a state-level study was completed here, the 3W model could be applied equally well to individual watersheds with varying sediment yields. By anticipating which reservoirs are most vulnerable to capacity loss from sedimentation, the 3W model approach is a tool with which managers can identify reservoirs at risk and can implement countermeasures where feasible and warranted to avoid the costs of sediment-filled reservoirs.

[29] **Acknowledgments.** We are indebted to reviewers William Renwick and Greg Morris and an anonymous reviewer for their comments on the manuscript, Bob Stallard and Dave Mixon for sharing the RESIS-II database and insights regarding data quality, Blair Greimann and Cope Willis for sharing reservoir sedimentation data, and Jim Kirchner for advice on statistical approaches. The study was partially funded by CALFED Science Fellowship U-04-SC-005 (Minear) and by the University of California, Berkeley, Committee on Research (Kondolf).

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G. M. Kondolf and J. T. Minear, Department of Landscape Architecture and Environmental Planning, University of California, 202 Wurster Hall, Berkeley, CA 94720, USA. (tminear@berkeley.edu)