TECHNICAL MEMORANDUM ◦ JULY 2021

Analyses of Fine Sediment Erosion Following the Proposed Scott Dam Removal, Eel River, California

PREPARED FOR

Two-Basin Solution Partners
California Trout
Humboldt County
Mendocino County Inland Water and Power Commission
Round Valley Indian Tribes
Sonoma County Water Agency

PREPARED BY

Stillwater Sciences
850 G Street, Suite K
Arcata, CA 95521

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Cover photo: Scott Dam on the Eel River, California. Photograph from CalTrout (caltrout.org, accessed September 1, 2020).

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1 INTRODUCTION

1.1 Background

The Potter Valley Project (Project) is an inter-basin hydroelectric project located 15 miles northeast of Ukiah (Figure 1) that annually diverts approximately 60,000 acre-feet (ac-ft) of water from the upper Eel River to the upper Russian River. Project features include Scott Dam, a 130-foot-tall concrete gravity dam that impounds Lake Pillsbury, a 2,300-acre storage reservoir; Cape Horn Dam that impounds the 106-acre Van Arsdale Reservoir; and a diversion system that diverts water from the Eel River at Van Arsdale Intake to the Project's powerhouse located in the headwaters of the Russian River watershed. The Project began diverting water in 1908 when Cape Horn Dam and the Van Arsdale Diversion were built. Scott Dam was built in 1922 approximately 12 miles upstream of Cape Horn Dam at river mile (RM) 168.5.

Pacific Gas and Electric Company's (PG&E's) Project license expires in 2022. PG&E filed a Pre-Application Document (PAD) and Notice of Intent (NOI) to formally initiate the relicensing process for the Project in April 2017. PG&E withdrew its NOI and PAD and discontinued its efforts to relicense the Project in January 2019, and in March 2019, the Federal Energy Regulatory Commission (FERC) issued a notice soliciting interested potential applicants other than PG&E to file an NOI and PAD. In May 2019, the Two-Basin Solution Partners (Partners) entered into a Planning Agreement to explore pathways to obtain a new license for the Project. In June 2019, the Partners filed a NOI with FERC stating the intent to undertake a Feasibility Study of a potential licensing proposal for the Project. The Feasibility Study examined the practicability of potential actions in meeting agreed upon common goals and to inform the Partners of cost and performance tradeoffs associated with those actions. Phase 1 of the Feasibility Study, completed and filed with FERC in May 2020, included the following key elements: (1) a Regional Entity that will apply for the new license and assume the new license if issued, (2) a Project Plan, (3) a Fisheries Restoration Plan, (4) an Application Study Plan, and (5) a Financial Plan. Phase 2 of the Feasibility Study was initiated in April 2020 with grant funding from the California Department of Fish and Wildlife to supplement technical analyses conducted during Phase 1, and to conduct new technical analyses.

This Technical Memorandum was prepared for the Partners by the Consultant Team to supplement technical analyses performed during Phase 1 of the Feasibility Study. The information provided in this document is a continuation of work along a path starting with preliminary analyses of feasibility, transitioning towards more refined analyses of a focused project plan and implementation of the best possible project that meets programmatic goals in a cost-effective manner. This Technical Memorandum is informational, is not binding of any of the Partners, and will not be filed with FERC as the basis for compliance under the Integrated License Process or other FERC regulations. While this Technical Memorandum contributes to the information available to the Partners, the Partners have not solely relied on this document for justification for any decision they have made or will make regarding FERC filings or cooperative agreements. More detailed environmental and engineering studies will be conducted during implementation of the FERC study and outside of the FERC process. Accordingly, this Technical Memorandum reflects a step that will be expanded and built upon through additional studies, analysis, synthesis, and ultimately decisions by the Partners on proceeding with a Project Plan.

1.2 Purpose

The potential removal of Scott Dam is being studied because it is considered the most effective and reliable approach to provide successful upstream and downstream fish passage and restore anadromous fish access to the 289-square mile watershed upstream of the dam. Scott Dam (see cover photograph) is a located at river mile (RM) 168.5 on the Eel River and impounds Lake Pillsbury (Figure 1) with a storage capacity of 94,400 acre-feet (acre-ft) at the top of the spillway (i.e., 1,821.12 ft elevation[1]) upon its completion in 1922 (PG&E 2017). By 2015, the storage capacity of Lake Pillsbury was reduced to 76,876 acre-ft at the same pool level (McBain and Princeton Hydro 2019) due to sedimentation. Although these storage capacities imply a minimum[2] 2015 Lake Pillsbury sediment deposition volume of 17,524 acre-ft (i.e., the difference between 94,400 and 76,876 acre-ft, or 28.3 million cubic yards [CY]), the most recent, more refined analyses that combine Digital Elevation Model (DEM) data and thalweg survey data estimate a 2015 sediment deposition volume of 13,016 acre-ft (21 million CY; Stillwater Sciences et al. 2021). This Technical Memorandum provides an order-of-magnitude analysis for the erosion of fine sediment from the 21 million CY of sediment stored in Lake Pillsbury following the proposed removal of Scott Dam under two possible dam removal alternatives: a vertical notch alternative that would result in a one-time fine sediment release, and a staged removal alternative that would result in multiple fine sediment releases. Scott Dam removal would release a substantial amount of the sediment stored in the Lake Pillsbury impoundment downstream through natural erosion (i.e., no mechanical sediment removal or stabilization prior to dam removal), and this Technical Memorandum focuses on the general magnitude of suspended sediment concentration and duration of high suspended sediment concentration impact.

[1] NAVD88 datum is used throughout the report unless labeled otherwise. At Scott Dam site, add 78.78 ft to NAVD88 elevation to convert to Pacific Gas and Electric Company (PG&E) elevation. Other relevant documents may also have used NVGD29 elevations. Subtract 81.7 ft from PG&E elevations or subtract 2.92 ft from NAVD88 elevations to obtain NVGD29 elevations.

[2] The sediment accumulation calculated by differencing storage values calculated at different times is generally less than the actual amount of sediment accumulation because sediment deposition upstream of the storage area, which is generally a small fraction of the overall sediment deposition, is not accounted for.

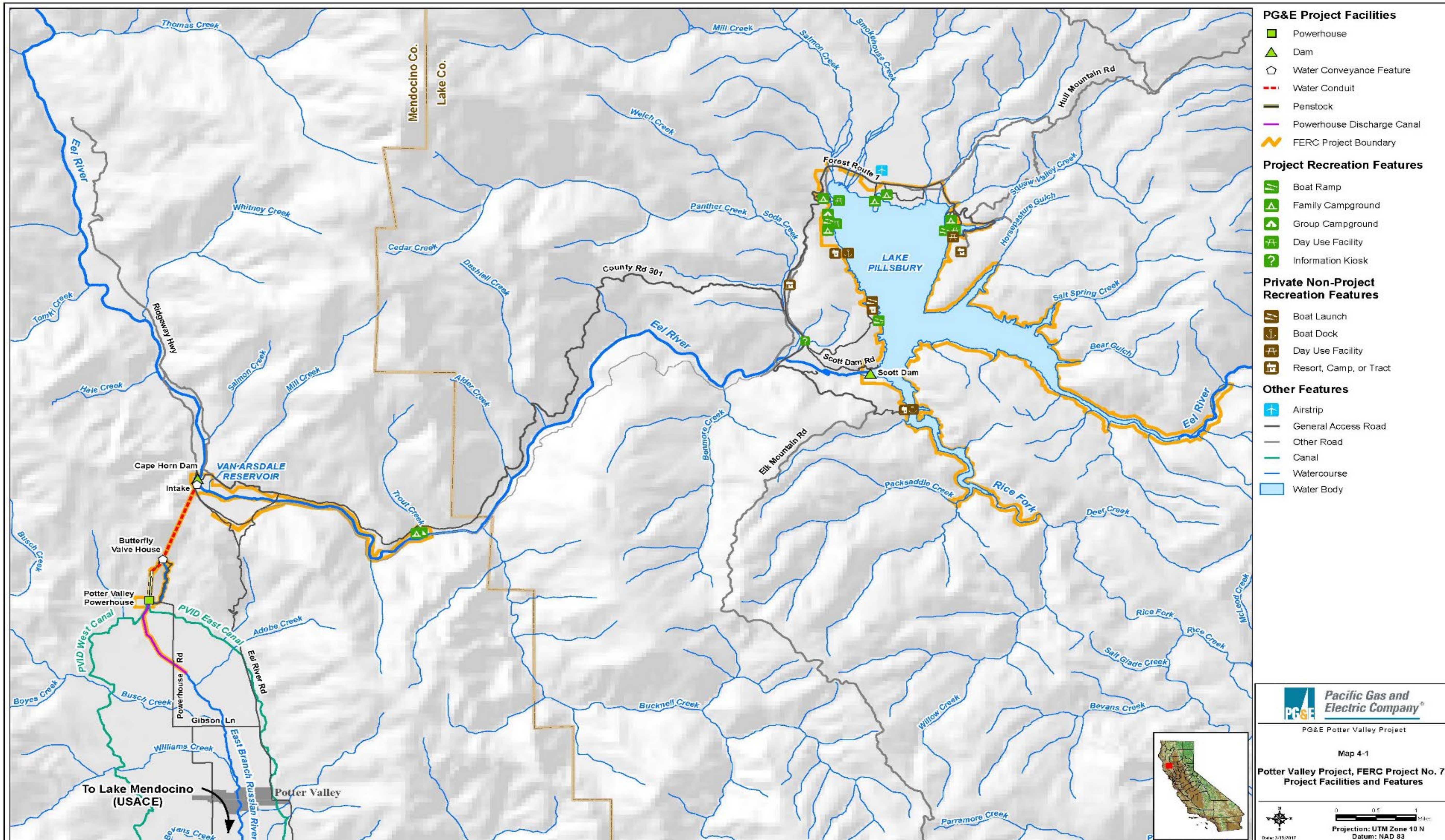

Figure 1. Scott Dam and Lake Pillsbury vicinity, Eel River, California. Figure adapted from PG&E (2017).

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2 METHOD OF ANALYSES

Although numerical modeling has been the primary tool for predicting sediment transport following dam removal (e.g., BOR 1996, 2004, 2011; Stillwater Sciences 2000, 2008; Bountry and Randle 2001; MEI 2003; Cui et al. 2006a, 2006b, 2014, 2018; Langendoen et al. 2005; Cui and Wilcox 2008; Langendoen 2010; Bountry et al. 2013), there are challenges for simulating the erosion of fine sediments, primarily because their release is often driven by a rapid erosional process not addressed by traditional sediment transport theory, making the modeling results unreliable (Cui et al. 2017). Realizing that precise quantification of fine sediment transport is rarely necessary and to avoid the difficulty of numerical modeling, Cui et al. (2017) applied an empirical approach to assess the likely magnitude and duration of high suspended sediment concentration following the proposed removal of Matilija Dam in Southern California, which proved to be adequate to address the potential environmental impacts of alternative scenarios for planning and design purposes. The analyses of Cui et al. (2017) relied on three components to inform the likely magnitude and duration of high suspended sediment concentration following Matilija Dam removal: (1) a two-phase conceptual model (TPCM) for fine sediment erosion from an impoundment following a rapid dam removal; (2) general principles governing geomorphic processes of fine sediment erosion from the reservoir sediment deposit; and (3) comparison of results from the analyses with observations in rivers during flood events, during reservoir drawdown for sediment sluicing, and following dam removal. A combination of these three components provided order-of-magnitude estimates that were adequate and sufficient for the project to move forward. It is our belief that the method of analyses used in Cui et al. (2017) is still appropriate for similar conditions and there are no recent additional advances in fine sediment transport theory to warrant significant amendment to the analyses, although minor adaptions may be appropriate when applied elsewhere due to site specific differences.

A TPCM for fine sediment erosion following dam removal (Cui et al. 2017) addresses dam removal alternatives that would quickly lower the base level control (lake surface elevation in our case) at the dam site to a level that would allow for natural erosion of the bottom-set fine sediment deposit (Figure 2) down to the pre-dam riverbed and historical channel. A TPCM can be adapted to a more general form of base level lowering that may not erode the fine sediment down to the pre-dam riverbed (e.g., notching part of the dam to release part of the fine sediment in storage).

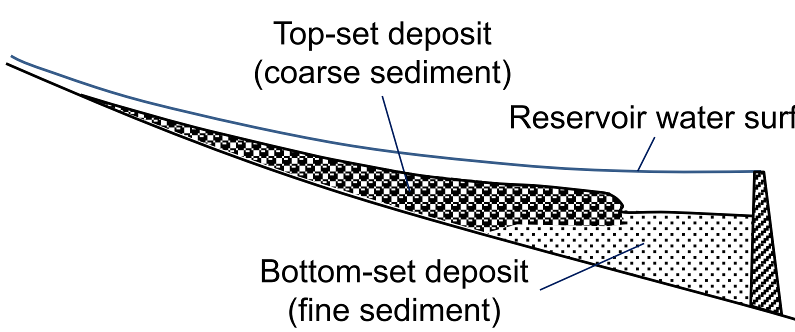

Figure 2. Sketch of a typical reservoir deposit, showing the coarse top-set deposit and fine bottom-set deposit, adapted from Cui et al. (2017).

As illustrated in Figure 3a, years of dam operation results in the accumulation of sediment (mostly fine sediment, plus a small fraction of coarse particles) that can completely bury the historical main channel, and also elevate the historical floodplains or high terraces that were not usually accessible by the flow prior to dam construction. Following a quick lowering of base level control, either by removing a section of the dam to its base or by opening large tunnels near the base of the dam, the flow rapidly cuts through the sediment deposit as a result of the suddenly increased shear stress driven by the significantly elevated local bed slope (Figure 3b). This process is termed Phase 1 erosion and occurs before the flow reaches the pre-dam historical channel bed that prevents further channel degradation and lateral channel migration. During Phase 1 erosion, the flow is in contact with the sediment deposit, which provides virtually unlimited fine sediment supply. The erosion of fine sediment during Phase 1 erosion is "transported limited", meaning the amount of fine sediment transport is determined by the hydraulic sediment transport carrying capacity of the flow.

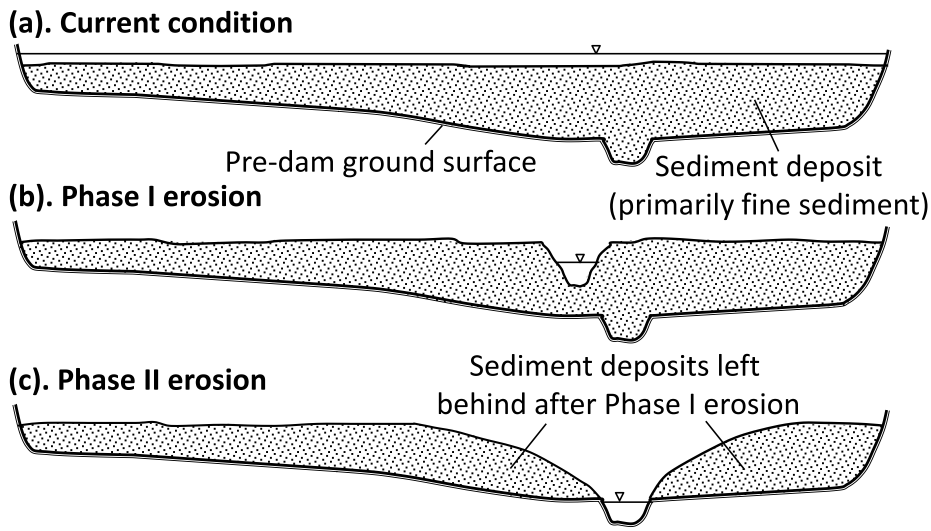

Figure 3. Phase 1 and Phase 2 erosion following dam removal. (a) Reservoir sediment deposit with dam in place; (b). Phase 1 erosion when fine sediment is directly accessible to the flow, presenting a virtually unlimited supply of sediment with transport limited only by the capacity and rate of discharge; and (c) Phase 2 erosion when fine sediment is no longer directly accessible to the flow. Figure adapted from Cui et al. (2017).

Based on the work of Chang (1963), Cui et al. (2017) provided the following equation (Equation 1) to quantify the fine sediment carrying capacity during Phase 1 erosion:

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

in which C denotes suspended sediment concentration in milligrams per liter (mg/L); V denotes mean velocity of the flow; g denotes acceleration of gravity; H denotes mean water depth; and v_s denotes settling velocity of sediment particles.

Once the flow reaches the pre-dam historical channel (or other non-erodible surface), the fine sediment deposits become inaccessible to the flow and fine sediment transport becomes supply limited. This is termed Phase 2 erosion, during which fine sediment transport and suspended sediment concentration is determined by how quickly the fine sediment can be delivered into the main channel through out-of-channel processes (Figure 3c). Cui et al. (2017) noted that there are two primary mechanisms for such processes: (1) bank slumping as water drains out of the deposits, driven by gravity; and (2) 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. Based on observations of Hengshan Reservoir sediment sluicing, Cui et al. (2017) reasoned that the duration of Phase 2 erosion due to bank slumping would be short (i.e., most likely on the order of hours and at most a couple of days) for the Matilija Dam removal project, and this conclusion should be applicable for other projects as there is minimal site-specific parameter applied in the reasoning. Cui et al. (2017) also derived a maximum possible duration of impact determined by the finite volume of fine sediment deposit left to erode after Phase 1 erosion. Additionally, Cui et al. (2017) assumed the rate for sediment to slump into the main channel for fluvial transport likely decreases approximately exponentially over time, similar to many natural processes (e.g., Graf 1977, Collins et al. 2017). The rate of sediment delivery is derived as follows:

$$E = E_0 exp[-k(t - t_0)] \qquad \text{Equation 2}$$

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 2 erosion and is assumed to equal the fine sediment transport rate at the end of Phase 1; t denotes time following the start of sediment erosion; t_0 denotes the duration of Phase 1 erosion; and k defines the rate of exponential decaying of sediment erosion and delivery to the channel during Phase 2 erosion.

Because there is 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 4a). A faster decrease of the erosion rate (i.e., a higher k value), on the other hand, would more quickly reduce the suspended sediment concentration to a level that is insignificant compared to the background conditions (Figure 4b). Thus, the worst-case-scenario (i.e., the longest possible duration of discernable impacts from Phase 2 erosion) would be that 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 4). Based on above reasoning, Cui et al. (2017) derived the following equation (Equation 3) to quantify the likely maximum duration of impacts:

$$t_i = t_0 + \frac{M_2}{C_1 Q_{w1} - C_i Q_{wi}} ln \frac{C_1 Q_{w1}}{C_i Q_{wi}} \quad \text{Equation 3}$$

in which C_i denotes the incremental suspended sediment concentration that is defined to be minimal (or acceptable) increase in impact to the downstream environment relative to background conditions (referred to as critical suspended sediment concentration hereafter); C_1 denotes suspended sediment concentration at the end of Phase 1 erosion; Q_{w1} denotes water discharge at the end of Phase 1 erosion; Q_{wi} denotes 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 impact duration for combined Phase 1 and Phase 2 erosion; and M_2 denotes the total mass of fine sediment deposit that will be eroded during Phase 2 erosion.

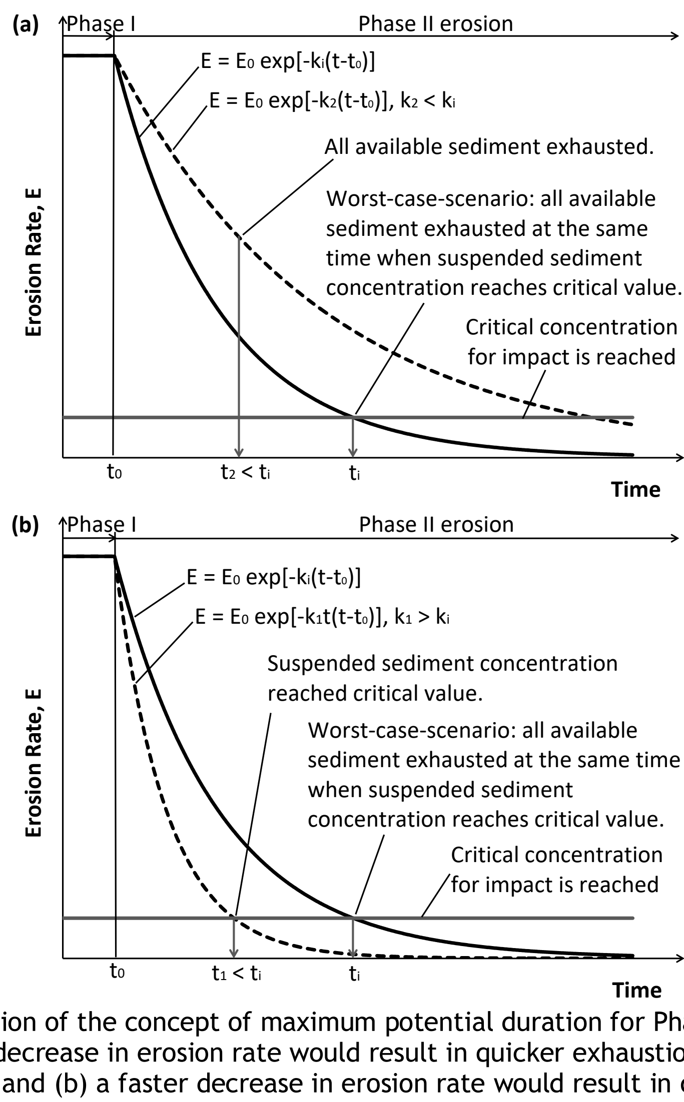

Figure 4. Illustration of the concept of maximum potential duration for Phase 2 erosion: (a) a slower decrease in erosion rate would result in quicker exhaustion of sediment source; and (b) a faster decrease in erosion rate would result in quicker realization of critical suspended sediment concentration for impact. Figure adapted from Cui et al. (2017).

For erosion due to surface erosion during precipitation, Cui et al. (2017) noted that the surface area of the newly exposed land is only a small fraction of the upstream drainage area and the natural sediment production in the watershed is high. The combination of these two conditions made the increased suspended sediment due to surface erosion of the newly exposed land during precipitation insignificant and negligible.

Below we provide a summary of Lake Pillsbury sedimentation (Section 3) and analyses for two dam removal alternatives for Scott Dam (Section 4), with adaptations where necessary.

3 LAKE PILLSBURY SEDIMENTATION

An estimated 21 million CY of sediment was accumulated in Lake Pillsbury between 1922 and 2015 based on the most recent analyses, among which 12 million CY was estimated to be available for fluvial transport downstream following dam removal (Stillwater Sciences et al. 2021). Although sediment accumulation within Lake Pillsbury continued after 2015 and will continue until the day the dam is removed, the 2015 estimates will not be extrapolated primarily because the increased deposit after 2015 was assumed small compared to the existing deposit, and the accuracy of the analyses is only on the order-of-magnitude level. In addition, we will make more conservative assumptions[3], wherever possible, that will more than compensate the neglected future fine sediment deposits to ensure that the results of the analyses are on the conservative side.

Two sources exist for grain size distribution of the Lake Pillsbury sediment deposit: U.S. Geologic Survey (USGS; 1964) and Geosyntec (2020). Neither is comprehensive, and both the USGS and Geosyntec samples were collected from only shallow cores. The USGS (1964) samples included 24 density samples collected using calibrated density probe and 26 grain size samples collected using a split-core sampler suspended by boat-mounted streamflow-measuring equipment that likely penetrated only shallow depths into the deposits. Dry density of the USGS (1964) samples ranged between 1,096 and 2,349 pounds per cubic yard (lb/CY; 41–87 pounds per cubic foot [lb/ft^3]) with an average density of 1,590 lb/CY (59 lb/ft^3). Median grain size of the samples ranged between 0.0031 and 0.32 millimeters (mm) with an overall median value of 0.011 mm. The Geosyntec (2020) sampling did not provide dry density and grain size distribution information, but the fractions of silt and clay data from the samples were consistent with the data provided in USGS (1964). With additional sediment sampling still in the planning stage and with the logical assumption that continued sediment accumulation after the USGS (1964) study would be similar to that which occurred prior to the 1964 study, the dry density and median grain size information from USGS (1964) discussed above is used as input for analyses provided in this Technical Memorandum. Future refinements/updates to the analyses may be warranted if it is determined that new information collected during the subsequent studies might change the results and conclusions of the analyses presented in this report.

3 Conservative means that the estimated duration of impact will be longer than the actual impact duration because the primary purpose of the alternative is to minimize the duration of impact. This applies for all occasions in this document.

4 SCOTT DAM REMOVAL ALTERNATIVES

There have been several preliminary dam removal alternatives for discussion regarding Scott Dam removal (e.g., McMillen Jacobs Associates 2018, McBain and Princeton Hydro 2019), many of which would manage the lake deposits in such a way that variable amounts of erosion of fine sediment would occur (i.e., mechanically remove or stabilize most sediment prior or during removal). This report focuses on two dam removal alternatives that would release fine sediment downstream through natural erosion: (1) a new vertical notching dam removal alternative proposed in this document, and (2) a four-stage dam removal alternative described in McBain and Princeton Hydro (2019). The two alternatives are discussed briefly below.

4.1 Vertical Notching Dam Removal Alternative

Dam removal with the vertical notching alternative would start in late spring during the low flow season (May through November), by drawing the lake level down to approximately 1,781 ft elevation (~1,860 ft PG&E elevation) using the existing valve located near the right bank, and potentially the grizzly and/or sluice outlets if functional (Figure 5a,b). Dam removal would occur concurrently with lake level drawdown, mostly working dry above lake surface level. Minimal wet operation may be needed once the outlets are becoming inadequate to keep up with the drawdown or unable to drawdown to the designed removal elevation due to their limited capacity or unexpected blockage of valve inlet by woody debris. A section of the dam would be removed a few feet (exact value to be determined) lower than the rest of the dam to allow for overflow that exceeds the capacity of the outlets and to keep the rest of the section dry (Figure 5b). The rationale for selecting 1,781 ft elevation as the target for initial drawdown is because this lake level was reached during the drought of 2014, and thus it is likely that the drawdown will result in minimal sediment release. Once the top of the dam is removed, vertical holes would be drilled from the top of the remaining dam to reach the pre-dam riverbed elevation of 1,709 ft (1,787.7 ft PG&E elevation) for a narrow section of the dam (the notching section hereafter, section width to be determined, but will likely be on the order of 10–20 ft) (Figure 5c). Concurrent with the drilling, the lower spillway within the notching section would be removed using hydraulic hammers and explosives to finish the preparation for final dam removal and sediment release (Figure 5c). To start the final dam removal, explosives would be installed into the holes drilled earlier just before the first winter storm event or preferably before a forecasted target high flow event, and the section would be blasted open to allow for sediment erosion and quick lake drawdown (Figure 5d). The section width would be determined later to ensure the action will not result in unacceptable flooding risks downstream. It is our initial judgement that blasting a vertical notch on the dam would be unlikely to destabilize the remainder sections of the dam because Scott Dam is a concrete gravity dam, but additional assessment is needed by dam safety engineers if this removal method is deemed as potentially feasible. Once the vertical notch is open, the remaining of the dam can be removed using hydraulic hammers or other mechanical methods deemed appropriate (Figure 5e). This method would result in a single high turbidity event similar to that of the proposed Matilija Dam removal project described in Cui et al. (2017).

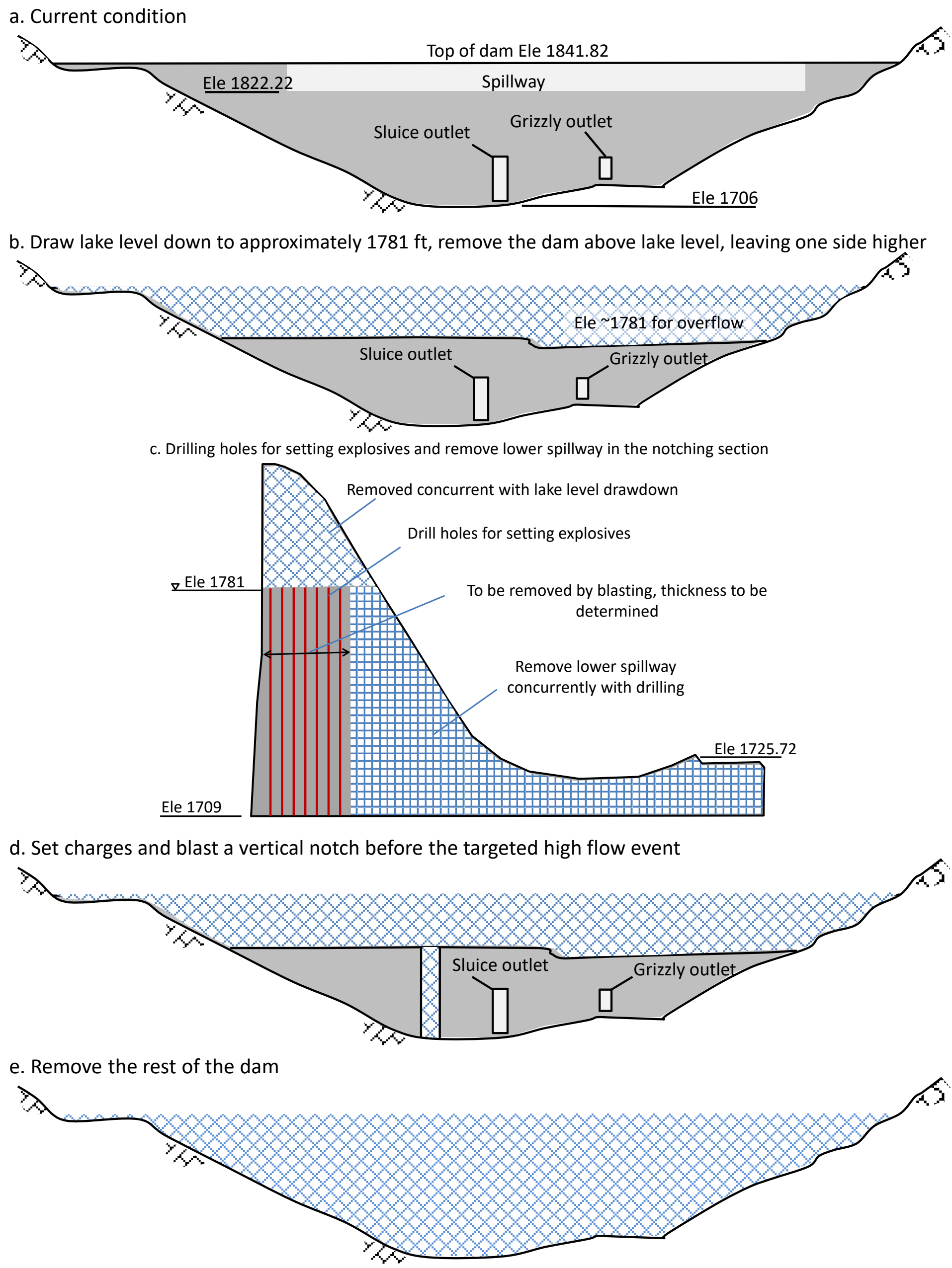

Figure 5. Schematics illustrating the proposed vertical notching alternative for Scott Dam removal for rapid sediment evacuation from Lake Pillsbury. (a) Current Scott Dam cross section; (b) draw lake level down using available outlets during the low flow season (May through November), to an elevation of approximately 1,781 ft, remove the portion of the dam above lake level after drawdown, leaving one side (the one that is more easily accessible) of the dam a few feet higher so that high flow passes only through the other side; (c) and (d) drill holes and remove lower spillway in the notching section, install explosives in the holes and blast open a vertical notch just before the first winter storm event or before a forecasted target high flow event to allow for quick sediment erosion and lake drawdown; and (e) remove the remaining portion of the dam to complete dam removal. Note (c) is a profile view rather than a cross section view, and thus has a different scale from the other sketches.

Another method that could achieve the same effect on sediment transport would be to blast open tunnels near the base of the dam prior to the first winter storm event or preferably prior to a forecasted target high flow event similar to that proposed for Matilija Dam removal (Cui et al. 2017), but the cost associated with tunnel construction is most likely much higher than the vertical notching alternative, unless it can be accomplished with the existing Sluice and Grizzly outlets (*i.e.*, one or both outlets can be opened either mechanically or by blasting, and the combined capacity of the outlets is adequate to accommodate the design flow as open channel flow). If, however, Scott Dam is reenforced with steel bars, which is extremely unlikely, the proposed vertical notching alternative may become infeasible, and tunneling through the base of the dam may become a preferred method for quick fine sediment release. In that case, the analyses and results provided in this Technical Memorandum will be equally applicable without the need for additional adjustments.

4.2 Four-stage Dam Removal Alternative

The four-stage dam removal alternative as described in MA & PH (2019) would remove the dam through successive notching, removing the dam to 1771.22 ft (1,768.3 ft NVGD29 elevation, 1,850 ft PG&E elevation), 1751.22 ft (1,748.3 ft NVGD29 elevation, 1,830 ft PG&E elevation), 1731.22 ft (1,728.3 ft NVGD29 elevation, 1,810 ft PG&E elevation), and 1708.92 ft (1,706.0 ft NVGD29 elevation, 1,787.7 ft PG&E elevation) in four dry seasons. Refined analysis that assumed removing the dam to a certain elevation would release all reservoir deposits above that elevation resulted in 1.1 million CY, 8.5 million CY, 2.4 million CY, and 36.5 thousand CY sediment release for Stage 1, 2, 3 and 4 removal, respectively (Stillwater Sciences et al. 2021). For safety reasons, dam removal and sediment mobilization would occur during the low flow season (May through November) when the discharge in the river is low. The staged removal would be completed in multiple years: following the completion of one stage of removal, personnel and equipment would be demobilized, allowing the winter high flow to pass over the partially removed dam, and the next stage of removal would occur during the next low flow season or seasons.

5 ANALYSES OF FINE SEDIMENT EROSION DURING SCOTT DAM REMOVAL

Below we start the analyses with the vertical notching alternative because the TPCM of Cui et al. (2017) briefly described in Section 2 above can be directly applied under this alternative.

5.1 Fine Sediment Erosion under Vertical Notching Alternative

Equation (1) needs to be closed with Manning's equation below in conjunction with a series of assumptions on the value of parameters to provide some useful information regarding the potential magnitude of high suspended sediment concentration and potential duration of impact following dam removal.

$$Q_w = \frac{1.48}{n} B H^{5/3} S^{1/2} \qquad \text{Equation 4}$$

in which Q_w denotes water discharge; n denotes Manning's n; B denotes channel width; H denotes average water depth; and S denotes channel gradient. Equation (4) is expressed in imperial unit with water discharge in cfs and channel width and water depth in feet. It also needs to convert suspended sediment concentration to the rate of fine sediment erosion with

$$Q_s = CQ_w/\rho_d$$ Equation 5

In which Q_s denotes the rate of fine sediment erosion expressed as bulk volume per unit time; C denotes suspended sediment concentration expressed as dry mass per unit volume, and ρ_d denotes dry density of the sediment deposit (dry mass per unit bulk volume). The duration of Phase 1 erosion is then calculated as

$$t_0 = M_1/Q_s$$ Equation 6

In which t_0 denotes Phase 1 erosion duration; and M_1 denotes the bulk volume of Phase 1 fine sediment erosion. The parameters used for evaluation are discussed below:

5.1.1 Water Discharge (Q_w)

The intention of the vertical notching alternative is to minimize the duration of high suspended sediment concentration through rapid sediment evacuation as a measure to minimize the downstream ecological impacts. As such, it is advantageous to initiate sediment mobilization (i.e., to blast open the vertical notch) prior to a large storm event that would provide high discharge that lasts for a relatively long period of time. Here we use the simulated unimpaired water discharge into Lake Pillsbury (Addley et al. 2019) for analysis as water discharge in the study reach will revert back to unimpaired flow following Scott Dam removal.

Figure 6 shows the unimpaired annual maximum daily average discharge downstream of Scott Dam, and Figure 7 shows the number of days unimpaired water discharge exceeds 2,000 cfs. Data in Figure 6 and Figure 7 indicates that a 2,000 cfs daily average discharge is exceeded for almost all the water years, with durations longer than at least 5 days for most of these years. With that, we selected 2,000 cfs as our target dam removal water discharge for examination. We also examine 1,000 cfs and 5,000 cfs to provide a range of sensitivity as what would likely occur if water discharge is significantly lower or higher than the 2,000 cfs target discharge.

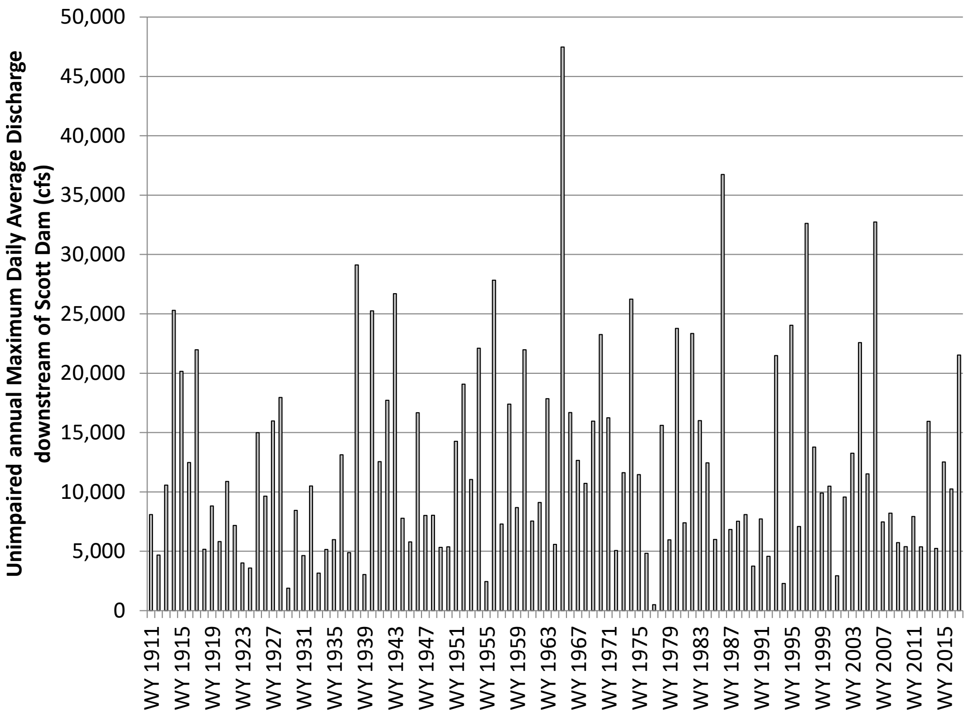

Figure 6. Annual maximum daily average discharge downstream of Scott Dam, based on simulated unimpaired daily average discharge series (Addley et al. 2019).

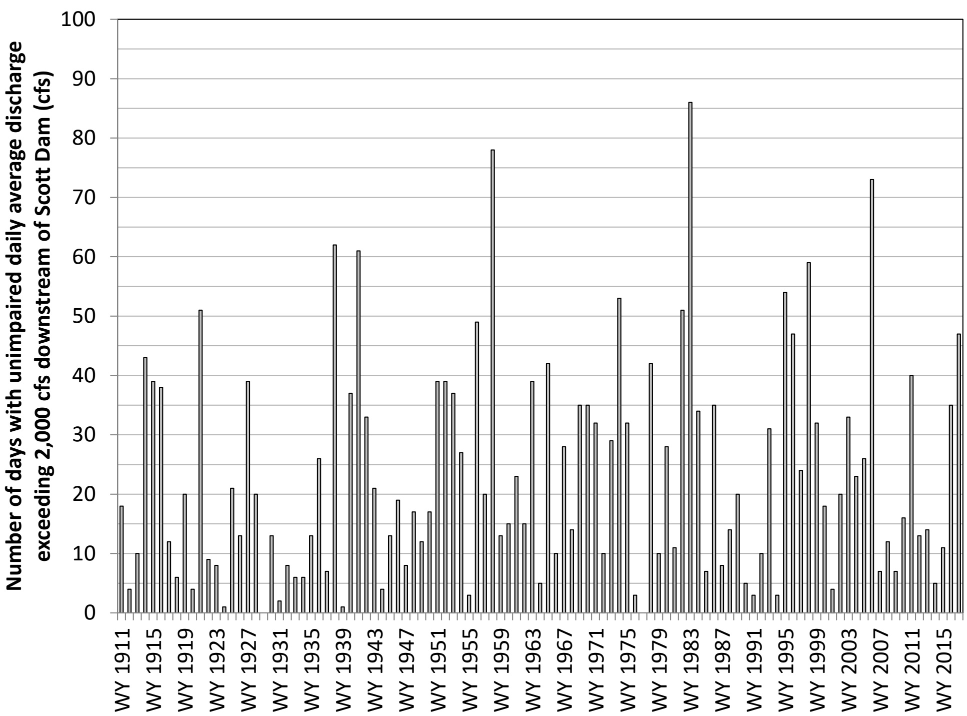

Figure 7. Number of days with unimpaired daily average discharge downstream of Scott Dam exceeds 2,000 cfs, based on simulated unimpaired daily average discharge series (Addley et al. 2019).

5.1.2 Channel Width (B)

Base level would be lowered by approximately 70 ft following the blast opening of the vertical notch, resulting in rapid down cutting of the reservoir sediment deposits, which in turn will promote the formation of a narrow active channel. For the analyses here, we assume an active channel width of 300 ft, which is the estimated bankfull width of the Eel River downstream of Scott Dam. The actual active channel width formed following the opening of the vertical notch cannot be accurately assessed, but is expected to be significantly narrower than this assumed value based on Google Earth aerial photographs of recent years. Using a larger width value for analysis will result in conservative assessment of the impact.

5.1.3 Channel Gradient (S)

With the rapid down cutting of the reservoir sediment deposit, channel gradient would become much steeper than the ambient channel gradient in the area of active sediment erosion. For the analysis here, we assume a channel gradient of 0.01, which is the minimal reach average channel gradient of the tributaries entering Lake Pillsbury just upstream of the inundated area (Figure 8). The local channel gradient with active sediment erosion is expected to be much steeper than this assumed value. Using a lower channel gradient value for analysis will result in conservative assessment of the impact (see Section 3 for definition of conservative assessment).

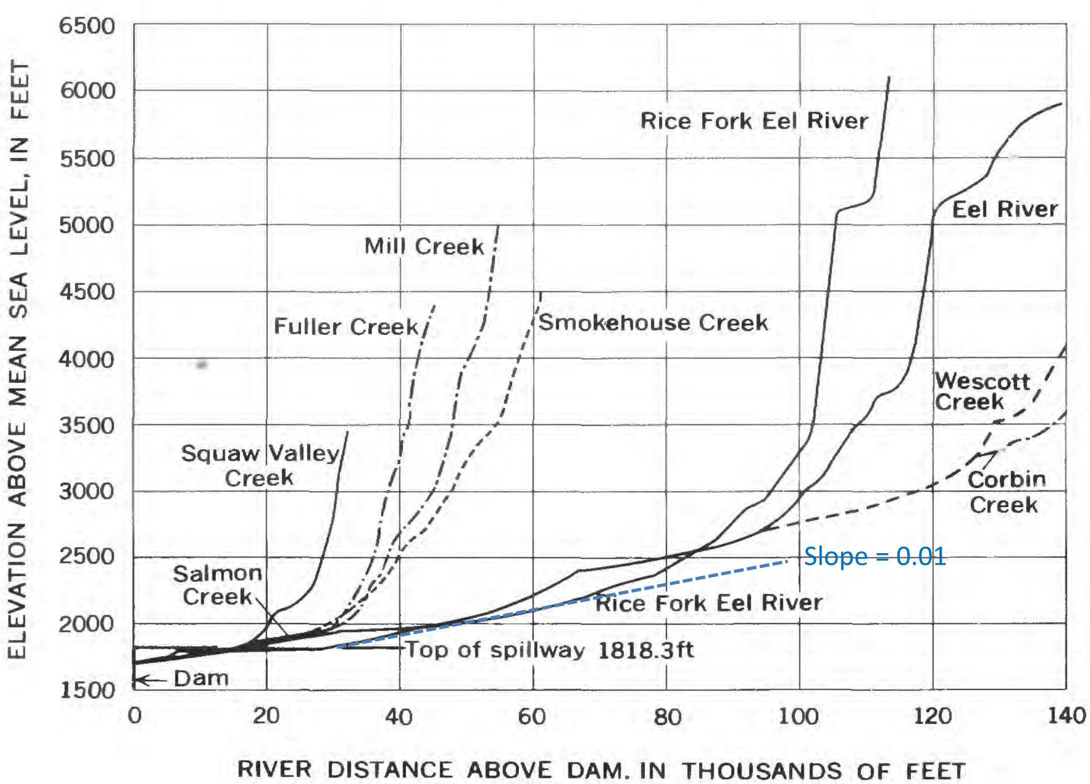

Figure 8. Longitudinal profile of the tributaries entering Lake Pillsbury, showing a minimum slope of 0.01 just above the inundation zone. Figure adapted from USGS (1964).

5.1.4 Settling Velocity of Sediment Particles (v_s)

We use the median value of the 0.011 mm median grain size of the 26 USGS (1964) samples as a representative of the sediment particles to calculate the particle settling velocity. Applying the procedures of Dietrich (1982) using the 0.011 mm particle size resulted in a settling velocity of 3.58×10^{-4} ft/s (1.09×10^{-4} m/s).

5.1.5 Dry Density of the Sediment Deposit (ρ_d)

We use the average dry density of the USGS (1964) samples (1,590 lb/CY, or 943,000 mg/L) for analyses. Note that the calculated Phase 1 erosion suspended sediment concentration must be limited to within the 943,000 mg/L level as the suspended sediment concentration cannot exceed the dry density of the deposits.

5.1.6 Volume of Phase 1 Sediment Erosion (M_1)

An estimated 12 million CY of sediment can potentially be mobilized, which includes both fine and coarse sediment (Stillwater Sciences et al. 2021). For the Phase 1 erosion calculation, we assume all the 12 million CY of sediment erosion will be fine sediment, and all of which will be eroded during Phase 1 erosion. This would result in a conservative impact assessment because the actual Phase 1 fine sediment erosion will likely be smaller. In addition, we also provide an estimate assuming 21 million CY Phase 1 fine sediment erosion, which is the absolute (and impossible) maximum, just to illustrate that the duration for Phase 1 erosion cannot be overly long.

5.1.7 Manning's n (n)

Manning's n value is assumed to be 0.025, a typical value for straight channels (e.g., Henderson 1966).

5.1.8 Results

Table 1 below provides the calculated magnitude of suspended sediment concentration and duration for Phase 1 erosion assuming 12 million CY Phase 1 fine sediment erosion, indicating that opening the vertical notch under 2,000 cfs flow would result in approximately 600,000 mg/L suspended sediment concentration with less than 3 days Phase 1 erosion. If water discharge is only 1,000 cfs, the suspended sediment concentration would be between 400,000 and 500,000 mg/L with less than 8 days of Phase 1 erosion. If water discharge is 5,000 cfs, the suspended sediment concentration would be 900,000 mg/L during Phase 1 erosion that would last for approximately a full day following the opening of the vertical notch.

Table 1. Calculated magnitude of suspended sediment concentration and duration for Phase 1 erosion for 12 million CY fine Phase 1 sediment erosion under the vertical notching dam removal alternative.

Water discharge (cfs)	**1,000**	**2,000**	**5,000**
Suspended sediment concentration (mg/L)	457,800	612,500	900,000
Duration of Phase 1 erosion (days)	7.7	2.9	0.8

Although the assumptions used for the assessment provided in Table 1 are most likely already conservative (i.e., over-estimated Phase 1 erosion duration, and assumptions with channel width and channel gradient), we also provide the calculated Phase 1 erosion duration in case the Phase 1 erosion volume is 21 million CY, which is the total estimated volume of sediment deposition

(Table 2). Note this is the absolute maximum and an impossible scenario, but the results demonstrate that Phase 1 erosion will not be more than a few days even if some of our parameters in the calculation happen to be assigned on the less conservative side, which we do not believe to be the case.

Table 2. Calculated duration of Phase 1 erosion assuming the absolute (and impossible) 21 million CY Phase 1 fine sediment erosion under the vertical notching dam removal alternative.

Water discharge (cfs)	**1,000**	**2,000**	**5,000**
Duration of Phase 1 erosion (days)	13.5	5.0	1.4

Note: Calculated magnitude of suspended sediment concentrations are identical to that provided in Table 1

For Phase 2 erosion, the assessment of Cui et al. (2017) that it would last only for a few hours, and a few days at most, is applicable for Scott Dam removal because their reasoning used minimal site-specific information, with the only mentioned site-specific information being the median size of the fine sediment deposit. Ironically, the Matilija sediment deposit in Cui et al. (2017) has an identical median size as Scott Dam fine sediment deposit (i.e., both are 0.011 mm). We can also apply the limitation analysis of Cui et al. (2017), briefly described in Section 2 and Figure 4, to calculate a maximum possible (but most likely improbable) Phase 2 impact duration. To do that, we need to assign a critical suspended sediment concentration (C_i in Equation 3), with impact to fisheries and other resources becoming acceptable once the suspended sediment concentration become lower than this critical value. Examinations of the recorded suspended sediment concentration at USGS gage 11477000 (Eel River at Scotia) in Figure 9 indicate that suspended sediment in the Eel River exceeds 5,000 mg/L in many of the recorded years, and the highest recorded suspended sediment concentration exceeds 10,000 mg/L. Here we assume that a relatively high but short duration suspended sediment concentration on the order of 5,000 mg/L would be acceptable to fisheries and other resources due to the anticipated post-project benefit, and therefore assigned 5,000 mg/L as the critical concentration. We further assumed that water discharge would be kept at 2,000 cfs during the entire period of fine sediment erosion. Applying these assumptions to Equation 3 resulted in a maximum possible duration of Phase 2 impact on the order of a few days (Figure 10). Note that it is unclear what volume of fine sediment erosion would occur during Phase 2 erosion, but given that the Lake Pillsbury deposit is very deep (> 40 ft in some area), it is expected that the majority of the sediment erosion would occur during Phase 1 erosion, resulting in a very small amount of Phase 2 erosion and tight limitation to its duration. In case of a 2 million CY Phase 2 erosion, for example, the duration of impact would be limited to within 2 days based on the results in Figure 10.

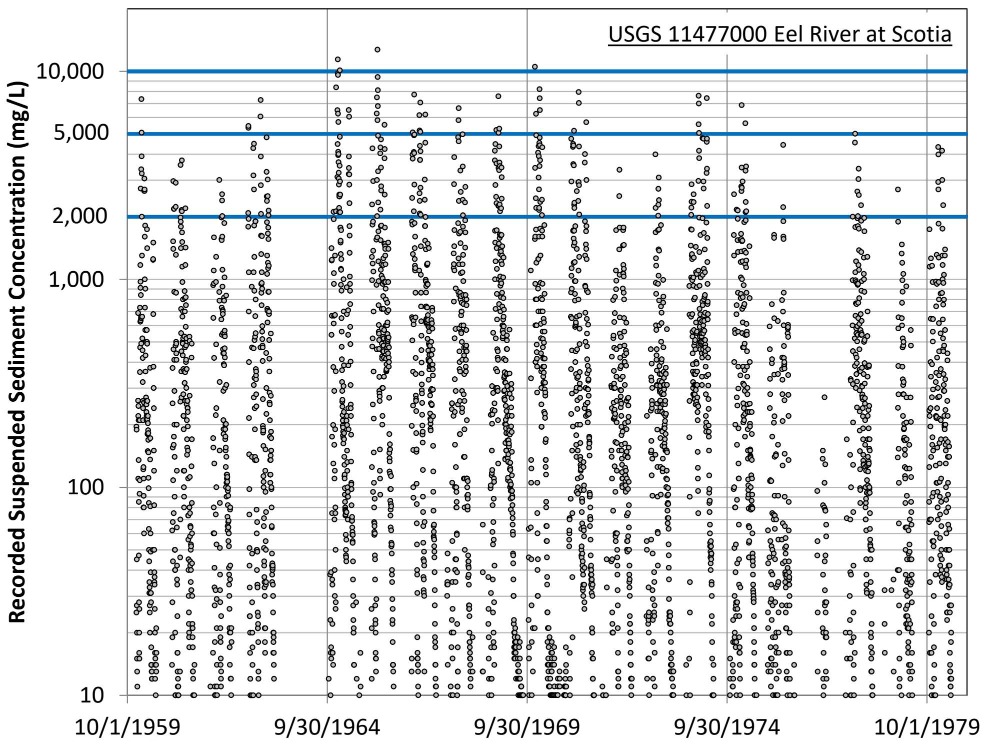

Figure 9. Recorded suspended sediment concentration at USGS gage 11477000 (Eel River at Scotia) (Horizontal blue lines highlight suspended sediment concentration thresholds of 10,000, 5,000, and 2,000 milligrams per liter [mg/L]).

As discussed earlier, surface erosion of the exposed impoundment deposits during precipitation after dam removal would also contribute additional fine sediment supply, but the area of the newly exposed land following dam removal (< 2,300 acres) would be only a small fraction (approximately 1%) of the catchment area upstream of Scott Dam (approximately 289 mi^2). This, in combination with the fact that the Eel River has a high ambient sediment production should make the impact from the additional Phase 2 suspended sediment contribution due to precipitation and surface runoff negligible, especially when compared with the extremely high suspended sediment concentration in the first few days following dam removal. In addition, Phase 1 and Phase 2 erosion mainly addresses the erosion of the bottom-set deposit (Figure 2) that is composed primarily of silt, clay and fine sand. Upon the conclusion of Phase 1 and Phase 2 erosion, the top-set deposit (Figure 2), which is composed primarily of gravel and perhaps coarser sand, will continue to degrade during high flow events, releasing fine sediment previously locked within the deposits. The increased suspended sediment concentration due to top-set erosion, however, is expected to have minimal impact for two reasons: (1) the amount of fine sediment content in the top-set deposit is much smaller compared to the bottom-set deposit; and (2) significant top-set erosion occurs only during high flow events, during which ambient suspended sediment concentration is high, and the large discharge would also make the increased suspended sediment concentration from top-set erosion low. In short, we do not expect significant impact from increased suspended sediment concentration once Phase 1 and Phase 2 erosion is concluded for the case of vertical notching alternative.

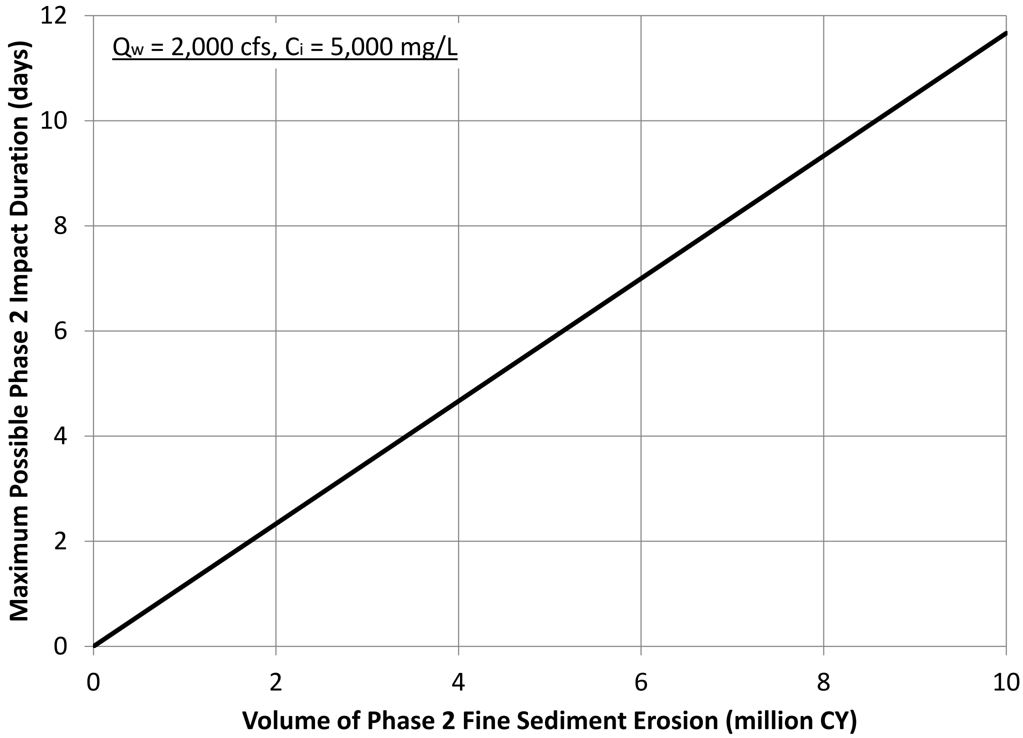

Figure 10. Calculated maximum possible duration of Phase 2 erosion duration based on Equation 2 under 2,000 cfs water discharge; actual Phase 2 erosion is expected to last for a few hours.

5.2 Fine Sediment Erosion Under Four-stage Removal Alternative

There are two major differences in fine sediment erosion between the four-stage removal alternative to be analyzed in this section and the vertical notching alternative analyzed in the previous section: (a) vertical notching would release fine sediment before a relatively large flow event while staged removal would likely release fine sediment primarily during low flow seasons; and (b) vertical notching would result in a single major sediment release event while staged removal would result in multiple fine sediment release events.

Figure 11 below shows the recorded monthly average discharge downstream of Scott Dam, indicating that the low flow season is between May and November, and the average unimpaired discharge during this period is 133 cfs. In the analysis below we assume that dam removal work would be conducted during this low flow period, and the discharge would be kept at a constant value of 133 cfs for simplicity.

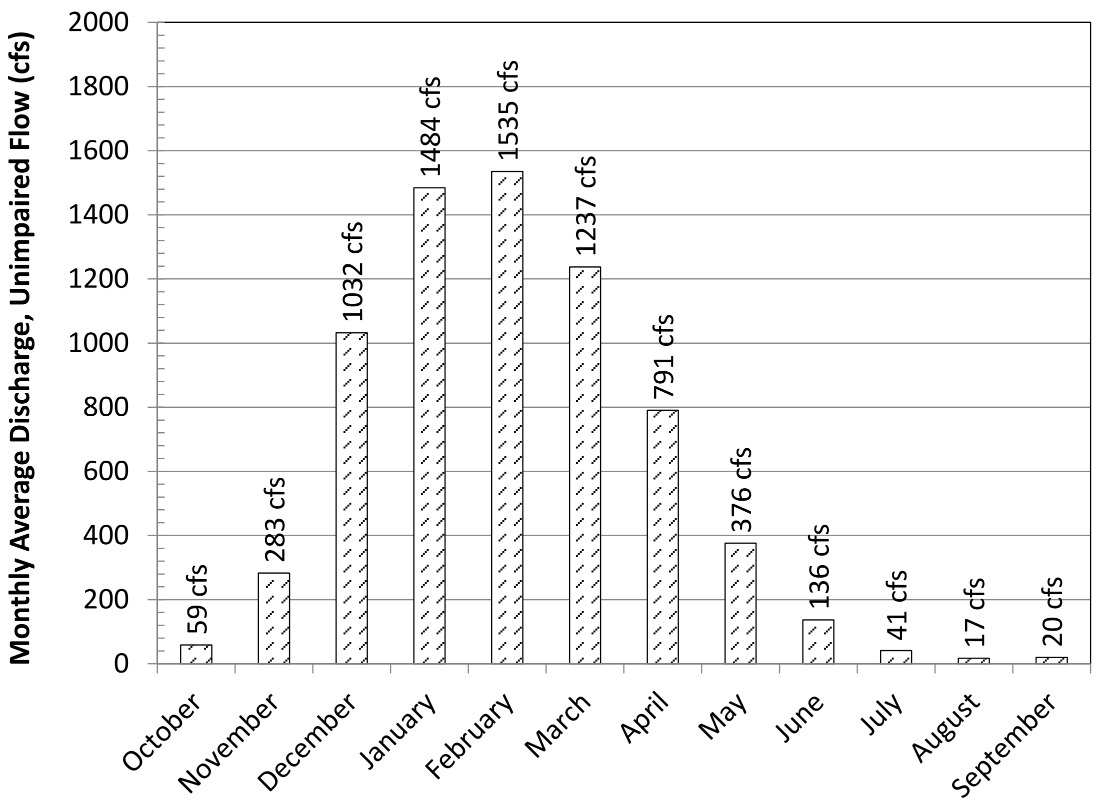

Figure 11. Unimpaired monthly average water discharge downstream of Scott Dam based on simulated unimpaired discharge series WY 1911–2017 (Addley et al. 2019), indicating staged removal and lake drawdown will likely occur in the low flow season of May through November (the assumed construction season). Figure provided by McBain Associates.

With the progress in dam removal during the assumed May through November construction season, base level would be lowered gradually using the existing valve and overflow if the valve capacity is inadequate to keep up with the lowering of the dam surface. The initial part of the removal (prior to Lake Pillsbury Lake level reaching 1,781 ft, as discussed above in Section 4.1) would result in minimal release of fine sediment deposited in the impoundment as the water depth is still relatively deep and shear stress relatively low, but at certain point significant fine sediment erosion would start to occur as shear stress continuously increase with the lake level drawdown. If the rate of dam lowering is quick enough, the equations for TPCM Phase 1 erosion analysis presented above (i.e., Equations 1, 4, and 5) can be used to provide an estimated suspended sediment concentration. Applying the same channel width and channel gradient as used in Section 5.1 and change water discharge to 133 cfs would result in a suspended sediment concentration value of 196,000 mg/L. But in general, the rate of dam lowering is likely much slower than what is needed to maintain this erosion rate, resulting in a suspended sediment concentration lower than the above calculated value. A more precise suspended sediment concentration, however, cannot be estimated reliably due to limitations in current sediment transport theory. With the estimated volume of fine sediment erosion discussed in Section 4.2 and applying Equation (6), a suspended concentration – impact duration (number of days for fine sediment release) curve can be developed for each stage of dam removal, as shown in Figure 12.

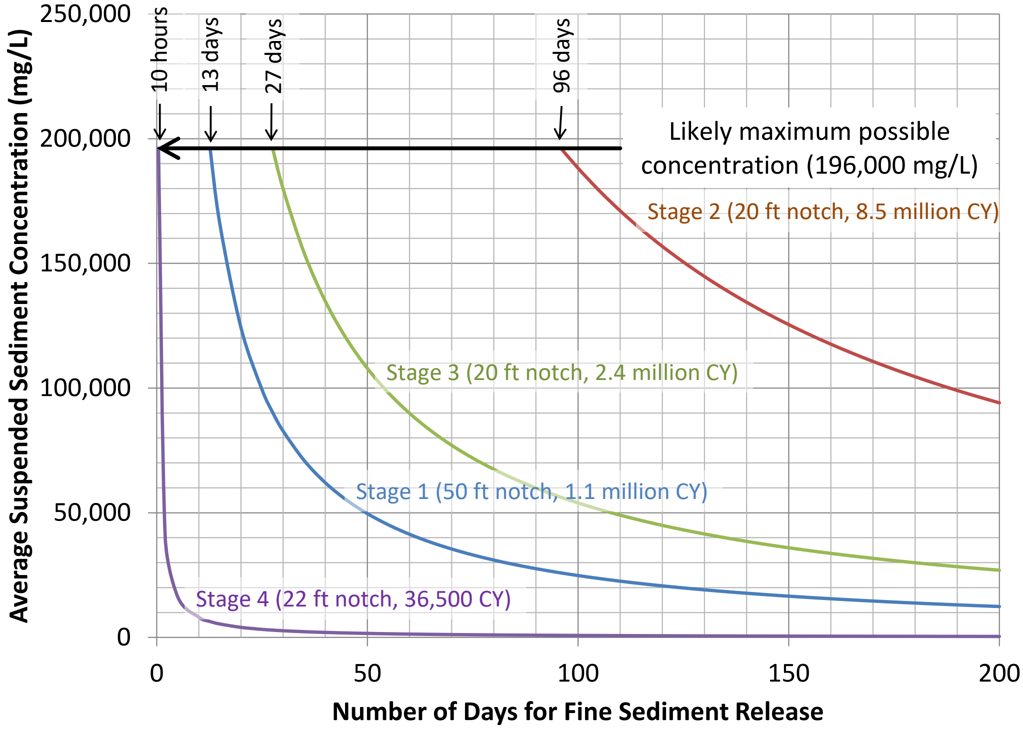

Figure 12. Suspended sediment concentration vs. duration of high suspended sediment concentration for the four-stage dam removal alternative at 133 cfs discharge, assuming sediment release occurs only during lake level drawdown.

In the absence of reliable estimate of the suspended sediment concentration, the curves presented in Figure 12 would be useful to develop some "what-if" scenarios to inform the potential downstream impacts. For example, results in Figure 12 indicate that there would be a minimum of 136 days (13 days + 96 days + 27 days + 10 hours ≈ 136 days) of fine sediment release for the four stages of dam removal with likely maximum suspended concentration of 196,000 mg/L. Note in Figure 12, the suspended sediment concentration is inversely correlated to the duration of number of days of fine sediment release because the concentration is constrained by the available sediment in each notching phase. If, for example, the suspended sediment concentration is kept at 100,000 mg/L, there would be 25 days of fine sediment release during Stage 1 removal, 189 days during Stage 2, 52 days during Stage 3, 1 day during Stage 4, or a combined 267 days of high turbidity impact compared to the 118 days for the case of 196,000 mg/L suspended sediment concentration.

Note the above discussions are entirely based on the volume of sediment erosion during different stages of dam removal estimated from GIS analysis (Stillwater Sciences et al. 2021), and the actual volume release will certainly differ. Stage 1, for example, removes the dam to an elevation of 1,771.22 ft, which is only approximately 10 ft lower than the pool level during the summer of 2014 drought. As a result, the amount of fine sediment release is likely much smaller than the 1.1 million CY assumed in the analysis, and there is likely very few to no days with elevated suspended sediment concentration during the construction season. However, the smaller amount of assumed sediment release during Stage 1 removal implies the amount of sediment erosion during the next three stages would need to be higher than assumed in the analysis, meaning more days of high suspended sediment concentration during these stages. Because of that, the combined number of days with high suspended sediment concentration during all four construction seasons should be similar if we redistribute the volume of erosion amongst the four construction seasons.

It needs to be realized that the actual case will be significantly complicated, with both the lake lowering speed and water discharge varying over time. The estimated average inflow for the dry season (July through September), for example, is only 34 cfs (Figure 11), which is significantly lower than the 133 cfs used for the calculations presented above. With a lower inflow during the dry season, suspended sediment concentration is likely somewhat lower than that at 133 cfs, but probably not significantly lower (i.e., still on the same order of magnitude): a lower water discharge will result in a lower (and still unknown) channel gradient, which would drive down the suspended sediment concentration; meanwhile, a lower discharge would also result in a narrower channel, which would drive up the suspended sediment concentration and canceling part of the effect from the decreased channel gradient. As a result, the combined effect of a lower channel gradient and narrower channel for a 34 cfs discharge would likely result a suspended sediment concentration that is only marginally lower than that at 133 cfs. As a demonstration, reducing both the channel gradient and channel width to half of that used for early calculations (i.e., change channel gradient and channel width to 0.005 and 150 ft, respectively) and use a discharge of 34 cfs would result in a calculated maximum suspended sediment concentration of 83,000 mg/L, or about half of what was calculated for the 133 cfs discharge. With a lower discharge and high volume of available fine sediment for erosion, it is almost guaranteed that high suspended sediment concentration would persist during the entire low flow season (i.e., May through September). Despite the high suspended sediment concentration during the low flow season, the amount of fine sediment erosion is limited due to the low water discharge throughout the season. During the dry season of July through September, for example, a 34 cfs water discharge combined with an 83,000 mg/L suspended sediment concentration would result in only approximately 700 tons of fine sediment erosion, leaving much of fine sediment for erosion during the winter high flow events and during subsequent seasons. Because of that, it is expected that an acute peak high suspended sediment concentration event would occur during the first winter high flow event, eroding a significant amount of fine sediment. The suspended sediment concentration during this event is expected to be somewhat similar to that of the vertical notching alternative, perhaps with a slightly lower magnitude and significantly shorter duration because the amount of sediment release is much less than that for vertical notching alternative (i.e., fine sediment release in four years instead of one single event).

It is useful to note that the above analysis is based on the worst-case-scenario assumptions that did not consider the trapping of sediment in the deeper part of the lake during the early phases of dam removal and the possible occurrence of higher flows during the construction season. The trapping of the mobilized fine sediment in the deeper part of Lake Pillsbury during dam deconstruction can potentially lower the suspended sediment concentration downstream of the dam during construction, and the trapped sediment can be released during winter high flow events or in the later phases of the deconstruction. However, given the fine sized particles in the deposit (median size = 0.011 mm, with settling velocity for the median sized particles = 3.58×10^{-4} ft/s), the majority of the mobilized fine sediment will pass the dam without settling, and the contribution from the trapping to suspended sediment concentration is likely minor. Relatively high flow during the construction season is likely a stronger contributor toward the lowering of the impact of suspended sediment concentration: a high flow would erode more sediment in a shorter period of time, resulting in a relatively lower suspended sediment concentration after the high flow event (i.e., instead of being in a constant state of high suspended sediment concentration, there would be periods of high and low suspended sediment concentration due to occasional high flow events during the construction season). Because of the uncertainties associated with potential high flows during construction season, it is recommended that the potential beneficial impact associated with the occurrence of high flow events during construction season not be considered for subsequent analysis as a conservative measure so that the actual duration of impact would not be longer than estimated by the analysis.

6 SUMMARY

Removing Scott Dam with the proposed vertical notching alternative would result in a one time high suspended sediment concentration on the order of 600,000 mg/L that would most likely last for approximately 4 days (3 days Phase 1 erosion, 1 day Phase 2 erosion) if water discharge following notch opening is around the targeted 2,000 cfs (Table 1). If the discharge following notch opening is only 1,000 cfs, however, the suspended sediment concentration would be reduced to 400,000–500,000 mg/L that would most likely last for approximately 9 days (8 days Phase 1 erosion, 1 day Phase 2 erosion). If the discharge following notch opening is 5,000 cfs, the suspended sediment concentration would be increased to approximately 900,000 mg/L that would most likely last for approximately 2 days (1 day Phase 1 erosion, 1 day Phase 2 erosion). A higher discharge following notch opening would result in higher suspended sediment concentration up to a little bit more than 900,000 mg/L and would shorten the duration of the high suspended sediment and turbidity.

Removing Scott Dam with the proposed four-stage alternative would result in fine sediment erosion during the low flow season (May through November) up to approximately 196,000 mg/L for a combined duration of at least 136 days that spans four water years, if the rate of notching is adequately fast. The most likely result under this alternative, however, is a suspended sediment concentration lower than 196,000 mg/L that last significantly longer. Assuming a constant 100,000 mg/L suspended sediment concentration, for example, the combined duration in the four water years for dam removal could potentially exceed 267 days. A faster notching would mean a higher suspended sediment concentration but shorter impact duration (but still longer than 118 days); a slower notching would mean a lower suspended sediment concentration but increased duration of impact. In the absence of mechanical sediment removal and disposal, there is no method that we can think of to reduce the magnitude of suspended sediment concentration and shorten the impact duration simultaneously under the natural sediment erosion scenario.

The potential impact to fisheries resources for the vertical notching and four-stage removal alternatives will be presented in a separate technical memorandum (Stillwater Sciences 2021 — *Analyses of fine sediment erosion effects on aquatic species following the proposed Scott Dam removal*.).

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