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RESEARCH PAPER

Analyses of the erosion of fine sediment deposit for a large dam-removal project: an empirical approach

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ABSTRACT

Large quantities of fine sediment can be accumulated in reservoirs, and the potential impact of their downstream release is often a great concern if the dams are to be removed. Currently, there are no reliable numerical models to simulate the dynamics of the release of these fine sediments, mostly because their release following dam removal is often driven by a rapid erosional process not addressed by traditional sediment transport theory. However, precise quantification of fine sediment transport is rarely necessary to evaluate potential environmental impacts of alternative scenarios. Using the removal of Matilija Dam in southern California, USA, as an example, we quantify the likely magnitude of suspended sediment concentration and the duration of associated downstream impacts, two necessary (and most likely adequate) parameters for assessing alternatives. The analyses first estimate the general magnitude of suspended sediment concentration and duration of impacts based on field and experimental data; they then quantify the duration of impacts under both worst-case and reasonable assumptions according to the underlying physics and common sense. For rapid sediment release with fine-grained impoundment deposits, initial suspended sediment concentrations are likely to approach 10^6 mg/L, persisting for a few hours to no more than a couple of days. Suspended sediment concentrations are expected to decline approximately exponentially after the initial peak, reaching background levels within a few hours to a few days, provided that sufficient flow is available. The general method presented in the paper should be useful for stakeholders choosing amongst dam-removal alternatives for implementation under similar conditions.

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Dam removal; numerical modelling and analysis; fine sediment erosion and transport; suspended sediment concentration and turbidity; empirical analysis

1 Introduction

Understanding how the sediment deposited within the reservoir impoundment may be managed is often the key component of a dam-removal planning project, which may ultimately determine whether a dam will be removed, and if so, then how it will be removed and how much funding is needed to have it removed. For medium- to large-sized dams, their reservoir deposits are usually stratified (e.g. Vanoni 1975) with fine sediment commonly deposited in the deeper water near the dam as a bottom-set deposit, overlain and potentially buried by coarse delta sediment that progrades from upstream of the delta area (i.e. top-set deposit) (Figure 1). Depending on the composition of upstream sediment supply, the top-set deposit can be composed of primarily gravel- to sand-sized sediments, while the bottom-set deposit is usually dominated by silt-sized particles, but can range from clay to sand. The exact morphology and texture of a reservoir deposit depends on many factors, including but not limited to the climate, geology, vegetation, composition of the upstream sediment supply, hydrological regime, height of the dam, number of years the reservoir has been in operation, operational history of the reservoir, and watershed land uses.

In order for stakeholders and regulating agencies to select and/or approve a dam-removal alternative, sediment transport modelling is often used to predict the transport dynamics of the release of the reservoir deposit upon dam removal (e.g. BOR 2006, Stillwater Sciences 2000, 2008, 2010, 2013, Bountry and Randle 2001, MEI 2003, Langendoen *et al.* 2005, Greimann and Huang 2006, Cui and Wilcox 2008, Langendoen 2010, Ferrer-Boix *et al.* 2014). The two different sets of reservoir deposits, however, can behave quite differently following dam removal and so require different analytical approaches to predict their behaviour. Erosion and subsequent release of the relatively coarse top-set deposit to the downstream reach following dam removal are usually relatively long-term processes (i.e. months to years) that are similar to traditionally studied sediment transport processes. As a result, numerical simulation of the erosion and transport of the top-set sediment deposit is usually feasible and often produces reasonable results, as confirmed by dam-removal projects where sediment transport modelling was conducted prior to dam removal and field data were collected before and after dam removal (e.g. Cui *et al.* 2014, Cui *et al.* under review).

In contrast, the erosion and transport of the fine-grained bottom-set deposit involve more rapidly varying hydrodynamic and fluvial processes not well-studied in traditional sediment transport research, making them more difficult to model and analyse. Making the matter more complicated, bottom-set deposits usually contain varying amounts of organic matter that can affect the erosional characteristics of the sediment deposits and their rheology once eroded. Where the volume of the bottom-set deposit is relatively small, its presence can probably be neglected because of its

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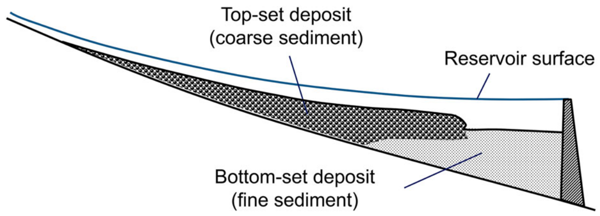

Figure 1. Sketch of a typical reservoir deposit, showing the coarse top-set deposit and fine bottom-set deposit.

expected short duration of impact upon dam removal. If there is a substantial amount of bottom-set sediment deposit, however, an analysis of its transport properties will likely be needed as it may impose a significant impact on the downstream ecosystem following dam removal and potentially on downstream water use.

Previous analyses and modelling involving bottom-set deposits generally have not distinguished the bottom-set deposit from the top-set deposit, but instead have used traditional modelling techniques (i.e. considering the sediment transport capacity of the flow) to simulate the erosion of the bottom-set deposit by applying simplifying assumptions. The modelling of dam removal on the Klamath River (Stillwater Sciences 2008) and the Englebright Dam on the Yuba River (Stillwater Sciences 2013), for example, assumed that erosion of both the top-set and bottom-set deposits is governed by the coarse-sediment transport capacity of the flow, and thus the fraction of coarse sediment contained in the top-set and bottom-set deposits partially determines the rate of erosion (i.e. sediment can be eroded more quickly if it contains less coarse sediment and more fine sediment). These techniques had answered the questions of concern for these two particular projects that were focused more on the longer term impacts, although there is still no validation as to how well the predictions match field observations because dam removal has not occurred in both cases.

There are modelling practices that consider the cohesive sediment properties that are more important to bottom-set deposits, such as the excess shear stress model of Partheniades (1965). Erosion of cohesive banks has also been incorporated into mechanistic models that simulate channel bed deformation according to the transport of coarse-grained particles similar to traditional sediment transport models, but consider bank erosion according to principles of bank stability (e.g. Langendoen *et al.* 2005, Langendoen 2010). Coupling mechanistic models of bed deformation with cohesive bank erosion for bottom-set deposit simulation in dam-removal projects, however, is a difficult task from the perspective of data collection. That is, to use these models in a predictive manner, the erosive parameters of the cohesive sediment deposits typically must be directly measured either *in situ* or in the laboratory (Hanson and Cook 2004), which is extremely difficult and time consuming because properties of the sediment deposits vary considerably longitudinally, transversely, and in depth.

For projects that require the prediction of short-term impacts, however, using the above techniques may not meet the need of the project because their short-term predictions are often deemed as not reliable. For example, stakeholders may ask questions with regard to the magnitude and duration of high suspended sediment concentration immediately following dam removal, which is something that the afore-mentioned modelling may not be able to reliably predict. In such cases, an approach that differs from that of traditional sediment transport modelling may be needed to satisfy project planning requirements. In this paper, we present the analysis for one such dam-removal project, Matilija Dam in southern California, as an example for how the erosion of these complex reservoir deposits can be analysed and how best to evaluate the impacts of post-removal sediment release.

2 Project background

Located on Matilija Creek within the Ventura River watershed in southern California, Matilija Dam (Figures 2 and 3) was 60 m tall upon its completion in 1948, with capacity of 8.7 million m^3. It was notched twice (in 1965 and 1977) to the current height of 51 m to reduce the risk of dam failure, reducing its capacity to approximately 6 million m^3. As a result of both sedimentation and notching, the Matilija Reservoir storage capacity had been reduced to less than 10% of its original design capacity by 2000, completely losing its design functionality for water storage (e.g. BOR 2006), with a sediment volume of approximately 4.5 million m^3 by 2000 (BOR 2006) and projected to be approximately 6 million m^3 by the end of 2014 (Stillwater Sciences 2014). The reservoir behind the dam will likely lose all its storage capacity by 2020 (BOR 2006). Because of the diminishing functionality

Figure 2. Photograph of the Matilija Dam, Matilija Creek, California, 30 April 2013. The scissors and the dashed line on the dam are not Photoshoped, but the product of unknown graffiti artist(s).

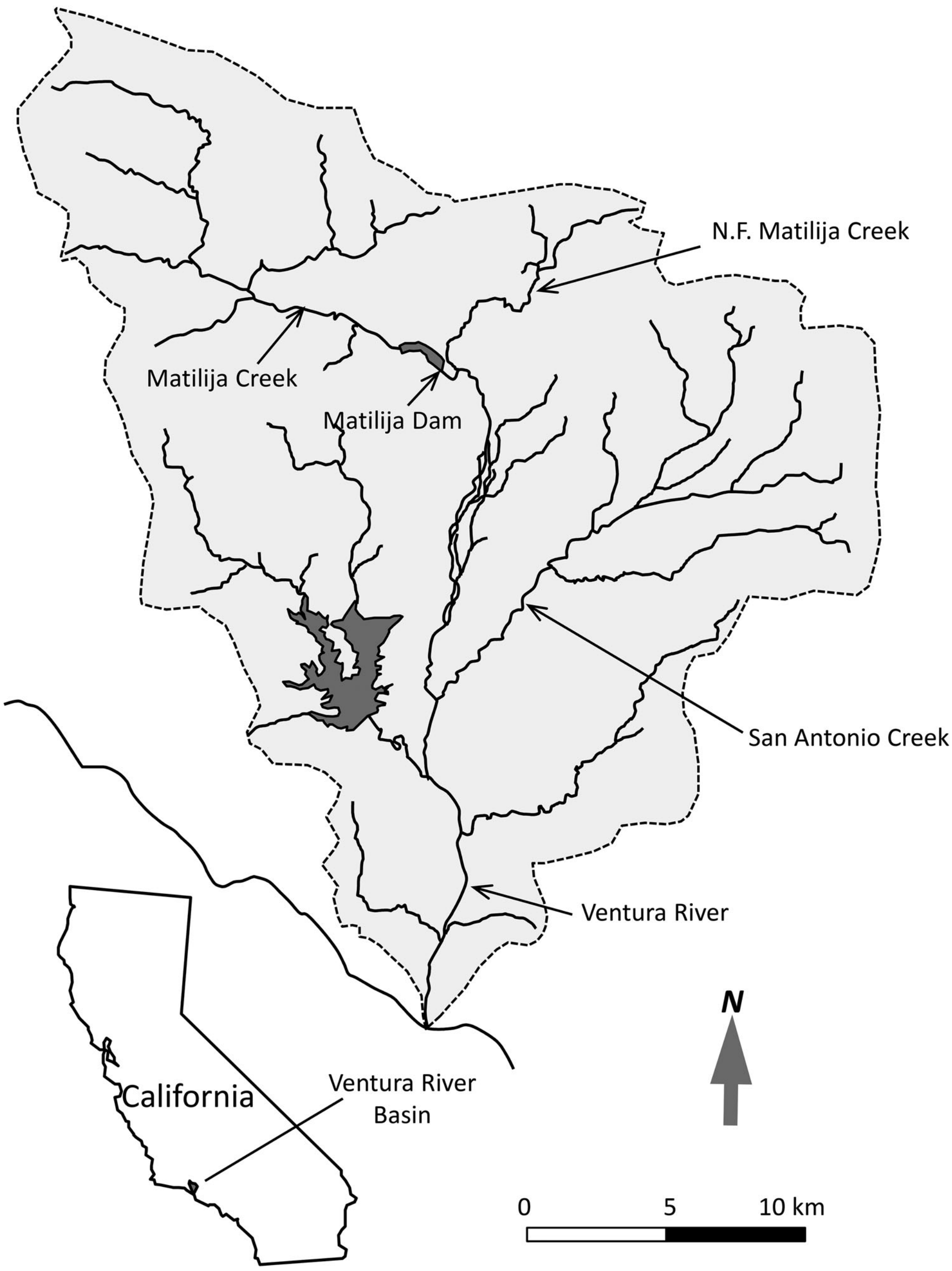

Figure 3. Map of the Ventura River watershed, modified from BOR (2006).

of Matilija Dam, Ventura County decided to pursue dam removal in 1998, and subsequent studies began in 2000. Removing Matilija Dam would not only eliminate a public safety liability, but also open up the valuable steelhead habitat in Matilija Creek and its tributaries currently blocked by the dam, potentially improving the fish population throughout the Ventura River watershed.

BOR (2006) classified the Matilija Dam impoundment sediment deposit into three distinct areas according to the composition of the deposits: an 'upstream channel' area composed primarily of coarse sediment, a 'delta' area composed of fine sediment covered by a coarse sediment cap, and a 'reservoir' area composed primarily of silt and clay (Table 1; Figures 4 and 5). Over four-fifths of the impoundment deposit is sand- and silt-sized sediment, of which most of this size fraction has settled in the delta and reservoir areas.

Since the initiation of the Matilija Dam removal feasibility study, there had been at least a score of potential alternatives evaluated, with the primary focus of these alternatives on how best to manage the sand and silt deposit in the delta and reservoir areas. The release of large quantities of fine sediment upon dam removal has been anticipated to generate a high suspended sediment concentration that would significantly impact the downstream riverine environment and potentially

Table 1. Volume and composition of Matilija Dam impoundment deposit in different areas as of year 2000, derived from data presented in BOR (2006).

Area	Reservoir	Delta	Upstream channel	Entire deposit
Gravel fraction (>2 mm)	<1%	13%	78%	20%
Sand fraction (0.0625–2 mm)	17%	54%	16%	34%
Silt fraction (<0.0625 mm)	83%	33%	6%	46%
Bulk volume (m^3)	1,600,000	2,100,000	800,000	4,500,000
Deposit mass (tonnes)	1,900,000	2,900,000	1,300,000	6,100,000
Bulk density (tonnes/m^3)	1.2	1.4	1.6	1.36

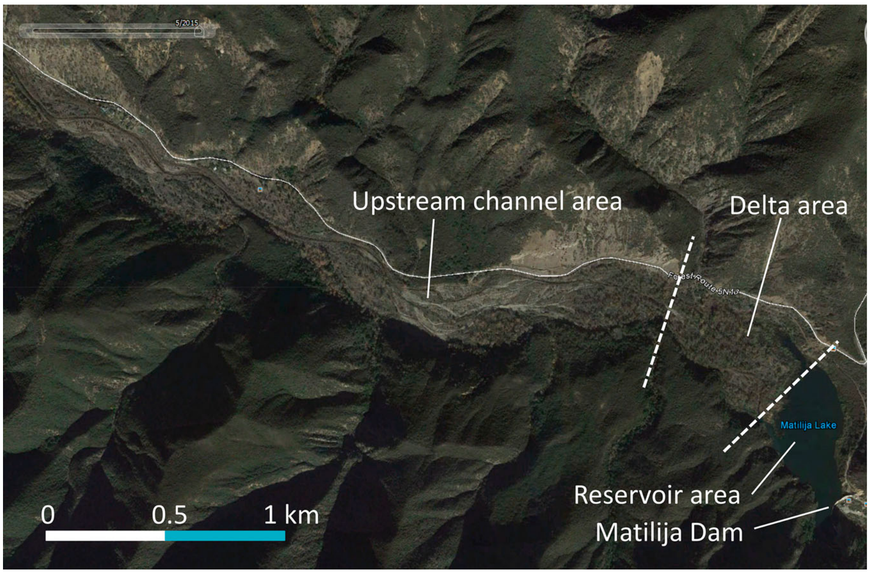

Figure 4. Aerial photograph (May 2015) of the Matilija Reservoir area, showing the approximate location of upstream channel, delta, and reservoir areas.

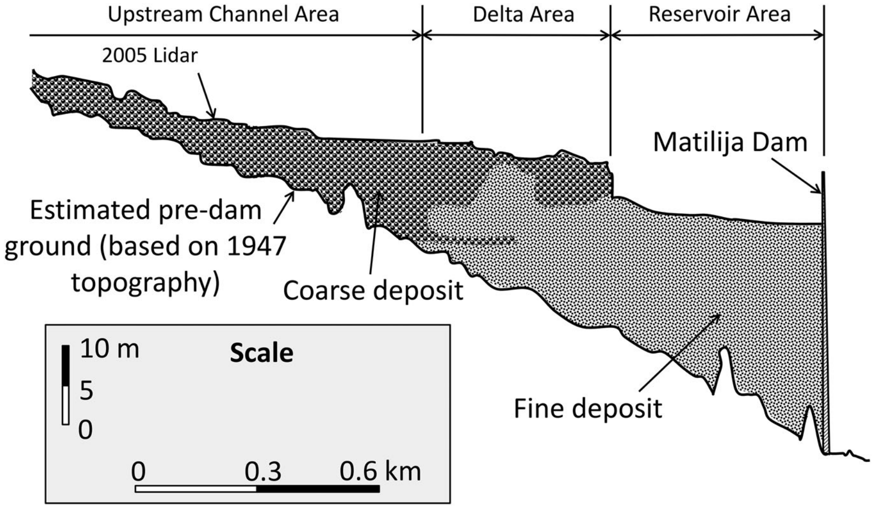

Figure 5. Interpreted longitudinal profile of sediment deposits within Matilija Dam impoundment, modified from Stillwater Sciences (2014).

affect a water-supply diversion at Robles Diversion Dam, located less than 4 km downstream of Matilija Dam. Because of these concerns, the primary removal alternatives favoured prior to 2014 called for the mechanical removal or stabilization of part of the fine sediment deposit in the delta and reservoir areas prior to dam removal. Over a decade of delay in advancing the project has been at least partially due to the difficulty and associated cost of removing and disposing the fine sediment of the impoundment deposit.

A recent study (URS and Stillwater Sciences 2014, AECOM and Stillwater Sciences 2015) has evaluated two dam-removal alternatives that would release the fine sediment to the downstream river by natural erosion during a designated high-flow event (4-year recurrence interval event or higher, with minimum 48 m^3/s daily average discharge and minimum 85 m^3/s peak discharge) without prior sediment management. The first of these alternatives includes the construction of cofferdams up- and downstream of the dam to divert water away from the dam site to facilitate dam removal. The cofferdams would be breached during a large flood event once the dam has been removed to initiate sediment erosion. The second alternative constructs one or more tunnels near the base of the dam from the downstream face of the dam, with a thin layer of concrete left at the upstream face of the dam to be blasted open only when a large flood event is forecasted to initiate sediment erosion. The combined size of the tunnel(s) would be large enough to accommodate the anticipated flow as open channel flow. Both alternatives rely on river transport of the reservoir deposit during the designed high-flow event. There is no sediment removal either by mechanical dredging or by natural erosion prior to the designed sediment erosion event for either of the two alternatives.

3 Lessons from prior dam removals

Observations from two dam-removal projects in the USA offer insight to the likely erosional process and suspended sediment concentration following Matilija Dam removal without prior sediment management: Condit Dam on the White Salmon River, Washington, and Marmot Dam on the Sandy River, Oregon.

Condit Dam was removed in October 2011 by first blasting a 5-m-diameter tunnel near the base of the dam to drain the reservoir and release the 1.8 million m^3 of sediment. The measured suspended sediment concentration in the White Salmon River downstream of Condit Dam reached 850,000 mg/L shortly after the opening of the tunnel (Figure 6) (Wilcox *et al.* 2014). Sediment deposit composition in Condit Reservoir is similar to that in Matilija Reservoir in that both have a fine (silt and clay) bottom-set deposit (i.e. the reservoir and delta area deposits in the case of Matilija Reservoir). As a result, the bottom-set deposit erosion from Condit Reservoir during dam removal should provide us with useful information on the potential erosion and transport of reservoir and delta area sediment deposits following Matilija Dam removal. The top-set deposits (the upstream channel area deposit in the case of Matilija Reservoir) for the two cases, however, are completely different: the Condit top-set deposit was composed primarily of sand-sized particles (60%) with a high fraction of silt and clay (35%), while the majority of the Matilija top-set deposit is gravel (78%) and sand (16%), plus a very small fraction of silt and clay (6%). The contrast between the top-set deposits in the two cases will result in a substantially different suspended sediment concentration during subsequent erosion phases, as discussed below.

Based on the information provided in Wilcox *et al.* (2014), the Condit Reservoir bottom-set deposit was approximately 600 m long and 10 m deep, and the estimated post-removal channel width in the bottom-set deposit area from a small-scale aerial photograph provided in Wilcox *et al.* (2014) is approximately 25 m, resulting in a total bulk volume of approximately 150,000 m^3. According to the estimate of Wilcox *et al.* (2014), approximately 160,000 m^3 of sediment was evacuated from the reservoir area within 90 min following the opening of the tunnel at the base of the dam, meaning most, if not all, of the bottom-set sediment was eroded and transported downstream within less than 2 h. Following the short period of bottom-set sediment erosion, suspended sediment concentration decreased from the 850,000 mg/L peak value to a negligible level of 100 mg/L, displaying a broadly exponential decline over about 7 weeks, during which the river maintained a slightly above 20 m^3/s base flow. After that period, a high suspended sediment concentration occurred only during high-flow events (Figure 6).

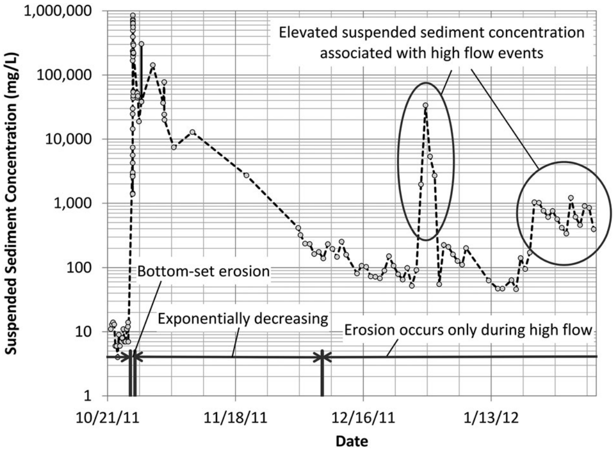

Figure 6. Measured suspended sediment concentration in White Salmon River at approximately 2.3 km downstream of Condit Dam during Condit Dam removal, showing different phases of sediment erosion. Suspended sediment data were provided by Wilcox et al. (2014).

Marmot Dam was removed in the summer of 2007, and the cofferdam constructed to divert the flow away from the impoundment area was breached in October of the same year during the first winter storm event, allowing the approximately 750,000 m^3 of coarse and fine sediment to be naturally eroded downstream. Unlike Matilija Reservoir deposit, the bottom-set sediment deposit in the Marmot impoundment was composed primarily of sand-sized particles and was completely buried under an approximately 5-m-thick coarse-sediment deposit, which happened to have almost identical grain size distribution to the top-set deposit of Matilija Dam impoundment (AECOM and Stillwater Sciences 2015). The suspended sediment concentration peaked shortly after cofferdam breaching, reaching approximately 37,000 mg/L (Figure 7) (Major *et al.* 2012, Cui *et al.* 2014). In addition to contributions from the erosion of buried sand deposit, the erosion of the cofferdam, which was constructed with gravel and sand mined from the reservoir deposit, also contributed to the increased suspended sediment concentration. The suspended sediment concentration quickly receded after peaking, reaching the background level within 10 h following cofferdam breaching. Other than the 10-h increase in suspended sediment concentration immediately after cofferdam breaching, only one mild increase (by approximately 1000 mg/L, with background concentration as high as 7000 mg/L) was observed in the next high-flow event.

4 Analyses of fine sediment transport

4.1 Conceptual model

We propose that the erosion processes of reservoir fine sediment deposits can be divided into two phases: 'Phase I' erosion, when the highly turbulent flow is in direct contact with the sediment deposit itself; and 'Phase II' erosion, when the flow is confined into the historical pre-dam main channel and thus cannot directly access the fine sediment deposit (Figure 8). During Phase I, the rate of sediment erosion (and hence the magnitude of suspended sediment concentration) is determined by the carrying capacity of the flow (i.e. transport-limited); whereas during Phase II, the rate of fine sediment erosion will be determined by how fast the sediment is delivered into the channel through out-of-channel processes such as bank slumping, gullying, and other mass wasting processes (i.e. supply-limited).

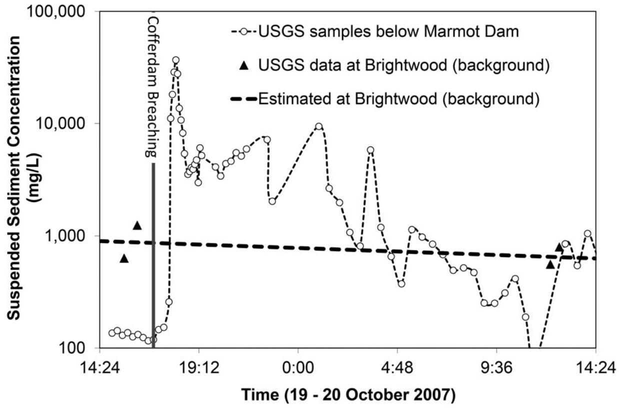

Figure 7. Measured suspended sediment concentration in Sandy River downstream of Marmot Dam during cofferdam breaching after Marmot Dam removal. Suspended sediment concentrations were derived from data provided by Major et al. (2012) and Cui et al. (2014).

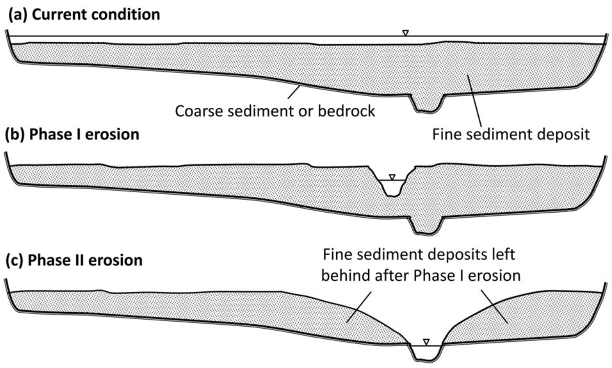

Figure 8. Sketches illustrating Phase I and Phase II erosion following Matilija Dam removal. (a) Current condition; (b) Phase I erosion when fine sediment is directly accessible to the flow, presenting a virtually unlimited supply of sediment with transport limited only by the capacity and rate of discharge; and (c) Phase II erosion when fine sediment is no longer directly accessible to the flow.

Although the processes of channel formation and sediment erosion during both Phase I and Phase II are not amenable to traditional approaches to modelling sediment transport that calculate sediment transport capacity based on shear stress on channel bed (e.g. Wilcock *et al.* 2009), alternative analytical approaches for each phase are available. The suspended sediment concentration during Phase I can be estimated with field and experimental data initially presented in Chang (1963) and summarized in Chien and Wan (1991) (Figure 9). A visual fit for Chang's (1963) data can be described by the following equation:

$$C = \begin{cases} 50\left(\frac{V^3}{gHv_s}\right)^{1.55}, & \frac{V^3}{gHv_s} \le 10 \\ 135\left[\ln\left(\frac{V^3}{gHv_s}\right)\right]^{3.1}, & 10 < \frac{V^3}{gHv_s} \le 100, \\ 620\left(\frac{V^3}{gHv_s}\right)^{0.7}, & \frac{V^3}{gHv_s} > 100 \end{cases} \quad (1)$$

in which C denotes suspended sediment concentration, in mg/L; V denotes the average velocity of the flow; g denotes

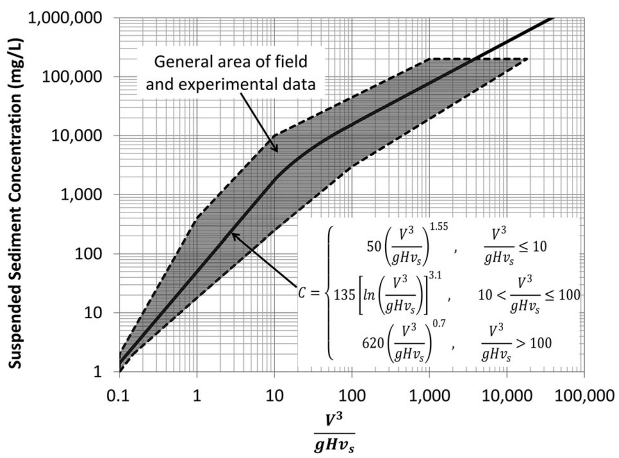

Figure 9. Relation quantifying suspended sediment concentration and dimensionless parameter $V^3/(gHv_s)$, originally presented in Chang (1963) and summarized in Chien and Wan (1991). Field and experimental data are generally scattered in the shaded area collected from: the Yangtze River, Yellow River, People's Victory Canal, Qingtong Gorge Irrigation District, Sanmen Gorge Reservoir, Guanting Reservoir, and flume data from Wuhan Institute of Water Conservancy and Nanjing Water Conservancy Research Institute, all located in China. The solid curve is a fit by visualization to capture the general trend of the data.

acceleration of gravity; H denotes average water depth; and v_s denotes the settling velocity of median-sized sediment particles.

Assuming an effective channel width of 25 m (based on the observation that channel width just downstream of the dam is generally less than 25 m), a Manning's n value of 0.025, a channel gradient of 0.023 (average local slope from 1947 topography), a discharge of 48 m^3/s (minimum daily average discharge during the first day of sediment erosion), and a median size of 0.011 mm (estimated based on data in BOR [2006]), the settling velocity for median-sized particles, average water depth, and average flow velocity are estimated to be 0.1 mm/s, 0.5 m, and 3.8 m/s, respectively. These values result in a $V^3/(gHv_s)$ value of approximately 1.1×10^5, well into the third expression for Equation (1). The predicted suspended sediment concentration is in excess of 1,000,000 mg/L (or 1 tonnes/m^3) for Phase I erosion by extrapolating the field and experimental data in Figure 9, or by applying Equation (1). It should be noted, however, the bulk density of sediment deposit in the reservoir area is 1.2 tonnes/m^3 (BOR 2006, Stillwater Sciences 2014; and Table 1). As a result, the suspended sediment concentration following dam removal cannot exceed 1.2 tonnes/m^3, or 1,200,000 mg/L. This limitation is considered in the analysis below.

Note that the $V^3/(gHv_s)$ and suspended sediment concentration values above far exceed the range of field and experimental data presented in Figure 9, but suspended sediment concentrations in excess of 1,000,000 mg/L occur regularly in the Yellow River basin in China under natural conditions (e.g. Table 2). The highest measured natural suspended sediment concentration in the Yellow River basin in the literature was 1,570,000 mg/L, recorded at Huang-Pu station in Huang-Pu-Chuan Creek in 1974 (Chien 1989). These observations indicate that a suspended sediment concentration close to or higher than 1,000,000 mg/L (but less than 1,200,000 mg/L) during Phase I erosion when there is unlimited sediment supply, as extrapolated using the data in Figure 9 or calculated with Equation (1), is not unreasonable. Field observations during sediment sluicing in Hengshan Reservoir, Shanxi Province, China, over the period of 1974–1982 (Table 3) (Qi *et al.* 2010) also indicate that suspended sediment concentrations of 1,000,000 mg/L do occur.

Note in Table 3 that the suspended sediment concentration during Hengshan Reservoir sediment sluicing not only reached 1,000,000 mg/L, but also was sustained at high levels for more than 24 h, with the mean suspended sediment concentration over the duration of the sluicing in excess of 400,000 mg/L in all the sluicing events except one. The relatively low mean suspended sediment concentration during that one sluicing event, however, was likely the result of previous sluicing events that occurred less than two months earlier (May 28 and 29, 1982), with potential additional contribution from the higher discharge during the sluicing (13.7 m^3/s, the highest amongst all the sluicing events) that may have resulted in a pressured flow through the sluice tunnel, which, in turn, elevated the pool level and thus reduced the erosion power of the flow.

The 850,000 mg/L suspended sediment concentration during bottom-set deposit erosion at Condit Dam provides additional confidence of the early estimate that suspended sediment concentration will likely be in the range of 10^6 mg/L following the initiation of sediment erosion for the Matilija Dam removal project. The 7-week-long

Table 2. List of the number of days when daily average suspended sediment concentration exceeded 400,000 mg/L in the mid Yellow River basin during the period of 1962–1971.

Region	River	Station	Number of occurrences with daily average suspended sediment concentration in the range of (×10³ mg/L)				Total number of occurrences >400×10³ mg/L	Maximum instantaneous (×10³ mg/L)	Calendar year maximum occurred
			400–600	600–800	800–1000	>1000			
He-Long Region, West Bank Tributaries	Huang-Pu-Chuan	Huang-Pu	22	18	12	4	56	1480	1967
	Ku-Ye-He	Wen-Jia-Chuan	19	11	4	1	35	1500	1964
	Wu-Ding-He	Shuan-Kou	34	19	3		56	1290	1966
	Qing-Jian-He	Yan-Chuan	39	45	8	1	93	1150	1964
	Yan-Shui	Gan-Gu-Yi	35	34	4	1	74	1210	1963
	Wu-Lan-Mu-Lun-Chuan	Wang-Dao-Heng-Ta	3	3	3	1	10	1510	1966
	Xiao-Li-He	Li-Jia-He	21	30	23	2	76	1220	1963
He-Long Region, East Bank Tributaries	Zhu-Jia-Chuan	Hou-Gu Villiage	39	46	4		89	1260	1964
	Lan-Yi-He	Pei-Jia-Chuan	20	4			24	923	1967
	Qiu (Jiao)-Shui-He	Lin-Jia-Ping	60	9			69	960	1965
	San-Chuan-He	Hou-Da-Chen	21	1			22	819	1969
	Xin-Shui-He	Da-Ning	22				22	741	1966
Mainstem Wei River	Wei River	Qiu-Jia-Xia	17	4			21	939	1966
	Wei River	Nan-He-Chuan	29	4			33	811	1963
	Wei River	Hua-Xian	16	2			18	753	1968
Tributary to Wei River	San-Du-He	Gan-Gu-Yi	61	31			92	980	1969
	Hu-Lu-He	Qin-An	37	4			41	905	1968
Jing-He River Basin	Jing-He	Yang-Jia-Ping	34	1			35	875	1970
	Jing-He	Zhang-Jia-Shan	36	17			53	1040	1963
	Huan-Jiang	Hong-De	57	82	74	1	214	1130	1970
	Pu-He	Mao-Jia-He	49	10			59	992	1965
Luo River	Luo River	Fu-Tou	57	46	7		110	1090	1967

Note: Data in the table were obtained from Chien (1989).

exponentially decreasing suspended sediment concentration following Condit Dam removal (Figure 6), however, was the result of the erosion of the top-set deposit that released the 35% silt and clay contained in that deposit. The top-set deposit in Matilija Reservoir (upstream channel area) contains a minimal amount of silt and clay (6%), and as a result, the increased suspended sediment concentration associated with its erosion will likely be minimal, as discussed below in comparison with observations during Marmot Dam removal.

4.2. Volume of fine sediment erosion

Approximately 2,830,000 tonnes of fine sediments are deposited in the roughly 1-km-long delta and reservoir areas of Matilija dam impoundment (Figures 4 and 5). Both theory (discussed below) and observations (e.g. Condit Dam removal discussed earlier) indicate that fine sediment will be readily transported once sediment erosion is initiated during a large flood event, as the fine sediment deposit is unconsolidated and lacks the strength to withstand erosion. The critical shear stress for fine sediment erosion, for example, is slightly below 0.1 Pa using the diagram provided in Pant (2013), whereas the estimated shear stress of the flow under 48 m^3/s discharge (the minimum daily average discharge in day one following dam removal) is no less than 73 Pa, or almost three orders of magnitude higher. Due to the minimal resistance to erosion of the fine sediment deposit for this specific case, it is expected that the flow will quickly settle into the pre-dam topographic low (i.e. pre-dam main channel), being constrained at the dam site by bedrock walls. Once the flow settles into the pre-dam main channel,

Table 3. Suspended sediment concentration in Tangyu River downstream of Hengshan Dam in Shanxi Province, China, during Hengshan Reservoir sediment sluicing between 1974 and 1982.

Date of sluicing	Sluicing duration (h)	Maximum discharge (m^3/s)	Mean discharge (m^3/s)	Maximum concentration (mg/L)	Average concentration (mg/L)
28 July 1974	63.3	8.0	1.1	944,000	422,000
8 August 1979	26.0	54.4	4.9	1,200,000	622,000
28 May 1982	31.5	33.0	1.1	1,320,000	837,000
24 July 1982[a]	19.3	36.3	13.7	1,200,000	215,000

Note: Data in the table were obtained from Qi et al. (2010).

[a]This event occurred within two months of the May 1982 sediment sluicing events, which was likely a primary contributor to the significantly lower average suspended sediment concentration compared to other sluicing events; the significantly higher discharge (13.7 m^3/s) might also have contributed to the lower suspended sediment concentration because the sluicing gate might not have been able to accommodate the flow as open channel flow, resulting in an elevated reservoir pool level and reduced sluicing efficiency.

it will be steep (~2% gradient) and confined by the pre-dam banks, precluding significant river meandering. As such, the potential volume of fine sediment erosion can be estimated by assuming a post-erosion trapezoidal channel with reasonable assumptions for the channel width and bank slope. Assuming a base width of 20 m and a bank slope of 35°, for example, would result in approximately 880,000 tonnes of fine sediment erosion; increasing the base width to 30 m and decreasing the bank slope to 30° would increase the fine sediment erosion to approximately 1,170,000 tonnes.

4.3 Duration of Phase I erosion

A large but ultimately finite volume of fine sediment has been deposited in the impoundment, and its release into flood flows with concentrations approaching 10^6 mg/L will surely result in downstream impacts. However, the *duration* of any such impacts will be limited if the discharge in the creek is sufficiently high during dam removal. For example, consider the erosion of 1 million tonnes of sediment, a likely first-order estimate of the magnitude of fine sediment that would be eroded during Phase I. Assuming a suspended sediment concentration of 500,000 mg/L, it would take approximately 23 days to erode all the 1 million tonnes of sediment under a 1 m^3/s discharge, but less than just 6 h if the discharge was 100 m^3/s. Since suspended sediment concentrations usually increase with increased water discharge, the degree to which the duration is shortened by virtue of greater water discharge is usually even more dramatic.

Although suspended sediment concentration during Phase I erosion will likely be in the 1,000,000 mg/L range, Table 4 provides the estimated duration of Phase I erosion under more conservative suspended sediment concentration values: 850,000 mg/L is identical to the observed suspended sediment concentration during Condit Dam removal (see above), and 500,000 mg/L is less than 50% of the potential suspended sediment concentration estimated above. As discussed earlier, the bankfull channel width in the Matilija Creek downstream of Matilija Dam is no more than 25 m, which would result in approximately a 20-m base width under a 35° bank slope and 2-m bankfull depth for a trapezoidal channel. As a result, a 30-m base width is a conservative estimate (i.e. an estimate that would produce more sediment erosion). Because of the rapid downcutting during Phase I erosion, the resulting channel banks are likely steep, and both the 35° and 30° estimates provided in Table 4 are also likely conservative for Phase I erosion, even though the bank slope may continue to flatten by episodic slope failure after the conclusion of Phase I erosion.

Results in Table 4 indicate that Phase I erosion at the Matilija Dam impoundment following instantaneous dam removal during flood flows will last for no more than 12–27 h under conservative assumptions. Even under the implausible, end-member case of a channel expanding to evacuate all the fine sediment in reservoir and delta areas during Phase I (over 2 million m^3 volume) erosion would only take 38–65 h to finish (but then there will be minimal Phase II erosion). That is, Phase I erosion, and the downstream impacts associated with extremely high suspended sediment concentrations, will most likely be confined within a full day, and almost certainly not last for more than three days.

4.4 Duration of Phase II erosion

Once the flow settles into the historical channel and loses direct contact with the fine sediment deposit, the rate of erosion and downstream sediment transport will be driven by out-of-channel processes that deliver sediment to the channel. There are two primary mechanisms for such processes: (a) bank slumping as water drains out of the deposit, driven by gravity; and (b) local surface erosion during precipitation. The duration of bank slumping is primarily determined by how fast the deposit will be drained to a water content that allows the deposits to maintain their stability. Observations during the Hengshan Reservoir sediment sluicing indicated that bank slumping lasted for a short while (less than 8 h) (video clips analysed/described in URS and Stillwater Sciences 2014, AECOM and Stillwater Sciences 2015). Due to the finer sediment deposit in Matilija reservoir area (0.011 mm median size) compared to Hengshan Reservoir deposit (0.02 mm median size), we expect bank slumping in Matilija Reservoir to last longer compared to Hengshan Reservoir sediment sluicing, but it is unlikely to exceed a couple of days.

For surface erosion driven by precipitation, the exposed area subject to surface erosion following Phase I erosion is less than 0.1% of the total drainage area of the Matilija Creek at Matilija Dam, making the relative importance of this process on downstream watercourses critically dependent on the background suspended sediment concentrations during 'typical' floods: for a watershed with low intrinsic sediment yields, this may be a significant contribution; for a watershed with high sediment yields, however, this process may be indistinguishable from background levels. Prior investigations into sediment yields of the Transverse Range of southern California (e.g. Booth *et al.* 2014) suggest that the latter condition is far more likely here, with measured suspended sediment levels in channels throughout the Ventura River watershed regularly exceeding 1000 mg/L for even modest flood flows (BOR 2006), confirming this supposition.

The direct erosion of the top-set sediments will also produce some additional fine sediment, but its contribution to increased suspended sediment concentration is likely

Table 4. Estimated duration for Phase I erosion, assuming a 48 m^3/s discharge under various assumptions.

Suspended sediment concentration (mg/L)	Base width (m)	Bank angle[a] (degrees)	Fine deposit erosion (tonnes)	Phase I erosion duration (h)	Evaluation of presumed channel geometry
500,000 (very conservative estimate)	20	35	880,000	20.4	More likely scenario
	30	30	1,170,000	27.0	Conservative, but plausible
			2,830,000	65.4	Absolute maximum[b]
850,000 (conservative estimate)	20	35	880,000	12.0	Likely scenario
	30	30	1,170,000	16.0	Conservative, but possible
			2,830,000	38.4	Absolute maximum[b]

[a]Assumes a trapezoidal channel will form in the reservoir area, cutting through the existing deposit to reach the pre-dam bed.
[b]Assumes all the sand and silt deposit in reservoir and delta areas are eroded during Phase I erosion.

minimal given the low fraction of fine sediment in this deposit (Table 1). This condition was observed in the Marmot Dam removal project, which had similar top-set deposit as Matilija Reservoir (discussed above).

The maximum possible duration of Phase II erosion can also be considered analytically. The key assumption of this analysis is that the rate of sediment delivery into the channel (erosion rate hereafter) decreases exponentially:

$$E = E_0 \exp[-k(t - t_0)], \quad (2)$$

in which E denotes the rate of sediment delivery to the channel (mass per unit time); E_0 denotes E at the beginning of Phase II erosion and is assumed to equal the (constant) concentration during and at the end of Phase I; t denotes time following the start of sediment erosion; t_0 denotes the time over which Phase I erosion occurred; and k defines the rate of exponential decaying of sediment erosion and delivery to the channel.

An exponential decay function such as Equation (2) fits many natural processes, and has been a long-standing hypothesis in geomorphology to describe the fluvial response rate to disturbance (Graf 1977). The measured suspended sediment concentration during Condit Dam removal, for example, can be expressed nicely as an exponential decay function before it reached a negligible level of approximately 100 mg/L (Figure 6). Collins *et al.* (in review) also reported the exponential decay of deposit volume following dam removal, which translates to exponential decay of erosion rate.

Because there is a finite volume of fine sediment that is available for delivery to the channel, a slowly decreasing erosion rate (i.e. a smaller k value) would keep the erosion rate high, but as a result will exhaust the sediment source more quickly (Figure 10(a)). A faster decrease in the erosion rate (i.e. a higher k value), on the other hand, would reduce more quickly the suspended sediment concentration to a level that is insignificant compared to the background conditions (Figure 10(b)). Thus, the worst-case scenario (i.e. the longest possible duration of discernable impacts from Phase II erosion) would be that the erosion rate declines such that the sediment source exhausts at the exact time when the suspended sediment concentration reaches a defined 'insignificant' or non-impact level (i.e. $k = k_i$ in Figure 10). To evaluate this condition, an initial value for E_o must be chosen, which for simplicity is assigned the presumed erosion rate during Phase I erosion under the 48 m^3/s discharge (i.e. minimum daily average discharge). Considering that $C = E/Q_w$, the above-described worst-case scenario can be expressed as follows:

$$C_i = \frac{C_1 Q_{w1}}{Q_{wi}} \exp[-k_i(t_i - t_0)] \quad (3)$$

and

$$M_2 = \int_{t_0}^{t_i} C_1 Q_{w1} \exp[-k(t - t_0)]\, dt, \quad (4)$$

in which C_i denotes the incremental suspended sediment concentration that is defined to be a minimal (or acceptable) increase in impact to the downstream environment relative to background conditions; C_1 denotes the suspended sediment concentration at the end of Phase I erosion; Q_{w1} denotes water discharge at the end of Phase I erosion; Q_{wi} denotes

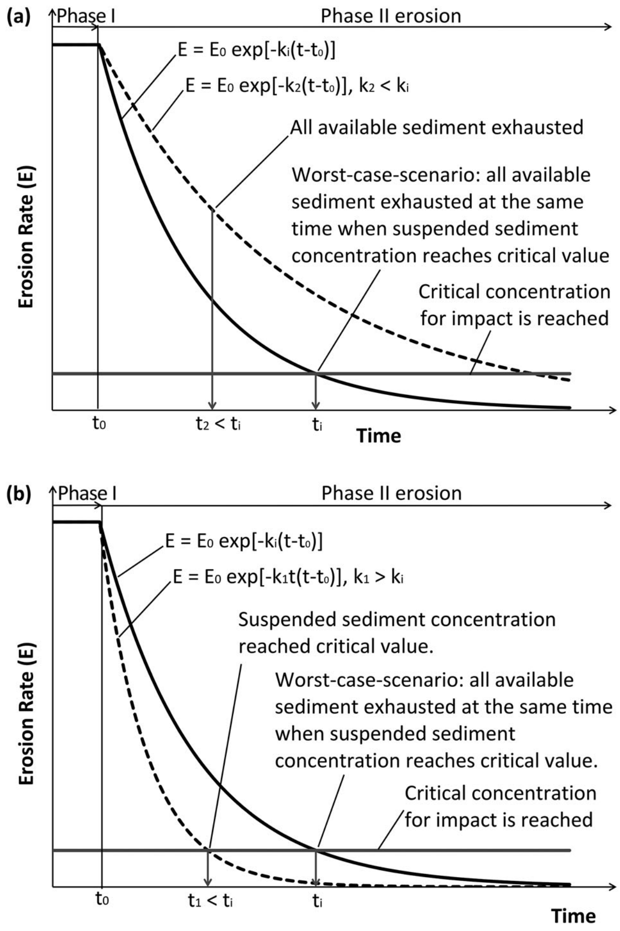

Figure 10. Illustration of the concept of maximum potential duration for Phase II erosion. (a) A slower decrease in erosion rate would result in a quicker exhaustion of sediment source; and (b). a faster decrease in erosion rate would result in a quicker realization of critical suspended concentration for impact.

water discharge at the time incremental suspended sediment concentration reached the non-impact level; k_i denotes the exponential coefficient that would result in the longest possible duration of impact; t_i denotes the longest possible Phase II impact duration; and M_2 denotes the total mass of fine sediment deposit that will be eroded during Phase II erosion. Solving Equations (3) and (4) results in the following expression for the longest possible impact duration:

$$t_i - t_0 = \frac{M_2}{C_1 Q_{w1} - C_i Q_{wi}} \ln \frac{C_1 Q_{w1}}{C_i Q_{wi}}. \quad (5)$$

Table 5 presents a few sets of calculated maximum possible durations for Phase II impact (i.e. $t_i - t_0$), with the assumptions that (a) all the 2,830,000 tonnes of fine sediment in the reservoir and delta areas will be released to the downstream during Phase I and II erosion, and (b) the non-impact suspended sediment concentration is 1000 mg/L, a value that is now reached in Matilija Creek and Ventura River during virtually all flood events (see above). Note that the 1000 mg/L non-impact suspended sediment concentration used here is only an assumption for the purpose of analysis, and project stakeholders have not agreed on a non-impact level for the project yet. Results in Table 5 indicate that the maximum potential Phase II erosion duration is likely a few days (rather than weeks), even under the worst-case-scenario assumptions. Note that a significant portion of the fine sediment in the reservoir and delta areas will be left behind

Table 5. Calculated maximum duration of potential Phase II impact, assuming a 48 m^3/s water discharge during Phase I erosion, 1000 mg/L non-impact incremental suspended sediment concentration, and erosion of all the fine sediment in the reservoir and delta areas.

Phase II water discharge at the time of non-impact condition (m^3/s)	Phase I erosion (tonnes)	Maximum possible Phase II erosion (tonnes)	Maximum potential Phase II erosion duration (days)	Note
48	880,000	1,950,000	3.7/5.8	20-m/35° Phase I channel
	1,170,000	1,660,000	3.2/5.0	30-m/30° Phase I channel
	2,830,000	0	0.0	All fine eroded during Phase I erosion
14	880,000	1,950,000	4.4/7.0	20-m/35° Phase I channel
	1,170,000	1,660,000	3.7/5.9	30-m/30° Phase I channel
	2,830,000	0	0.0	All fine eroded during Phase I erosion
4.8	880,000	1,950,000	5.0/8.0	20-m/35° Phase I channel
	1,170,000	1,660,000	4.2/6.8	30-m/30° Phase I channel
	2,830,000	0	0.0	All fine eroded during Phase I erosion

Note: The two duration values in the table are the results of two different Phase I concentration values (i.e. 850,000 and 500,000 mg/L, see Table 4).

permanently after Matilija Dam removal due to the high deposit-width to channel-width ratio (up to approximately 15:1). As a result, the assumption that all the fine sediment will be eroded following dam removal is a conservative assumption, and the actual Phase II impact is likely significantly shorter than what is provided in Table 5. This analysis supports the prior, physics- and empirical-based assessments that the impact duration will most likely be confined to within a couple of days of high flow following dam removal.

Note the analysis above assumed that water discharge in the creek maintains a constant value that equals the daily average discharge during the 12- to 20-hour Phase I erosion. While the actual water discharge in the creek will surely not maintain a constant value as assumed, changing the discharge to a non-constant (but averaged to be close to or higher than the assumed constant discharge) does not change the overall physics of the process. As a result, it is reasonable to believe that the results of the analysis can be extended to variable discharge conditions.

Once the fine sediment erosion from the reservoir and delta areas are diminished, the erosion of the top-set deposit during high-flow events will likely continue to deliver a small amount of additional fine sediment to the downstream reach. Fine sediment production from top-set erosion, however, is unlikely to significantly increase suspended sediment concentrations, as demonstrated by the quickly diminishing suspended sediment concentration observed in the Sandy River during Marmot Dam removal (Figure 7), where the grain size distribution of the top-set deposit is almost identical to that of the Matilija impoundment top-set deposit.

Also note that our analysis assumed that the channel within the impoundment will initially form directly above or very close to the historical channel following dam removal. In the unlikely event that the initial channel formation is far away from the historical channel in the historical floodplain area, there can be considerably more Phase I erosion as the channel slides from its initial location to the historical channel, removing the sediment in between. If this occurs, however, the amount of sediment left behind for subsequent Phase II erosion will be reduced correspondingly. As a result, the duration for combined Phase I and Phase II erosion will also be reduced at least for the worst-case scenario that all the fine sediment be eroded during the two phases of erosion, because the suspended sediment concentration (and erosion rate) for Phase II erosion is projected to be lower than that during Phase I erosion. That is, the scenario for the initial channel to form away from the historical channel is a more favoured scenario in terms of minimizing impact duration, and as a result, it is not analysed in this paper.

5 Discussion

We have presented semi-quantitative assessments of sediment transport dynamics following Matilija Dam removal under the quick sediment release scenario, focusing on the possible magnitude and duration of impact from increased suspended sediment concentration. Due to limitations in the current state of the science in sediment transport theory and practice, attempting to provide a more precise modelling of the erosion process following dam removal is unlikely to be fruitful. Our analyses rely on a conceptual model of sediment erosion processes in these settings (i.e. the two phases of fine sediment erosion), applying simple mathematical representations of the net erosion resulting from those processes, and verifying the predictions using observations from natural rivers, prior reservoir management activities, and dam-removal projects (i.e. observations in the Yellow River basin, Hengshan Reservoir sediment sluicing, Marmot Dam removal project, and Condit Dam removal project) to reach useful conclusions. Rather than providing a simulated suspended sediment concentration time series, our analyses provide the general magnitude of suspended sediment concentration, and the most likely and maximum possible durations of impact due to increased suspended sediment concentration.

For a broad evaluation of the costs and environmental impacts of multiple dam-removal alternatives, this level of detail is proving more than adequate for the stakeholders to make their decisions. For example, knowing the impact is likely going to be limited to within a day or two and unlikely to exceed a few days, as opposed to the credible prospect of weeks or months of impact, may allow water diverters to feel comfortable enough to make a decision to accept the associated dam removal alternative by shutting down water diversion operations for the short duration of impact and to find other ways to cope with the lost water diversion. It also provides a basis to develop a more quantitative assessment of ecological impacts (e.g. Newcombe and Jensen 1996) that can be compared to the long-term benefits of increased access of migratory fish to the upstream channel network, for which an associated analysis (AECOM and Stillwater 2015) suggests minimal impacts due to increased fine sediment concentration beyond those associated with the one-time flush of high sediment during Phase I.

6 Conclusions

Major conclusions of our analyses with regard to the quick sediment release alternatives for Matilija Dam removal include the following: (a) initial suspended sediment concentration is likely to be in the order of 10^6 mg/L, which will most likely last for a few hours and extremely unlikely to exceed three days; (b) suspended sediment erosion will likely decrease approximately exponentially after the initial peaking, and suspended sediment concentration will likely reach a watershed background (and assumed non-impact) level of 1000 mg/L within a few hours and is extremely unlikely to exceed a few days. Thus, downstream impacts, both physical and ecological, associated with extremely high initial suspended sediment concentrations will be substantial but extremely brief; and chronic impacts will not persist. These conditions are a direct consequence of two key elements of Matilija Creek and watershed: a wide range of sediment sizes that have been deposited behind the dam, and a relatively high natural watershed sediment yield. These conditions are not universal, and so these conclusions will not be applicable to all dam-removal projects. The analysis presented here should suggest an appropriate analytical framework for other dam-removal projects, however, particularly where concerns over the downstream release of fine sediment have resulted in ultimately unnecessary sediment-management alternatives whose cost and technical challenges threaten to compromise the possibility of dam removal altogether.

We hope the presented approach, after adaptations by considering individual project conditions, will be useful for other similar dam-removal projects where the increased suspended sediment concentration due to the erosion of fine reservoir sediment deposit is a concern.

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