Title
Six years of fluvial response to a large dam removal on the Carmel River, California, USA

Journal
Earth Surface Processes and Landforms, 48(8)

ISSN
0197-9337

Authors
East, Amy E
Harrison, Lee R
Smith, Douglas P
et al.

Publication Date
2023-06-30

DOI
10.1002/esp.5561

Received: 2 December 2022 | Revised: 1 February 2023 | Accepted: 5 February 2023
DOI: 10.1002/esp.5561

RESEARCH ARTICLE

ESPL WILEY

Six years of fluvial response to a large dam removal on the Carmel River, California, USA

Amy E. East[1] | Lee R. Harrison[2] | Douglas P. Smith[3] | Joshua B. Logan[1] | Rosealea M. Bond[2]

[1]U.S. Geological Survey, Santa Cruz, CA, USA
[2]NOAA Southwest Fisheries Science Center, Santa Cruz, CA, USA
[3]Applied Environmental Science, California State University, Monterey Bay, Seaside, CA, USA

Correspondence
Amy E. East, U.S. Geological Survey, Santa Cruz, CA 95060, USA.
Email: aeast@usgs.gov

Funding information
National Oceanic and Atmospheric Administration; U.S. Geological Survey; California State University, Monterey Bay

Abstract

Measuring river response to dam removal affords a rare, important opportunity to study fluvial response to sediment pulses on a large field scale. We present a before–after/control–impact study of the Carmel River, California, measuring fluvial geomorphic and grain-size evolution over 8 years, six of which postdated removal of a 32 m-high dam (one of the largest dams removed worldwide) and included 11 flow events exceeding the 2-year flood magnitude. We find that the reservoir-sediment pulse following dam removal was relatively small (97 000 ± 24 000 t over 4 years), owing to deliberate reservoir-sediment stabilization. Scaled to the size of the Carmel River watershed and compared against long-term bedrock denudation rates, the post-dam-removal sediment release was slightly less than the annualized long-term sediment export from this basin. New sediment transited >30 km to the river mouth in less than 2 years, assisted by floods 2 and 4 years after dam removal. The sediment pulse fined the downstream riverbed while causing mostly low-magnitude bed-elevation changes: commonly 0.5 to 1 m or smaller, occurring as discontinuous sediment patches or interstitial deposits, aside from the filling and subsequent partial scour of deep pools. There was no major geomorphic reset downstream from the dam site. Geomorphic changes were driven almost entirely by flow rather than by the modest increase in sediment supply, in contrast to recent examples from other large dam removals. The relatively minor disturbance caused by dam removal on the Carmel River is likely analogous to many future dam removals: a relatively small sediment pulse after deliberate limitation of reservoir-sediment erosion, and with an upstream dam remaining in place. Thus, a large dam removal need not lead to major downstream impacts.

KEYWORDS
dam removal, floods, fluvial geomorphology, river management, sediment transport

1 | INTRODUCTION

Understanding fluvial responses to disturbances, such as from land use, climate change, or seismic activity, remains an important problem in geomorphology (Costa & O'Connor, 1995; Dadson et al., 2004; Gilbert, 1917; Madej & Ozaki, 1996; Trimble, 1981; Tucker & Slingerland, 1997; Wohl, 2015). Within this problem there is a particular need to understand better how long a disturbance signal persists, and how it diminishes after an initial forcing event, as well as understand how landscapes respond to superposed types of disturbances, as these inevitably occur over long time scales (e.g. Baynes et al., 2018; Keller et al., 1997; Moody, 2017). Landscape recovery depends upon connectivity within the sediment-routing system (Lane et al., 2017; Wohl et al., 2019), antecedent geomorphic conditions

(Hooke, 2015; Masteller & Finnegan, 2017; Yellen et al., 2016), and post-disturbance hydrology (Gray, 2018; Keller et al., 1997; Warrick et al., 2012). However, trying to project recovery timelines after substantial landscape disturbance remains difficult. Dam construction and removal are modern disturbance regimes that have myriad societal and ecological implications. This study documents river response to removal of a large dam, characterizing the post-dam-removal evolution as sediment from the former reservoir eroded and moved downstream, affecting fluvial morphology. Long-term documentation of post-dam-removal response and recovery has important implications for guiding river restoration and for understanding the likely evolution of a riverscape following natural sedimentary disturbances such as extreme floods (Moody, 2017; Tunnicliffe et al., 2018) or volcanic eruptions (Gran & Montgomery, 2005; Major et al., 2018; Meyer & Martinson, 1989).

Intentional dam removal affords valuable opportunities for before–after/control–impact (BACI) studies of fluvial disturbance. The number and magnitude of dam removals have increased greatly in the past 20 years (Figure 1), prompted by economic and environmental considerations (Doyle et al., 2008; Foley, Bellmore, et al., 2017; Sawaske & Freyberg, 2012). At least 1900 dams in the United States have been removed intentionally since 1912, of which 1455 were removed between 2000 and 2021 (American Rivers, 2021; Figure 1). Dam removal is receiving more research attention internationally as well (Ibisate et al., 2016; Tang et al., 2021; Wang & Kuo, 2016), particularly as concerns about habitat fragmentation and fish populations contrast with the growing need for renewable energy such as hydropower (Barbarossa et al., 2020; Birnie-Gauvin et al., 2020; Duda et al., 2021; Habel et al., 2020; Hess et al., 2021; O'Connor et al., 2015; Zarri et al., 2022).

Important findings have recently emerged from some of these dam removals. The style and magnitude of geomorphic response appear to be primarily controlled by dam height (which affects the amount of stored sediment and base-level fall after dam removal), reservoir-sediment volume and grain size, and whether dam removal

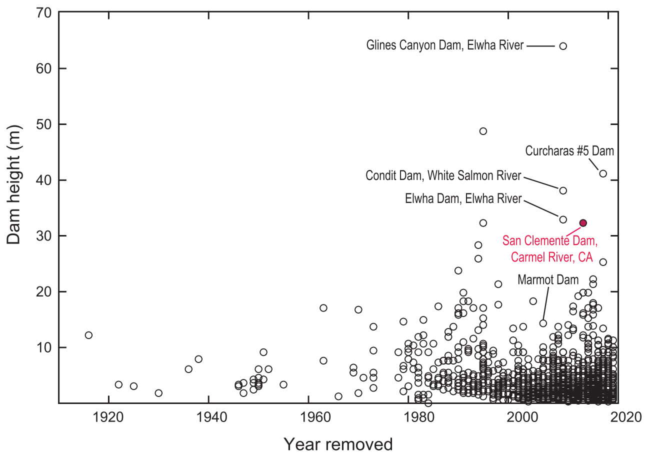

FIGURE 1 Dams removed intentionally in the United States, 1912 to 2021 (data from American Rivers, 2021). These include 1785 dams (shown on plot) and another 144 with unknown removal date. Names of the largest dams discussed in the text are indicated: San Clemente Dam, Carmel River, California; Elwha and Glines Canyon Dam, Elwha River, Washington; Cucharas #5 Dam, Colorado; and Condit Dam, White Salmon River, Washington.

is phased or instantaneous (Bountry et al., 2013; Collins et al., 2017; East et al., 2015, 2018; Foley, Bellmore, et al., 2017; Major et al., 2012, 2017; Pearson et al., 2011; Wilcox et al., 2014). Recent studies have measured the rates and processes of sediment erosion upstream from removed dams: the dam removal and reservoir drainage are commonly followed by knickpoint migration and fluvial incision (Doyle et al., 2003; Major et al., 2012; Randle et al., 2015; Ritchie et al., 2018; Wilcox et al., 2014; Wildman & MacBroom, 2005). Downstream, sediment accumulates after dam removal, at least in the short term (days to 1–2 years). The new sediment supply typically decreases the riverbed grain size, aggrades the channel, and reduces topographic relief as pools fill (Dahal et al., 2021; East et al., 2015; Evans & Wilcox, 2014; Harrison et al., 2018; Tullos et al., 2014; Zunka et al., 2015). Based on evidence from two dam removals in the eastern United States, Pearson et al. (2011) and Collins et al. (2017) proposed that a two-phase process governs fluvial response following dam removal, wherein an initial transport-limited, high sediment-supply phase (triggered by base-level fall as the reservoir no longer provides hydraulic control, and the riverbed is graded to a new elevation at the base of the former dam) is followed by a supply-limited phase in which floods are required to cause further geomorphic change (i.e. floods alter channel morphology and bed sediment below the former dam site partly because they remobilize additional sediment from the reservoir deposit). If the reservoir sediment supply is large enough, downstream aggradation can greatly increase fluvial channel width and braiding during the transport-limited phase (East et al., 2018). These responses often peak and subside rapidly; the physical environment and ecosystem can recover substantially from even large dam-removal sediment pulses (>10 Mt) in 1–2 years (East et al., 2018; Foley, Bellmore, et al., 2017; Major et al., 2017; Ritchie et al., 2018; Warrick et al., 2015; Wilcox et al., 2014). Eventually the sediment supply from erosion of the reservoir deposit becomes less important to downstream river evolution than does restored connectivity to natural sediment sources upstream (if no other upstream dams are present), and further geomorphic evolution is driven largely by episodic modification resetting by flood flows. Ecosystem recovery requires more time but can begin within ~2 years (Bellmore et al., 2019; Bushaw-Newton et al., 2002; Duda et al., 2021; Foley, Bellmore, et al., 2017; Foley, Warrick, et al., 2017; Pess et al., 2014; Tonra et al., 2015; Tullos et al., 2014).

Despite these recent advances, important knowledge gaps remain. Detailed, long-term studies of fluvial response accompany fewer than 10% of dam removals, across a limited range of geographic and hydroclimatic conditions, and most of those concerned small dams over a limited biogeographic and hydroclimatic range (dams <10 m tall and concentrated in the eastern and northeastern United States; Bellmore et al., 2016). There is uncertainty about the role of hydrology, especially flood flows, in driving fluvial response and recovery after dam removal (e.g. Major et al., 2012). Whereas floods are commonly the largest drivers of fluvial geomorphic change and might be expected to drastically reset a river carrying excess sediment, some post-dam-removal studies found that floods produced relatively minor changes downstream of the former dam site. Major et al. (2012) observed little geomorphic response to a 10-year flood on the Sandy River, Oregon, 4 years after the removal of 14 m-high Marmot Dam. East et al. (2018) and Ritchie et al. (2018) observed only modest downstream geomorphic change on the Elwha River, Washington, due to a 10-year flood 4 years after the removal of two large dams (64 and 32 m high), whereas earlier in the dam-removal time frame abundant sediment transport and geomorphic change had occurred under low to moderate flows (East et al., 2015; Magirl et al., 2015). Based on hydraulic modelling of reach morphology after removal of a 4 m-high dam, Fields et al. (2021) proposed that the rate of geomorphic adjustment after dam removal depends on the time needed for temporarily elevated critical Shields values (caused by increased fine-sediment supply) to decrease below that expected for the 2-year flood. Having measured the response of the Carmel River, California, to removal of a 32 m-high dam and erosion from a partially sequestered reservoir-sediment deposit, Harrison et al. (2018) proposed that large floods early in the post-dam-removal time frame are relatively more important in driving downstream fluvial response than large floods occurring later. The relative influence of sediment supply and hydrologic variability in dam-removal recovery is important to prediction of future dam-removal effects and can inform broader discussions on long-term landscape response to superposed disturbances (i.e. increased sediment supply followed by high discharge).

We extend a long-term BACI study of the Carmel River (Harrison et al., 2018) by four additional years to examine in greater detail the role of high flows versus dam-removal sediment supply in driving geomorphic change. This is one of few dam removals accompanied by long-term BACI investigations (cf. Collins et al., 2017; Collins et al., 2020; Duda et al., 2021; East et al., 2018; Major et al., 2012; Tang et al., 2021), and additional field data are now available from the Carmel River reflecting its disturbance and recovery. As discussed below, this river has undergone removal of a large dam but with relatively little base-level fall and reservoir sediment release, due to intentional efforts to manage and minimize downstream sediment impacts. This paper shows that despite passage of a sediment pulse along 30 km of the river (reaching the river mouth), geomorphic change was modest and driven by high flows more than by the increased sediment supply. Thus, the Carmel River provides an example of large dam removal having limited downstream impacts owing to a successful engineering strategy that minimized reservoir-sediment export.

2 | STUDY AREA

The Carmel River drains a 650 km^2 coastal watershed in the Santa Lucia Range of central California (Figure 2), a region with a Mediterranean hydroclimate (hot, dry summers and cool, wet winters) and interseasonal flow variability that ranges over four orders of magnitude. Floods can occur during the rainy season between late autumn and early spring. The 2, 5, 10, 25, and 50-year flood peak magnitudes are calculated to be, respectively, 80, 135, 182, 254, and 318 m^3/s using the stream-gauge record from USGS gauging station 11143200 (Figures 2 and 3; U.S. Geological Survey, 2022). The lowermost 40 km of the Carmel River are alternately bedrock and alluvial morphology, with various degrees of channel confinement (Table S1). Natural sediment supply includes dry ravel, landslides, and occasional debris flows, including from post-wildfire rainfall (Smith et al., 2021).

The 32 m-high San Clemente Dam was removed from the Carmel River in November 2015, the largest dam removal thus far in California and one of few this size removed worldwide. The dam removal was motivated by near-total loss of reservoir storage capacity due to sediment deposition over its 95-year history, and the potential for dam failure during an earthquake or large flood. The dam removal was carried out with the intent to minimize downstream impacts by limiting reservoir sediment erosion, in order to avoid bed aggradation that could increase the flood risk to structures built on the floodplain. The upper third of the 1.7 million m^3 reservoir deposit was accessible for natural fluvial erosion after dam removal, whereas the lower two-thirds were sequestered as the river was rerouted into a tributary channel, San Clemente Creek, to bypass the lower part of the former reservoir (Harrison et al., 2018; Smith et al., 2020). The elevation difference between the former full-pool water-surface elevation of San Clemente Reservoir and the point at which the river was rerouted down the newly cut bypass channel is 6 m; therefore, the base-level fall prompting erosion of the upper reservoir deposit was 6 m rather than the full 23 m of base-level drop to the base of the dam site. Thus, the removal of San Clemente Dam was not intended as a full watershed restoration involving entirely natural river erosion nor reconnection to natural upstream sediment supply. Another dam, Los

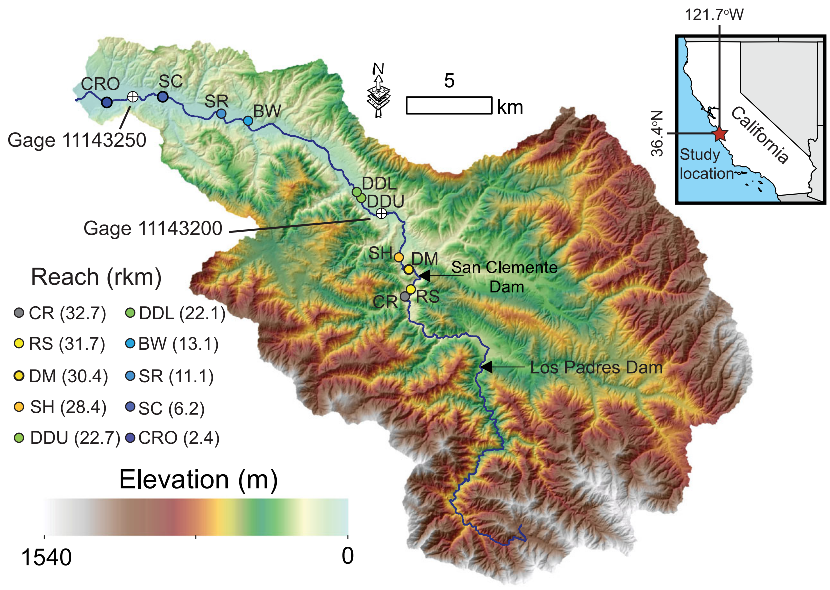

FIGURE 2 The Carmel River basin, central California coast. Locations of reaches monitored for this before–after/control–impact (BACI) study are identified by river kilometre and abbreviated as follows: control reach (CR), reservoir (RS), dam reach (DM, immediately downstream from the San Clemente Dam site), Sleepy Hollow (SH), DeDampierre upper (DDU), DeDampierre lower (DDL), Berwick (BW), Schulte Road (SR), San Carlos (SC), and crossroads (CRO). The locations of USGS gauging stations 11143200 and 11143250 are also shown (U.S. Geological Survey, 2022), as is the former location of San Clemente Dam, removed in 2015. Los Padres Dam, 42 km upstream from the river mouth, remains in place.

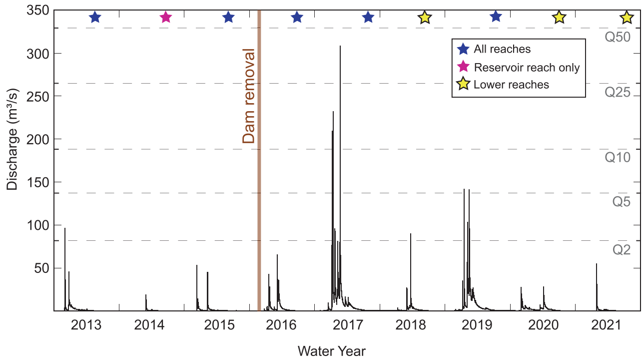

FIGURE 3 Discharge of the Carmel River during the study interval, water years 2013–2021 (1 October 2012 to 30 September 2021), measured at USGS gauging station 11143200 (see Figure 2 for location; data from U.S. Geological Survey, 2022). Discharge is shown at 15-min resolution. Dashed lines indicate magnitude of flow peaks with recurrence intervals of 2, 5, 10, 25, and 50 years (Q_2, Q_5, and so on), calculated on peak-flow data from 1956 to 2021 using a log-Pearson type III flood-frequency analysis with the multiple Grubbs–Beck test to remove low outliers (U.S. Geological Survey, 1981). Dam removal occurred in late autumn 2015. Coloured stars indicate dates of field surveys, 'lower reaches' in the legend refers to study reaches downstream of rkm 22 (DDU reach and below).

Padres Dam (40 m tall), remains in place 11 km upstream of the former San Clemente Dam site at river kilometre (rkm) 42, impounding 18% of the watershed area upstream of the BACI study region (described below; river kilometres are referenced to 0 at the river mouth). These factors were, by design, important to prevent major post-dam-removal bed aggradation that could have increased flood risk to properties along the lower river downstream of San Clemente Dam.

The Carmel River is unique thus far in examples of large dam removal in having experienced major floods shortly after the dam removal. Largely due to an ~40-year flood (Q_{40}, 309 m^3/s on 21 February 2017), two 10-year floods (Q_{10}, peaks of 209 m^3/s on 8 January and 232 m^3/s on 11 January), and four 2-year flood peaks (Q_2, i.e. flows above 80 m^3/s) occurring 14–15 months after dam removal during an extremely wet winter in 2017 (Figure 3), ~49 000 ± 21 000 t of sediment had moved downstream by spring 2017, filling pools and fining the riverbed grain size along 30 km between the dam site and the river mouth (Harrison et al., 2018). Here, we present results from new field surveys that followed an additional Q_2 flood in 2018, two 5-year flood peaks (Q_5) and a Q_2 peak in January 2019, and two additional dry years (2020 and 2021), extending the full Carmel River dataset to span 9 years (2013–2021) and a total of 11 flows at or above the 2-year flood magnitude (Figure 3).

3 | METHODS

We measured fluvial topography and riverbed grain size before and after dam removal, in one control reach and nine impacted reaches upstream and downstream of the San Clemente Dam site (Figure 2; cf. Harrison et al., 2018). Our control reach upstream of the San Clemente Reservoir (CR in Figure 2) is downstream of Los Padres Dam but was unaffected by San Clemente Dam removal. Our upstream-most impacted reach was within the San Clemente Reservoir deposit, upstream of the rerouted channel region (RS reach; Figure 2), where the river naturally eroded reservoir material beginning with knickpoint migration during reservoir drawdown in early 2015 (Harrison et al., 2018). We also surveyed eight impacted river reaches downstream from San Clemente Dam site (DM to CRO; Figure 2). In each of the 10 reaches, we surveyed four to six cross-sections during summer low-flow conditions in 2013, 2015, 2016, 2017, and 2019. The six reaches farthest downstream (DDU through CRO) were also surveyed in summer or early autumn 2018, 2020, and 2021. We established survey control points using either post-processed or real-time kinematic (RTK) GNSS occupations and used total-station and auto-level surveys to measure topography along channel-perpendicular cross-sections spaced 60 m apart, with a typical cross-stream point spacing of 1–2 m. Points were spaced more densely along slope breaks and within more complex topography. These measurements have an estimated uncertainty of 1–3 cm in the horizontal and vertical directions. For surveyed areas that included two deep pools, additional topographic data were collected at higher spatial resolution using a survey rod and a kayak-mounted echo sounder, acquiring 440–2550 points per survey in a 956 m^2 pool in the SH reach, and 420–3100 points per survey in a 987 m^2 pool in the DM reach. These high-resolution pool data were interpolated to form a continuous surface using Delaunay triangulation and resampled onto a digital elevation model (DEM) with 0.3 m resolution. An uncertainty analysis of the interpolated pool surveys indicated absolute vertical errors of 0.070 to 0.110 m, with a mean value of 0.083 m.

We used metrics developed by East et al. (2018) to summarize channel geomorphic changes through time, and to look for the influence of sediment supply independent of changes caused by hydrology. This method is based on calculating ΔC, the reach-averaged bed-elevation change between consecutive surveys. For each survey date, at 5 m intervals along each cross-section we measured the change in bed elevation since the previous survey, and then used the mean of these measurements for each reach to obtain a ΔC value (thus, for a reach containing six 50 m-long transects, ΔC would be the mean of 60 bed-elevation difference measurements between consecutive surveys). We calculated ΔC values using absolute elevation change to avoid spurious inferences of no change resulting from equal magnitudes of aggradation and degradation along a transect. This analysis used only the highest temporal-resolution data available for each reach (e.g. where several transects in the CRO reach were skipped in 2018, the ΔC values were calculated using only areas where surveys did occur at 1-year intervals in order to avoid mistakenly attributing the timing of change). Thus, we were able to track reach-averaged bed-elevation change throughout 2013 to 2021.

To evaluate topographic change while minimizing effects of hydrologic variations (i.e. looking for geomorphic response to variations in sediment supply rather than flow), we normalized the ΔC values in two ways, dividing ΔC by two different metrics that represented the flow regime between surveys. The first metric, a dimensionless parameter called Q^*, is simply the maximum peak-flow magnitude between surveys divided by the mean annual discharge of the Carmel River, 2.55 m^3/s. The second metric uses stream power (Ω), the product of water discharge (Q), slope (S), gravitational acceleration (g), and the density of water (ρ), so $\Omega = \rho g Q S$. We define a parameter, Ω_{99}, which is the total stream power calculated for 15-min intervals (the discharge record shown in Figure 3) in which flow exceeded the 99th percentile for discharge in that inter-survey interval. That is, we identified times when flow (Q) was above the 99th percentile of discharge (Q_{99}) occurring between two surveys, and for each 15-min time step when $Q > Q_{99}$ we calculated a value for Ω. By summing Ω values for each inter-survey interval, we obtained cumulative stream power (Ω_{99}) for each time step. The values of Ω_{99} were then made dimensionless, dividing them by the value of Ω corresponding to the mean annual flow, to keep the normalized ΔC values in units of metres. These metrics, the time series for which is shown in Figure S1, focus on high flows because channel morphology is commonly most sensitive to the highest recent flows and has been shown to reflect Q^* specifically (East et al., 2017; Magilligan et al., 2015). Characterizing stream power in addition to Q^* facilitates the transfer of our findings to other rivers and our use of cumulative stream power between surveys reflects the geomorphic importance of high-flow duration as well as peak magnitude (Costa & O'Connor, 1995; Gervasi et al., 2021; Papangelakis et al., 2022). We use stream power (Ω) rather than unit stream power (ω), which is width-dependent, because channel width can change greatly during and after dam removal (East et al., 2018; Harrison et al., 2018).

We examined longitudinal variation in sediment-pulse behaviour through spatio-temporal changes in sediment thickness. As in Zunka et al. (2015), sediment thickness, z, was calculated as the ratio of bankfull cross-sectional area to bankfull width for each survey year. Changes in this parameter, Δz, were calculated to assess reach-averaged cumulative changes in sediment thickness over time.

To characterize the evolution of bed-sediment grain size during and after dam removal, we measured surface grain-size distributions using pebble counts (Wolman, 1954) in the same 10 reaches where we surveyed channel topography, working during summer low flows (discharge typically 0.05 to 0.14 m^3/s). Along each of the same six transects per reach, we measured grain size having divided the bankfull width into five equal segments (quantiles). At each quantile within the bankfull channel we obtained 20 grain-size measurements using a 0.5 × 0.5 m sampling frame and gravelometer, thus collecting 100 or more counts per transect during each survey.

4 | RESULTS

The Carmel River showed changes in riverbed morphology and grain size throughout the 6 years studied after dam removal (Figures 4–9; data available at https://doi.org/10.5066/P9HG8UDS; East et al., 2022). All nine impacted reaches consistently showed larger-magnitude changes than did the control reach (CR; Figures 5 and 7A). The largest elevation changes occurred in the reservoir (RS reach), driven by erosion and sediment evacuation. These included 2.5 to 3.5 m of vertical incision over the 2017 flood season on each RS transect (e.g. Figure 5B), together with a major channel avulsion through the upper reservoir, as Harrison et al. (2018) reported. Incision and avulsion were followed by localized erosion of reservoir-sediment banks 3–4 m high between 2017 and 2019 (Figure 5B), creating a much wider river corridor through the former reservoir (Figures 4A–C). The 2017 floods also rearranged and reset an engineered step-pool channel downstream from our RS reach immediately above the dam site (Smith et al., 2020). In contrast, areas downstream from the dam site more commonly eroded and accreted without major lateral erosion (e.g. Figures 5D–H). However, as an exception, the upper part of the San Carlos (SC) reach doubled in width over the 2017 winter due to a 17 m retreat of the left bank

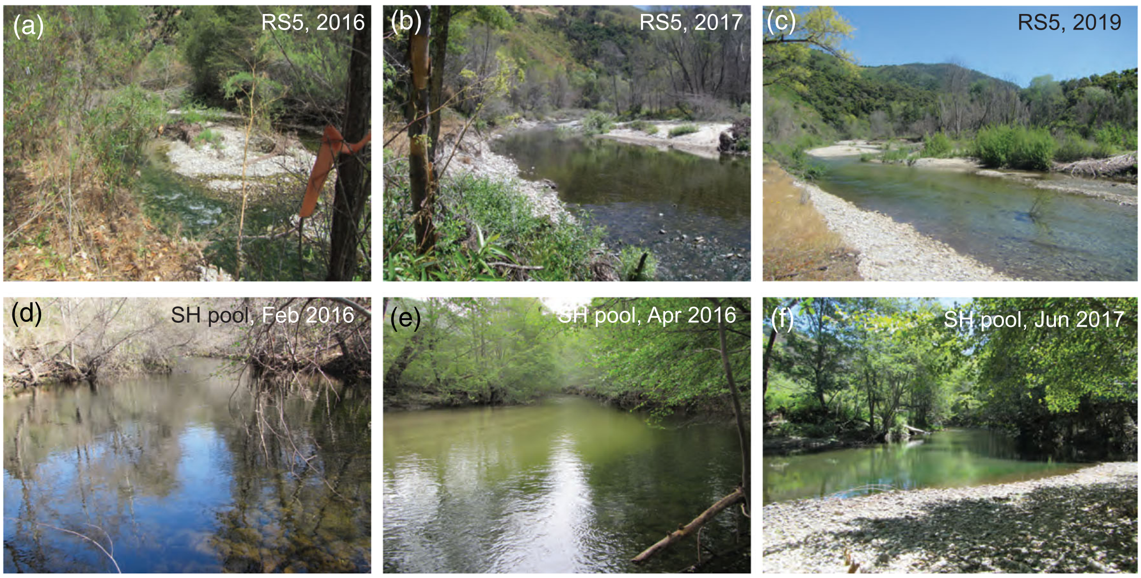

FIGURE 4 Field photographs showing examples of geomorphic change after dam removal. (A) Reservoir reach, viewed facing upstream at the river-right side of transect 5, in June 2016; (B) same view as in (A), seen in June 2017; (C) same view as in (A), seen in April 2019. A knickpoint migrated upstream through the reservoir reach between 2014 and 2017, accompanied by major widening and new channel avulsion. Images (D) to (F) show the pool in the Sleepy Hollow (SH) reach also plotted in Figures 6D–F, viewed here facing upstream. Between (D) February 2016 and (E) April 2016, the pool partially filled with sand, with deposition 2 m thick. This deposition was reflected in the difference between 2015 and summer 2016 surveys (Figure 6D). The 2017 floods removed some sediment from the deeper north (river-right) side of that pool but deposited new gravel on the south (river-left) side ~1 m thick (F and also Figure 6E). This deposit changed little between 2017 and 2019 (Figure 6F). Photographs by U.S. Geological Survey.

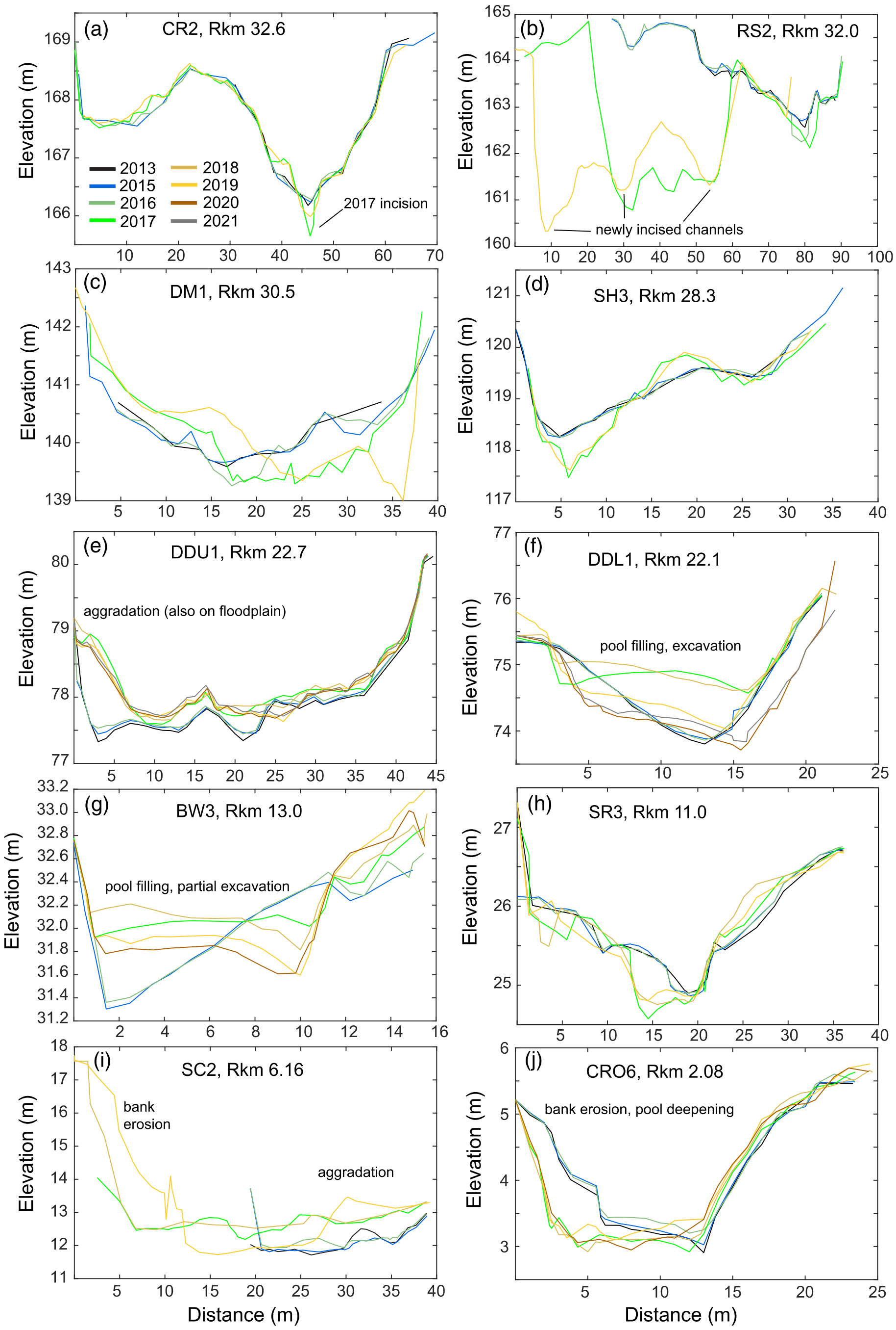

FIGURE 5 Geomorphic change on the Carmel River before and after removal of San Clemente Dam, exemplified by channel cross-section plots of one transect from each of the 10 study reaches, from the control reach centred at rkm 32.6 (A) through to the crossroads reach at rkm 2.08 (J); see Figure 2 for reach locations. All transects are oriented as if viewed facing downstream. Scale varies between panels to illustrate local changes most clearly. Panel labels indicate reach name and transect number (e.g. CR2 is transect 2 of the control reach), using the same naming convention as in the associated data repository (East et al., 2022). Transects were selected to show some of the more substantial geomorphic changes in each reach. Noteworthy features include: major channel incision and backwasting (lateral bank erosion) as the reservoir deposit eroded, particularly in 2017 and 2019 (B); scour and fill in parts of a pool in the Sleepy Hollow reach (D; see also Figures 4 and 6); post-dam-removal aggradation in the DDU reach (E); pool filling and partial excavation in the DDL and BW reaches (F, G); 17 m of bank erosion from the 2019 floods in the upper SC reach (I); and bank erosion and pool scour in the CRO reach (J). Most transects, including those not shown, experienced their largest-magnitude changes as a result of the 2017 floods.

(Figure 5I). Additional topographic changes occurred over the 2018–19 winter (Figures 4 and 6), which included a Q_5 flood (142 m^3/s) on 17 January 2019 and another Q_5 peak (141 m^3/s) on 14 February 2019 during a major atmospheric river storm (Hatchett et al., 2020). The 2019 floods induced minor bank erosion and widening in the confined DM reach immediately below the dam site (the river-right side of the upstream-most transect, T1, also eroded vertically 1.5 m then; Figure 5C), but lateral erosion there was limited by a bedrock wall on the river-right (east) bank. Elsewhere within the DM reach, the 2019 floods left new deposits up to 0.6 m thick.

High-resolution surveys of pools in the DM and SH reaches (at rkm 30.4 and 28.4, respectively) showed minor erosion and deposition between 2017 and 2019—generally less than 1 m of vertical change, with net volume differences that were within our survey uncertainty (Figures 6C and F). These smaller changes in the deep pools between 2017 and 2019 contrasted with their having accumulated 1–2 m of new sediment in the 2015–16 winter immediately after dam removal (Figures 4D and E, 6A and D) and then having been partially excavated by high flows in 2017 (Figures 6B and E).

Normalizing topographic change against metrics of flow strength shows that the reservoir reach (RS) experienced more flow-independent change than did any of the reaches downstream from the San Clemente Dam site and that those changes were largest after 2016 (Figures 7B and C). Differences between the evolution of the RS reach and that of the other, fluvial reaches in Figure 7 are not surprising given the different geomorphic processes at work: the transects through the reservoir sediment reflected metres of incision, channel avulsion, and widening (backwasting) through lake deposits in response to 6 m of base-level fall, processes not operating in the downstream reaches. Most reaches downstream from the dam site showed no significant change in $\Delta C/Q^*$ or $\Delta C/\Omega_{99}$ between 2015 and 2019. Notably, the lower reaches (from DDU to CRO, rkm 22.7 to

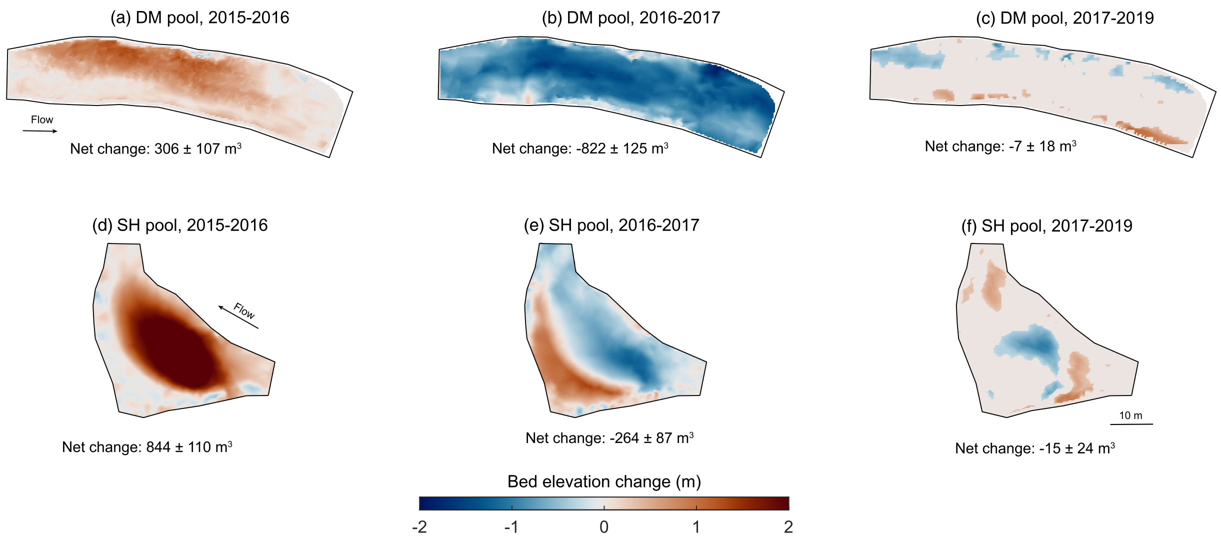

FIGURE 6 Digital elevation models (DEMs) of difference showing erosion and sediment deposition in two pools, one in the DM reach (A–C) and one in the SH reach (D–F) over the intervals from 2015 to 2016 (encompassing the dam removal), 2016 to 2017 (including the highest flows of the study interval), and 2017 to 2019 (spanning two additional ∼5-year flood peaks). See Figure 2 for reach locations. Between 2015 and 2016 both pools filled substantially, presumably receiving sediment from San Clemente Reservoir in the first winter after dam removal (A, D; Harrison et al., 2018). The 2017 winter floods caused net scour from both pools (B, E), although they also deposited a new gravel bar within the SH pool and sandbars at the downstream end (E). Little change was measured between 2017 and 2019, with net volume differences being within our survey uncertainty (C, F).

2.08) did experience increases in these parameters during 2020 and (less so) in 2021, after monitoring of the uppermost four reaches was discontinued (Figures 7B and C), indicating some geomorphic response to sediment supply in the lower river 5–6 years after dam removal. Repeating this flow-normalization exercise, applying flow data from the lower Carmel River stream gauge (USGS gauging station 11143250; Figure 2) to the lowest four study reaches, results in a pattern similar to Figures 7B and C (not shown).

Sediment thickness changes between survey intervals (Δz) showed peak positive values in the largely unconfined reaches (DDU to CRO, below rkm 22.7), whereas the largest net loss (negative Δz) was found in the reservoir reach, especially over the 2016–2017 and 2017–2019 intervals (Figure 8). The DM reach immediately below the dam site, in a confined canyon, showed no substantial reach-wide net sediment accumulation at any time during our study, and underwent minor net erosion between 2017 and 2019 (Figure 8). Accumulation of up to 0.4 m of sediment was observed in the BW reach (rkm 13) and maintained from 2018 through the final measurements there in 2020. The lowermost reach, CRO, initially accumulated sediment (2015 to 2016) but showed net loss in each year from 2017 to 2020.

Bed-sediment grain size became finer in most reaches downstream from the dam site after the dam removal. Most impacted reaches had a higher proportion of sand in 2017–2021 than before or shortly after dam removal (2013, 2015, and 2016; Figure 9). From 2017 to 2021, all reaches including and downstream of rkm 23 (reaches DDU and below) were dominated by grain sizes 12 mm and finer (pebble, granule, and sand clasts; Figure 9). Peak sand fractions occurred in the DDL reach (∼rkm 22) in 2017, then migrated downstream in 2019 and 2020, similar to the changes in sediment thickness (Figures 8 and 9). By 2021, the sand fractions began to resemble pre-dam-removal values, though they were still greater in the DDL reach. Mean grain size in the dam (DM) and Sleepy Hollow (SH) reaches, the two impacted reaches with the most confined river-corridor morphology (Table S1), remained in the pebble range throughout the measured dam-removal response (Figure 9).

5 | DISCUSSION

The data presented here provide a rare opportunity to examine river response to a large-scale sediment disturbance using a before–after/control–impact analysis. The Carmel River is one of only two watersheds where large dam removals have been accompanied by long-term BACI studies (the other being the Elwha River, Washington). We can use the extended time series of topographic and grain-size data to investigate sedimentary and geomorphic responses to increased sediment supply as well as variable hydrology, and can compare these against fluvial responses to other dam removals.

Our data show that the reservoir reach (RS) underwent very different rates and styles of evolution than did the reaches downstream of San Clemente Dam site (Figures 5B and 7), as different geomorphic processes governed change in the reservoir deposit: incision and widening after base-level fall as the dam was removed, in contrast to new sediment deposition dominating the downstream response. The geomorphic response of the reservoir reach also began earlier than in the downstream reaches, because by summer 2015 a knickpoint was already migrating through the upper reservoir sediment due to construction work having begun on the reroute channel, and thus the base-level drop was already affecting reservoir material to a small degree (Harrison et al., 2018). Geomorphic patterns of the San Clemente Reservoir erosion thus resembled those of reservoir erosion after other dam removals (Randle et al., 2015; Tullos et al., 2016; Wildman & MacBroom, 2005).

The largest geomorphic changes in the Carmel River corridor occurred during the winters with high flows (2017 and 2019), not during the winter of 2015–16 that immediately followed the dam

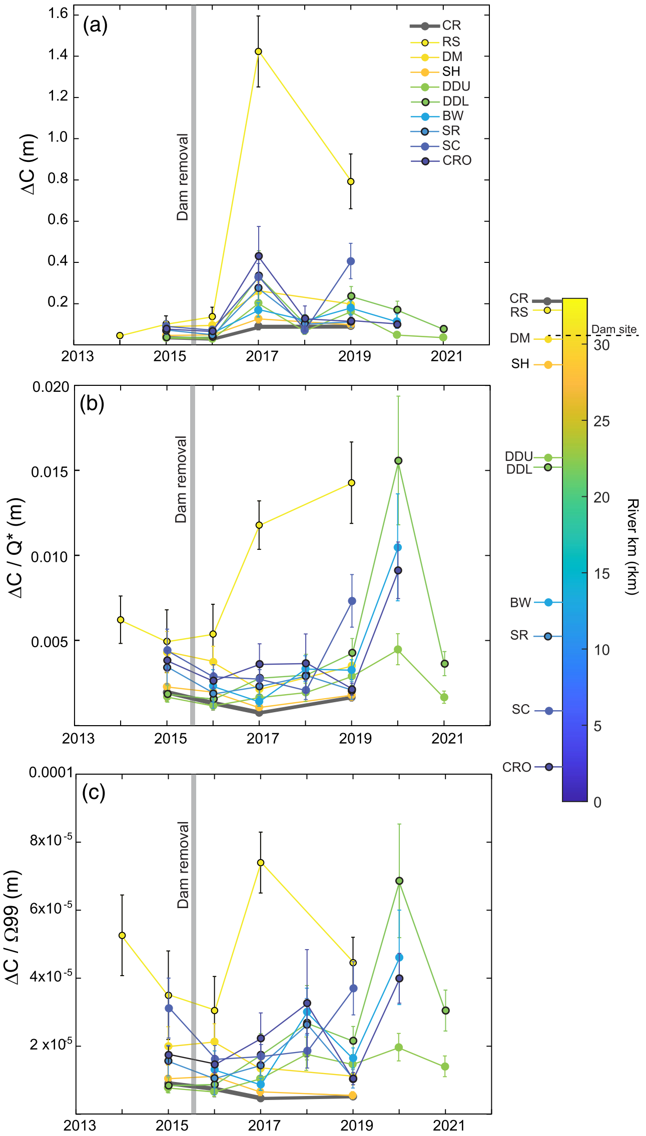

FIGURE 7 Reach-averaged bed-elevation change between each set of topographic surveys (Δ*C*) in each of the 10 study reaches, as measured directly (A) and then normalized by two metrics of flow history (B, C). Values are plotted to represent change between consecutive surveys (i.e. the data plotted for 2017 represent the difference between 2016 and 2017). (A) Mean Δ*C* values, with error bars representing standard error of the mean. (B) Bed-elevation change between topographic surveys (Δ*C* values) normalized by *Q**, the ratio of maximum flow in each inter-survey interval to the mean annual Carmel River flow. (C) Δ*C* normalized by Ω_{99}, the cumulative stream power for the 99th percentile of discharge in each inter-survey interval. Reach locations are shown in Figure 2.

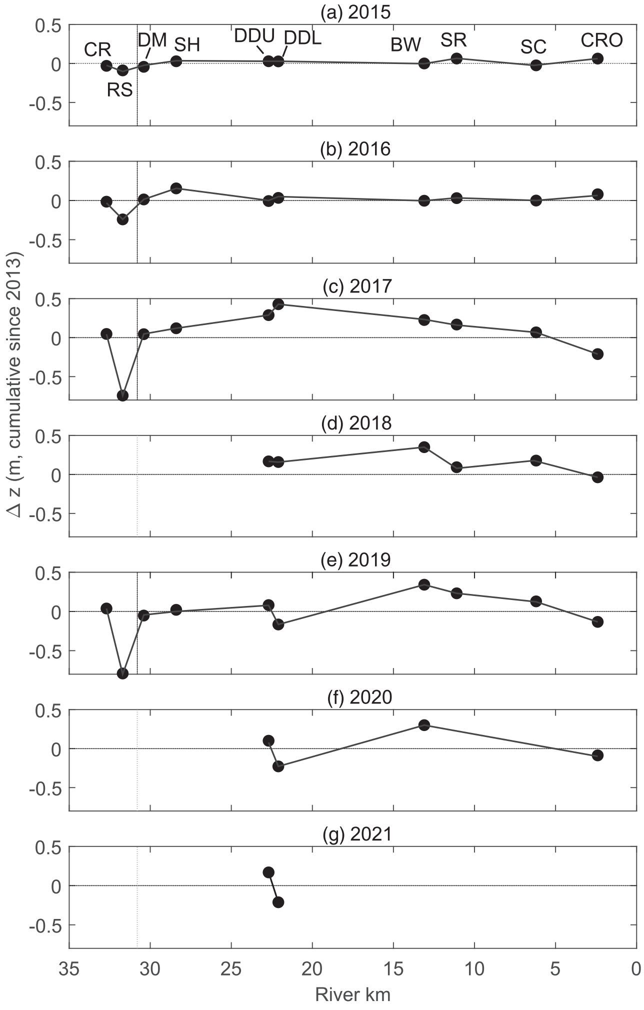

FIGURE 8 Cumulative changes in inferred sediment thickness over time (2013 to 2021) shown by Δ*z* (Harrison et al., 2018; Zunka et al., 2015). Individual data points represent reach-averaged values. Vertical dashed line represents the location of San Clemente Dam site; horizontal dashed line indicates no net change in sediment thickness.

removal but lacked floods. Downstream of the dam site, the immediate aftermath of dam removal (winter 2016) included only the filling of deep pools in the DM and SH reaches (Figure 6) but no reach-wide aggradation (Figures 7 and 8). This response differs somewhat from the two-phase model proposed by Pearson et al. (2011) and Collins et al. (2017) in that the Carmel River did not have a strong initial response to dam removal: although bed sediment fined slightly (Figure 9) in the first four reaches downstream from the dam site (DM, SH, DDU, DDL, spanning rkm 22 to 30.4), bed-elevation changes were negligible at most transects in winter 2015–16 (Figure 7A). Instead, substantial bed-elevation changes began only with the high flows of the second post-dam-removal winter, in 2017, and the largest changes were associated with the high-flow winters of 2017 and 2019 (Figure 7A). Bed-sediment fining all the way to the lowest reaches was observed in 2017 (and was sustained through 2021; Figure 9), indicating that reservoir sediment was transported more than 30 km downstream beginning with the 2017 floods. Peak sediment thicknesses following the 2017 floods moved from the SH reach down to the DDU, DDL, and lower reaches (Figure 8), with the trailing edge of the sediment pulse evidenced by erosion in the DM reach in 2019. Peak sediment thickness was found in the BW reach in 2019, tapering downstream to the SC reach (Figure 8), and the 2020 and 2021 surveys showed continuing scour and partial fill in the DDU, DDL, and lower reaches (Figures 5E and F, 8). New sediment deposition was observed mostly in isolated, disconnected patches or as interstitial material between pre-existing cobbles. The new, post-dam-removal sediment did not aggrade over riffles, and so did not change the hydraulic control in any study reaches downstream of the dam site. Dam-removal sediment also caused no significant change in the estuary and coastal zone around the river mouth; a study of nearshore morphodynamic change that overlapped the time frame of this

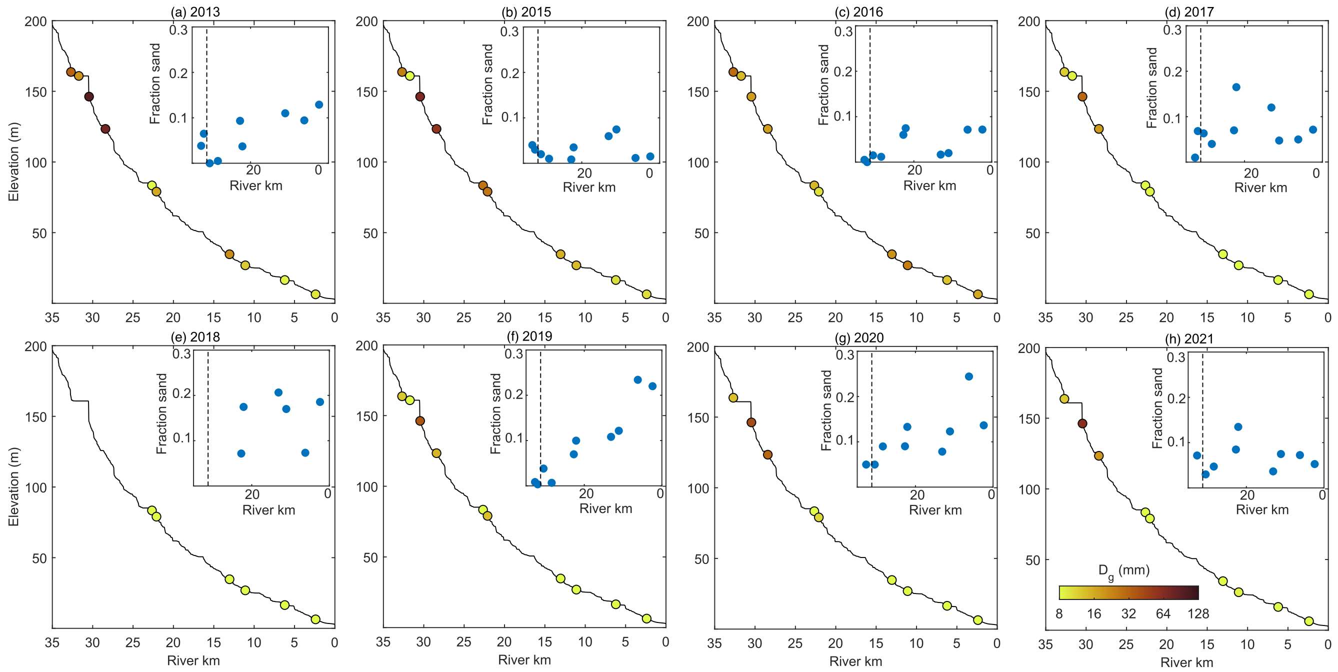

FIGURE 9 Changes in grain sizes (D_g, geometric mean particle size derived from pebble-count data) through time, plotted along a longitudinal profile of the Carmel River (black line in each plot). Individual data points are reach-averaged values for a given year, and colour scheme indicates geometric mean grain size. Inset plots on each panel show the fraction of sand in each study reach.

study made no mention of dam-removal effects (Orescanin & Scooler, 2018).

Having normalized the reach-averaged bed-elevation changes to remove the influence of high flows (Figures 7B and C), we find that sediment supply-driven geomorphic responses downstream of the dam site were minor to negligible. After removing flow-driven change, aside from continuing reservoir erosion the only remaining evident responses were small and localized in the downstream-most reaches over the last 2–3 years of the study, 2019–2021. The larger magnitude of change in the DDU, DDL, BW, and CRO reaches between 2019 and 2021, and in the SC reach in 2019 (in the $\Delta C/Q^*$ and $\Delta C/\Omega_{99}$ plots, Figures 7B and C) does suggest some sensitivity to sediment supply [i.e. sand moving through (Figure 8), which was represented in <0.5 m bed-elevation changes]. Although these were small-magnitude responses, they are consistent with other dam-removal studies showing that sediment pulses cause geomorphic change even without floods, as the riverbed responds to greater availability of mobile fine sediment (Cashman et al., 2021; East et al., 2015, 2018). Sand and fine gravel presumably derived from the San Clemente Reservoir deposit were still moving through the lowest 23 rkm of the Carmel River as of at least 2020, almost 5 years after dam removal (no other substantial sediment sources appear to have been accessed below the dam site that could explain the observed changes in sediment thickness and grain size). But overall, the geomorphic response of the river was driven more strongly by high-flow events than by increased sediment supply (i.e. the largest geomorphic changes happened during years with high flows, Figure 7A), and in contrast to observations on the Elwha River (discussed below), after removing effects of high flow there was relatively little change in any study reach below San Clemente Dam (Figures 7B and C).

The response of the Carmel River to dam removal was much more muted than on the Elwha River, the only other large dam-removal situation with long-term monitoring data for direct comparison (East et al., 2018). The Carmel riverbed did not aggrade enough to transition from pool–riffle–run morphology to a smooth, plane-bedded morphology with loss of topographic complexity, as occurred on the Elwha River and in other field and laboratory dam removals (Curran & Coveleski, 2021; East et al., 2018; Zunka et al., 2015). The Elwha River underwent a brief but dramatic shift from sediment supply-limited to transport-limited conditions accompanied by metres of aggradation during the peak of its dam-removal sediment pulse, becoming a plane-bedded, sand and gravel system over one winter season despite a lack of high flows (Draut & Ritchie, 2015; East et al., 2018; see Figure S2). In contrast, no such change occurred on the Carmel: throughout both the low- and high-flow years, the Carmel River remained hydraulically controlled by riffles that pre-dated the dam removal. On the Elwha River, the $\Delta C/Q^*$ values for three reaches below the Elwha Dam site increased by a factor of 8–17 as the main sediment pulse moved through (Figure S2), whereas on the Carmel River $\Delta C/Q^*$ increased by only a factor of 3–6 (Figure 7B). For the Elwha reach closest to Elwha Dam site (reach 1 of East et al., 2018), $\Delta C/\Omega_{99}$ increased by a factor of 100 during the peak of the sediment pulse, whereas no such increase in $\Delta C/\Omega_{99}$ occurred anywhere on the Carmel River (Figure 7).

The reasons for different disturbance response on the Carmel River in comparison to the Elwha River include: (1) a much smaller sediment volume released down the Carmel River as most of the reservoir sediment was deliberately sequestered, such that the rerouted channel design resulted in only 6 m of base-level fall rather than the full 23 m that would have resulted from natural river erosion throughout the reservoir; (2) the remaining presence of Los Padres Dam preventing reconnection of all the river's natural upstream sediment supply; (3) the Carmel River channel being confined in the reach immediately below the dam, limiting lateral erosion and accretion potential and presumably facilitating greater shear stress that kept fine sediment moving through the DM and SH reaches; and (4) vegetation stabilizing banks and some in-channel deposits in the lower Carmel River.

Regarding the Carmel River's smaller sediment-pulse size, on the Elwha River 20 Mt of sediment moved downstream from the reservoir deposits over 5 years after dam removal (Ritchie et al., 2018). Scaled basin-wide, this represented decades' worth of annual sediment output and was equivalent to sediment yield of 24 000 t/km^2 from that 833 km^2 watershed. Harrison et al. (2018) estimated that as of summer 2017, the Carmel River sediment pulse had comprised 49 000 ± 21 000 t. From our 2019 survey of the reservoir deposit, it was evident that lateral erosion of 20–25 m and 3–4 m of incision occurred along a 400 m-long portion of the reservoir deposit after 2017; aerial imagery in Google Earth suggests that no substantial additional reservoir erosion has occurred since 2019. Thus we infer that the post-2017 reservoir erosion released an additional 24 000 to 40 000 m^3 of sediment downstream; assuming a density of 1500 kg/m^3, this would equate to 36 000–60 000 metric tons (i.e. 48 000 ± 12 000 t). Adding that to the 2015–2017 sediment export quantified by Harrison et al. and summing the respective uncertainty ranges in quadrature (taking the square root of the sum of their squares), the total Carmel River dam-removal sediment pulse, released over ~3.5 years, can be estimated as 97 000 ± 24 000 t (similar to that of smaller dam removals, e.g. Collins et al., 2017). For this 650 km^2 watershed, that is equivalent to sediment yield of around 149 t/km^2 or, if considering only the portion of the watershed where sediment is not impounded behind Los Padres Dam (540 km^2), the sediment yield for the dam removal becomes 180 t/km^2. That value is more than two orders of magnitude lower than the sediment yield involved in the Elwha River dam removals (24 000 t/km^2), consistent with the more muted downstream geomorphic response on the Carmel River. Turbidity was also much higher during the Elwha River dam removals (1000–10 000 mg/l sustained for about a year; Magirl et al., 2015) compared to the Carmel River (rarely exceeding 1000 mg/l; Harrison et al., 2018).

Contextualizing the sediment release from San Clemente Reservoir relative to annual watershed sediment load further clarifies why little downstream impact resulted. Notably, the inferred dam-removal sediment yield for the Carmel River, 180 t/km^2, equates to 0.067 mm of bedrock denudation, slightly lower than the annual long-term denudation rate of 0.091 mm/year (sediment yield 241 t/km^2 per year) obtained from ^{10}Be analyses of the Carmel River by Young & Hilley (2018). The ratio of reservoir-sediment erosion resulting from dam removal to background sediment output (the E^* parameter of Grant & Lewis, 2015 and Major et al., 2017) is therefore 0.75, lower than for other large dam removals such as those on the Elwha River or Condit Dam, Washington, despite the total reservoir sediment volume (1.7 million m^3) having been essentially the same as that for Condit Dam (Figure 10). This scaling exercise for the Carmel River sediment pulse (see Figure 10) shows that this dam removal did not cause an anomalously large sediment-export event for this basin, and explains why flow, rather than sediment supply, evidently drove most of the geomorphic change over our 8-year study, in stark contrast to the sediment supply-dominated Elwha River response.

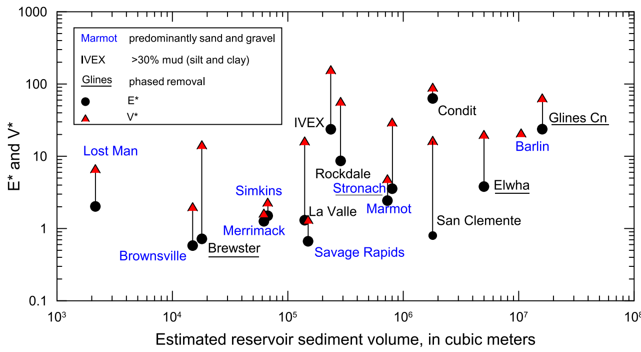

FIGURE 10 Reservoir sediment erosion after San Clemente Dam removal in the context of other dam removals for which sufficient data are available (figure modified from Major et al., 2017). Red triangles indicate total volume of stored reservoir sediment relative to background watershed sediment flux (V^* parameter of Major et al., 2017). Black dots show volumes of sediment eroded after dam removal relative to background sediment flux (E^* parameter of Major et al., 2017, adapted from Grant & Lewis, 2015). Data for San Clemente Dam removal are from this study; data for other dam removals are from Major et al. (2017).

However, the relative scale of sediment release (Figure 10) also points to the potential consequences of engineering design failure—considering that San Clemente Dam impounded the same sediment volume as Condit Dam, if the attempt to sequester two-thirds of the San Clemente Reservoir sediment had been unsuccessful, due to some combination of design flaw and extreme weather, the Carmel River might have experienced a geomorphic response comparable to the substantial change that followed Condit Dam removal (Wilcox et al., 2014). Natural river erosion after San Clemente Dam removal almost certainly would have produced a larger response than that of Marmot Dam removal, which impounded less sediment both overall and relative to the annual background load (Figure 10; cf. Major et al., 2012).

Differences between the geomorphic responses of the Carmel and Elwha rivers may also be related to river-corridor vegetation, as mentioned above. The Elwha River has wide expanses of unvegetated sediment in the river corridor below its former dam sites (and did before the dam removal, too), whereas exposed unvegetated sediment is rarer on the Carmel River downstream of rkm ~ 15, likely owing to differences in hydroclimate and human water use in the lower watershed. The SR, SC, and CRO reaches are all heavily vegetated, presumably helping to stabilize banks and in-channel sediment deposits. Therefore, the Carmel River evolved as expected for a largely vegetated, gravel-dominated river (e.g. Al-Ghorani et al., 2022) experiencing a relatively small sediment pulse.

The modest changes on the Carmel River after removal of a 32 m-high dam likely provide a representative example of what many future dam-removal situations could look like: a relatively minor reservoir-sediment pulse, with an upstream dam remaining in place. The method of sediment sequestration on the Carmel River may have been unique, by routing the river into a fortuitous parallel tributary immediately upstream of the dam site (Harrison et al., 2018), but deliberate reservoir-sediment stabilization in other future dam removals could be achieved by other engineering approaches, vegetation planting, or a combination of those. Another example of a large dam removal in which reservoir sediment erosion was deliberately limited is that of Cucharas #5 Dam, removed in Colorado in 2018 (third-largest dam removed in the United States; Figure 1): the dam was breached but part of its edifice was left in place, buttressed and stabilized, as a 'check dam' to limit the rate and amount of sediment release (Perry et al., 2020). A similar sediment-management approach is planned for the removal of 20 m-high Searsville Dam, California. Most dam removals are of small dams that do not impound much sediment (Bellmore et al., 2016), and, unlike the Elwha River case, a single dam removal is more common than a total watershed restoration involving multiple dam removals (e.g. Tang et al., 2021). Thus, many dam removals and even some large ones can be expected to produce little geomorphic change and short-term, non-remarkable sediment export (cf. Ralston et al., 2021). The Carmel River evolved similarly to the example of the Pierre Glissotte Dam (7.3 m high) removed from the Yvonne River in France, where despite 'intense morpho-sedimentary dynamics in the reservoir and effective restoration of bedload continuity', fluvial morphology below the former dam site remained largely unchanged (Gilet et al., 2021). In two other examples of similar response style, Amethyst Brook, Massachusetts remained sediment supply-limited during its 1–2-year geomorphic adjustment to removal of a 6 m dam (Magilligan et al., 2021), and geomorphic changes on the Penobscot River, Maine, in response to removal of two dams (6 and 10 m high), were small enough to be within measurement uncertainty (Collins et al., 2020). The changes we have documented in the Carmel River were larger than our uncertainty range but provide a worthwhile lesson that removal of even large dams does not necessarily produce major change downstream. We report on these modest effects to inform future large dam removals where the downstream sediment release is deliberately limited. The deliberate sequestration and stabilization of the San Clemente Reservoir sediment in the case of the Carmel River is also representative of how many other dam removals are conducted, unlike the case of the Elwha River, where reservoir sediment was eroded naturally by the river. In other dam removals, downstream impacts must be minimized to reduce risks due to bed aggradation (as was the case for the lower Carmel River, where the floodplain is inhabited) or dispersal of contaminants, and so reservoir deposits can be stabilized intentionally with vegetation or engineering measures (e.g. Ravot et al., 2020) or removed mechanically (e.g. at Milltown Dam, Montana, before its removal in 2008; Evans & Wilcox, 2014). Because most dammed watersheds have multiple dams (Foley, Magilligan, et al., 2017; Grill et al., 2019; Zarfl et al., 2015), and removing all dams from a watershed typically requires much more funding, political support, and economic or safety justification than removing just one dam, we consider it likely that many future dam removals will, as on the Carmel River, leave additional dams upstream that continue to limit natural sediment supply to the lowermost river (one example is the planned removal of the lowermost four large dams on the Klamath River, California and Oregon).

Dam removals commonly occur with the intent to improve aquatic habitat by restoring longitudinal connectivity along the river, often successfully (Bellmore et al., 2019; Duda et al., 2021; Foley, Bellmore, et al., 2017; Magilligan et al., 2021; Pess et al., 2014). The San Clemente Dam removal was expected to enhance habitat quality and availability for steelhead (*Oncorhynchus mykiss*, a salmonid fish), which are listed as threatened under the U.S. Endangered Species Act, and other biota. Although data on steelhead response to dam removal on the Carmel River are not yet published, Pacific lamprey (*Entosphenus tridentatus*) have successfully recolonized the Carmel River after dam removal and are spawning there (Reid & Goodman, 2020), indicating some ecosystem benefit. Our grain-size analyses (Figure 9) show that by 2021, 6 years after dam removal, all reaches had average bed-material size within the 5–75 mm range necessary for salmonid spawning (Kondolf & Wolman, 1993) and with less than 10% sand, consistent with appropriate salmonid spawning habitat. The introduction of large wood to the river during floods in 2017 and 2019 by new avulsion and bank erosion in the former reservoir also created new log jams downstream of the dam site, which we qualitatively assess as a likely additional ecosystem advantage (cf. Grabowski & Wohl, 2021).

The lower reaches of the Carmel River may undergo additional geomorphic change in future years as high flows continue to move the coarser grain sizes of the released sediment downstream. Sediment pulses are strongly grain size-dependent (Piantini et al., 2021) and those with heterogenous grain size tend to have longer-lasting impacts downstream because finer sizes translate quickly and pass through the fluvial system, whereas coarser sizes travel more slowly and coarse deposits show more dispersive behaviour (Ahammad et al., 2021). Some coarse gravel–pebble deposits that formed after the San Clemente Dam removal (e.g. in the SH pool and SC and SR reaches) could mobilize downstream during future floods, mostly by dispersion. The Carmel River sediment pulse was too small to create enough bed aggradation or supercritical flow conditions that could support more refined interpretations of sediment-pulse evolution (cf. An et al., 2017; Cashman et al., 2021; Castro-Bolinaga et al., 2020; East et al., 2015).

Lessons from the Carmel River help to define the expected time scale of landscape recovery after a large dam removal, albeit with a relatively small sediment release (∼100 000 t): after 6 years and 11 flow peaks exceeding the 2-year flood, the most substantial remaining evidence of the dam removal along the 30 rkm downstream was finer bed-sediment grain size and some pools that had been partially filled and partially rescoured. No major geomorphic 'reset' of the downstream river corridor had occurred, even with large flood flows. These findings can inform future efforts to restore rivers by removing dams, given the growing international interest in this approach (Birnie-Gauvin et al., 2020; Habel et al., 2020; Ibisate et al., 2016; Maxwell et al., 2021; Ravot et al., 2020; Wang & Kuo, 2016). Environmental planning of rivers, not only through dam removal but also dam renovation and revised operations, will remain a major application of fluvial geomorphology in an era of changing hydroclimate and the need for non-fossil-fuel energy (Chartrand, 2022; Curry et al., 2020; Guetz et al., 2022; Kondolf & Yi, 2022; Zarfl et al., 2015), as will proactively removing dams that are safety hazards (Vahedifard et al., 2020). We encourage additional research into the effects of these actions on river channels, even when geomorphic responses are not dramatic, to expand the literature base on which environmental management decisions are made. The largest disturbance response evident on the Carmel River during this 8-year study was that of major storms and floods, an informative finding given the expected increase in extreme rain in a warmer future in this region (Huang & Swain, 2022; Swain et al., 2018). Under future hydroclimate it is likely that extreme rain, wildfire, and post-fire erosion will increasingly dominate the disturbance response of western US rivers (East & Sankey, 2020), superposed on and at least locally exceeding anthropogenic disturbances.

6 | CONCLUSIONS

In summary, the Carmel River, California, provides rarely available information on the time scale and styles of fluvial response to large dam removal and thus on landscape response to the superposed disturbances of a dam-removal sediment pulse and 11 flow events exceeding the 2-year flood. We find that the reservoir-sediment pulse following the 2015 removal of 32 m-high San Clemente Dam was relatively small, estimated to be 97 000 ± 24 000 t, as a result of deliberate reservoir-sediment stabilization and the presence of a larger dam remaining upstream. Scaled to the size of the basin and compared against long-term denudation rates, the released sediment amount was slightly less than the annualized long-term sediment export from the Carmel River watershed. New sediment supply transited >30 km to the river mouth in less than 2 years, assisted by large floods in 2017 and additional floods in 2019. Dam removal mobilized enough sediment to fine the downstream riverbed while causing mostly low-magnitude bed-elevation changes (aside from the filling of pools, some of which were partially scoured later) but no major 'reset' of river morphology downstream from the dam site. Geomorphic changes were driven almost entirely by flow rather than by the modest increase in sediment supply from dam removal, due to the intentional engineering efforts to limit downstream sediment deposition. The relatively minor disturbance caused by dam removal on the Carmel River is probably representative of what many future dam-removal situations could look like: a relatively small sediment pulse owing to deliberate limitation of reservoir-sediment release, and with an upstream dam remaining in place. Therefore, these findings can inform the growing international efforts to restore rivers by demonstrating that large dam removal need not lead to major downstream impacts.

ACKNOWLEDGEMENTS

This study was supported by the U.S. Geological Survey, National Oceanic and Atmospheric Administration, and California State University Monterey Bay. The authors gratefully acknowledge discussions with S.M. Chartrand and J.A. Warrick that contributed to understanding of the Carmel River watershed sedimentary processes. Field assistance was provided by C. Nicol, K. Chow, and numerous additional students from California State University, Monterey Bay. We thank M.J. Collins, A.C. Wilcox, one anonymous reviewer, and the editors for constructive review comments that improved the manuscript. Any use of trade, firm, or product names is for descriptive purposes only and does not constitute endorsement by the U.S. Government.

DATA AVAILABILITY STATEMENT

All data presented in this paper are available at https://doi.org/10.5066/P9HG8UDS.

ORCID

Amy E. East https://orcid.org/0000-0002-9567-9460
Lee R. Harrison https://orcid.org/0000-0002-5219-9280
Douglas P. Smith https://orcid.org/0000-0002-4773-6766
Joshua B. Logan https://orcid.org/0000-0002-6191-4119
Rosealea M. Bond https://orcid.org/0000-0003-0939-2007

REFERENCES

Ahammad, M., Czuba, J.A., Pfeiffer, A.M., Murphy, B.P. & Belmont, P. (2021) Simulated dynamics of mixed versus uniform grain size sediment pulses in a gravel-bedded river. *Journal of Geophysical Research - Earth Surface*, 126(10), e2021JF006194. Available from: https://doi.org/10.1029/2021JF006194

Al-Ghorani, N.G., Hassan, M.A. & Langendoen, E.J. (2022) Reach-scale morphodynamics: Insights from 20 years of observations and model simulations. *Geomorphology*, 413, 108375. Available from: https://doi.org/10.1016/j.geomorph.2022.108375

American Rivers. 2021. *American Rivers dam removal database*. https://figshare.com/articles/_/5234068 (last accessed 26 July 2022).

An, C., Cui, Y., Fu, X. & Parker, G. (2017) Gravel-bed river evolution in earthquake-prone regions subject to cycled hydrographs and repeated sediment pulses. *Earth Surface Processes and Landforms*, 42(14), 2426–2438. Available from: https://doi.org/10.1002/esp.4195

Barbarossa, V., Schmitt, R.J.P., Huijbregts, M.A.J., Zarfl, C., King, H. & Schipper, A.M. (2020) Impacts of current and future large dams on the geographic range connectivity of freshwater fish worldwide. *Proceedings of the National Academy of Sciences*, 117(7), 3648–3655. Available from: https://doi.org/10.1073/pnas.1912776117

Baynes, E.R.C., van de Lageweg, W.I., McLelland, S.J., Parsons, D.R., Aberle, J., Dijkstra, J., et al. (2018) Beyond equilibrium: Re-evaluating physical modeling of fluvial systems to represent climate changes. *Earth-Science Reviews*, 181, 82–97. Available from: https://doi.org/10.1016/j.earscirev.2018.04.007

Bellmore, J.R., Duda, J.J., Craig, L.S., Greene, S.L., Torgersen, C.E., Collins, M.J., et al. (2016) Status and trends of dam removal research in the United States. *WIREs Water*, 4(2), e1164. Available from: https://doi.org/10.1002/wat2.1164

Bellmore, J.R., Pess, G.R., Duda, J.J., O'Connor, J.E., East, A.E., Foley, M.M., et al. (2019) Conceptualizing ecological responses to dam removal: If you remove it, what's to come? *Bioscience*, 69(1), 26–39. Available from: https://doi.org/10.1093/biosci/biy152

Birnie-Gauvin, K., Nielsen, J., Frandsen, S.B., Olsen, H.M. & Aarestrup, K. (2020) Catchment-scale effects of river fragmentation: A case study on restoring connectivity. *Journal of Environmental Management*, 264, 110408. Available from: https://doi.org/10.1016/j.jenvman.2020.110408

Bountry, J.A., Lai, Y.G. & Randle, T.J. (2013) Sediment impacts from the Savage Rapids Dam removal, Rogue River, Oregon. In: De Graff, J. V. & Evans, J.E. (Eds.) *The Challenges of Dam Removal and River Restoration*. Boulder, CO: Geological Society of America, pp. 93–104 https://doi.org/10.1130/2013.4121(08)

Bushaw-Newton, K.L., Hart, D.D., Pizzuto, J.E., Thomson, J.R., Egan, J., Ashley, J.T., et al. (2002) An integrative approach towards understanding ecological responses to dam removal: The Manatawny Creek study. *Journal of the American Water Resources Association*, 38(6), 1581–1599. Available from: https://doi.org/10.1111/j.1752-1688.2002.tb04366.x

Cashman, M.J., Gellis, A.C., Boyd, E., Collins, M.J., Anderson, S.W., McFarland, B.D., et al. (2021) Channel response to a dam-removal sediment pulse captured at high temporal resolution using routine gage data. *Earth Surface Processes and Landforms*, 46(6), 1145–1159. Available from: https://doi.org/10.1002/ESP.5083

Castro-Bolinaga, C.F., Diplas, P. & Bodnar, R.J. (2020) Modeling hydro-morphodynamic processes during the propagation of fluvial sediment pulses: A physics-based framework. *Journal of Geophysical Research - Earth Surface*, 125(12), e2020JF005722. Available from: https://doi.org/10.1029/2020JF005722

Chartrand, S.M. (2022) Environmental planning of river corridors considering climate change: A brief perspective. In: Chembolu, V. & Dutta, S. (Eds.) *Recent Trends in River Corridor Management*, Lecture Notes in

Civil Engineering, Vol. 229. Cham: Springer Nature, pp. 27–38 https://doi.org/10.1007/978-981-16-9933-7_2

Collins, M.J., Kelley, A.R. & Lombard, P.J. (2020) River channel response to dam removals on the lower Penobscot River, Maine, United States. *River Research and Applications*, 36(9), 1778–1789. Available from: https://doi.org/10.1002/rra.3700

Collins, M.J., Snyder, N.P., Boardman, G., Banks, W.S.L., Andrews, M., Baker, M.E., et al. (2017) Channel response to sediment release: Insights from a paired analysis of dam removal. *Earth Surface Processes and Landforms*, 42(11), 1636–1651. Available from: https://doi.org/10.1002/esp.4108

Costa, J.E. & O'Connor, J.E. (1995) Geomorphically effective floods. In: Costa, J.E., Miller, A.J., Potter, K.W. & Wilcock, P.R. (Eds.) *Natural and Anthropogenic Influences in Fluvial Geomorphology*, AGU Geophysical Monographs, Vol. 89. Washington, DC: American Geophysical Union, pp. 45–56 https://doi.org/10.1029/GM089p0045

Curran, J.C. & Coveleski, K.C. (2021) How sediment composition and flow rate influence downstream channel morphodynamics upon dam removal. *Earth Surface Processes and Landforms*, 46(12), 2437–2447. Available from: https://doi.org/10.1002/esp.5187

Curry, R.A., Yamazaki, G., Linnansaari, T., Monk, W., Samways, K.M., Dolson, R., et al. (2020) Large dam renewals and removals—Part 1: Building a science framework to support a decision-making process. *River Research and Applications*, 36(8), 1460–1471. Available from: https://doi.org/10.1002/rra.3680

Dadson, S.J., Hovius, N., Chen, H., Dade, W.B., Lin, J.-C., Hsu, M.L., et al. (2004) Earthquake-triggered increase in sediment delivery from an active mountain belt. *Geology*, 32(8), 733–736. Available from: https://doi.org/10.1130/G20639.1

Dahal, S., Crosato, A., Omer, A.Y.A. & Lee, A.A. (2021) Validation of model-based optimization of reservoir sediment releases by dam removal. *Journal of Water Resources Planning and Management*, 147(7), 04021033. Available from: https://doi.org/10.1061/(ASCE)WR.1943-5452.0001388

Doyle, M.W., Stanley, E.H. & Harbor, J.M. (2003) Channel adjustments following two dam removals in Wisconsin. *Water Resources Research*, 39(1), 1011. Available from: https://doi.org/10.1029/2002wr001714

Doyle, M.W., Stanley, E.H., Havlick, D.G., Kaiser, M.J., Steinbach, G., Graf, W.L., et al. (2008) Aging infrastructure and ecosystem restoration. *Science*, 319(5861), 286–287. Available from: https://doi.org/10.1126/science.1149852

Draut, A.E. & Ritchie, A.C. (2015) Sedimentology of new fluvial deposits on the Elwha River, Washington, USA, formed during large-scale dam removal. *River Research and Applications*, 31(1), 42–61. Available from: https://doi.org/10.1002/rra.2724

Duda, J.J., Torgersen, C.E., Brenkman, S.J., Peters, R.J., Sutton, K.T., Connor, H.A., et al. (2021) Reconnecting the Elwha River: Spatial patterns of fish response to dam removal. *Frontiers in Ecology and Evolution*, 9, 765488. Available from: https://doi.org/10.3389/fevo.2021.765488

East, A.E., Harrison, L.R., Smith, D.P., Bond, R., Logan, J.B., Nicol, C., & Chow, K. (2022) River-channel topography, grain size, and turbidity records from the Carmel River, California, before, during, and after removal of San Clemente dam. U.S. Geological Survey data release. https://10.0.19.202/P9HG8UDS

East, A.E., Jenkins, K.J., Happe, P.J., Bountry, J.A., Beechie, T.J., Mastin, M.C., et al. (2017) Channel-planform evolution in four rivers of Olympic National Park, Washington, USA: The roles of physical drivers and trophic cascades. *Earth Surface Processes and Landforms*, 42(7), 1011–1032. Available from: https://doi.org/10.1002/esp.4048

East, A.E., Logan, J.B., Mastin, M.C., Ritchie, A.C., Bountry, J.A., Magirl, C.S., et al. (2018) Geomorphic evolution of a gravel-bed river under sediment-starved versus sediment-rich conditions: River response to the world's largest dam removal. *Journal of Geophysical Research - Earth Surface*, 123(12), 3338–3369. Available from: https://doi.org/10.1029/2018JF004703

East, A.E., Pess, G.R., Bountry, J.A., Magirl, C.S., Ritchie, A.C., Logan, J.B., et al. (2015) Large-scale dam removal on the Elwha River, Washington, USA: River channel and floodplain geomorphic change. *Geomorphology*, 228, 765–786. Available from: https://doi.org/10.1016/j.geomorph.2014.08.028

East, A.E. & Sankey, J.B. (2020) Geomorphic and sedimentary effects of modern climate change: Current and anticipated future conditions in the western United States. *Reviews of Geophysics*, 58(4), e2019RG000692. Available from: https://doi.org/10.1029/2019RG000692

Evans, E. & Wilcox, A.C. (2014) Fine sediment infiltration dynamics in a gravel-bed river following a sediment pulse. *River Research and Applications*, 30(3), 372–384. Available from: https://doi.org/10.1002/rra.2647

Fields, J., Renshaw, C., Magilligan, F., Dethier, E. & Rossi, R. (2021) A mechanistic understanding of channel evolution following dam removal. *Geomorphology*, 395, 107971. Available from: https://doi.org/10.1016/j.geomorph.2021.107971

Foley, M.M., Bellmore, J.R., O'Connor, J.E., Duda, J.J., East, A.E., Grant, G.E., et al. (2017) Dam removal: Listening in. *Water Resources Research*, 53(7), 5229–5246. Available from: https://doi.org/10.1002/2017WR020457

Foley, M.M., Magilligan, F.J., Torgersen, C.E., Major, J.J., Anderson, C.W., Connolly, P.J., et al. (2017) Landscape context and the biophysical response of rivers to dam removal in the United States. *PLoS ONE*, 12(7), 1–24.

Foley, M.M., Warrick, J.A., Ritchie, A., Stevens, A.W., Shafroth, P.B., Duda, J.J., et al. (2017) Coastal habitat and biological community response to dam removal on the Elwha River. *Ecological Monographs*, 87(4), 552–577. Available from: https://doi.org/10.1002/ecm.1268

Gilbert, G.K. (1917) Hydraulic-mining debris in the Sierra Nevada. U.S. Geological Survey Professional Paper.

Gervasi, A.A., Pasternack, G.B. & East, A.E. (2021) Flooding duration and volume more important than peak discharge in explaining 18 years of gravel–cobble river change. *Earth Surface Processes and Landforms*, 46, 3194–3212. Available from: https://doi.org/10.1002/esp.5230

Gilet, L., Gob, F., Virmoux, C., Gautier, E., Thommeret, N. & Jacob-Rousseau, N. (2021) Morpho-sedimentary dynamics associated to dam removal: The Pierre Glissotte dam (Central France). *Science of the Total Environment*, 784, 147079. Available from: https://doi.org/10.1016/j.scitotenv.2021.147079

Grabowski, J. & Wohl, E. (2021) Logjam attenuation of annual sediment waves in eolian-fluvial environments, North Park, Colorado, USA. *Geomorphology*, 375, 107494. Available from: https://doi.org/10.1016/j.geomorph.2020.107494

Gran, K.B. & Montgomery, D.R. (2005) Spatial and temporal patterns in fluvial recovery following volcanic eruptions: Channel response to basin-wide sediment loading at Mount Pinatubo, Philippines. *Geological Society of America Bulletin*, 117(1), 195–211. Available from: https://doi.org/10.1130/B25528.1

Grant, G.E. & Lewis, S.L. (2015) The remains of the dam: What have we learned from 15 years of US dam removals? In: Lollino, G., Arattano, M., Rinaldi, M., Giustolisi, O., Marechal, J.-C. & Grant, G.E. (Eds.) *Engineering Geology for Society and Territory*, Vol. 3. Cham: Springer, pp. 31–35 https://doi.org/10.1007/978-3-319-09054-2_7

Gray, A.B. (2018) The impact of persistent dynamics on suspended sediment load estimation. *Geomorphology*, 322, 132–147. Available from: https://doi.org/10.1016/j.geomorph.2018.09.001

Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., et al. (2019) Mapping the world's free-flowing rivers. *Nature*, 569(7755), 215–221. Available from: https://doi.org/10.1038/s41586-019-111-9

Guetz, K., Joyal, T., Dickson, B. & Perry, D. (2022) Prioritizing dams for removal to advance restoration and conservation efforts in the western United States. *Restoration Ecology*, 30(5), e13583. Available from: https://doi.org/10.1111/rec.13583

Habel, M., Mechkin, K., Podgorska, K., Saunes, M., Babinski, Z., Chalov, S., et al. (2020) Dam and reservoir removal projects: A mix of social–ecological trends and cost-cutting attitudes. *Scientific Reports*, 10(1), 19210. Available from: https://doi.org/10.1038/s41598-020-76158-3

Harrison, L.R., East, A.E., Smith, D.P., Logan, J.B., Bond, R.M., Nicol, C.L., et al. (2018) River response to large-dam removal in a Mediterranean hydroclimatic setting: Carmel River, California, USA. *Earth Surface Processes and Landforms*, 43(15), 3009–3021. Available from: https://doi.org/10.1002/esp.4464

Hatchett, B.J., Cao, Q., Dawson, P.B., Ellis, C.J., Hecht, C.W., Kawzenuk, B., et al. (2020) Observations of an extreme atmospheric river storm with a diverse sensor network. *Earth and Space Science*, 6(8), e2020EA001129. Available from: https://doi.org/10.1029/2020EA001129

Hess, J.E., Paradis, R.L., Moser, M.L., Weitkamp, L.A., Delomas, T.A. & Narum, S.R. (2021) Robust recolonization of Pacific lamprey following dam removals. *Transactions of the American Fisheries Society*, 150(1), 56–74. Available from: https://doi.org/10.1002/tafs.10273

Hooke, J.M. (2015) Variations in flood magnitude–effect relations and the implications for flood risk assessment and river management. *Geomorphology*, 251, 91–107. Available from: https://doi.org/10.1016/j.geomorph.2015.05.014

Huang, X. & Swain, D.L. (2022) Climate change is increasing the risk of a California megaflood. *Science Advances*, 8(32), eabq0995. Available from: https://doi.org/10.1126/sciadv.abq0995

Ibisate, A., Ollero, A., Ballarin, D., Horacio, J., Mora, D., Mesanza, A., et al. (2016) Geomorphic monitoring and response to two dam removals: Rivers Urumea and Leitzaran (Basque Country, Spain). *Earth Surface Processes and Landforms*, 41(15), 2239–2255. Available from: https://doi.org/10.1002/esp.4023

Keller, E.A., Valentine, D.W. & Gibbs, D.R. (1997) Hydrological response of small watersheds following the southern California Painted Cave Fire of June 1990. *Hydrological Processes*, 11, 401–414.

Kondolf, G.M. & Wolman, M.G. (1993) The sizes of salmonid spawning gravels. *Water Resources Research*, 29(7), 2275–2285. Available from: https://doi.org/10.1029/93WR00402

Kondolf, M. & Yi, J. (2022) Dam renovation to prolong reservoir life and mitigate dam impacts. *Water*, 14(9), 1464. Available from: https://doi.org/10.3390/w14091464

Lane, S.N., Bakker, M., Gabbud, C., Micheletti, N. & Saugy, J.N. (2017) Sediment export, transient landscape response and catchment-scale connectivity following rapid climate warming and Alpine glacier recession. *Geomorphology*, 277, 210–227. Available from: https://doi.org/10.1016/j.geomorph.2016.02.015

Madej, M.A. & Ozaki, V. (1996) Channel response to sediment wave propagation and movement, Redwood Creek, California, USA. *Earth Surface Processes and Landforms*, 21(10), 911–927. Available from: https://doi.org/10.1002/(SICI)1096-9837(199610)21:10<911::AID-ESP621>3.0.CO;2-1

Magilligan, F.J., Buraas, E.M. & Renshaw, C.E. (2015) The efficacy of stream power and flow duration on geomorphic responses to catastrophic flooding. *Geomorphology*, 228, 175–188. Available from: https://doi.org/10.1016/j.geomorph.2014.08.016

Magilligan, F.J., Nislow, K.H., Dietrich, J.T., Doyle, H. & Kynard, B. (2021) Transient versus sustained biophysical responses to dam removal. *Geomorphology*, 3989, 107836. Available from: https://doi.org/10.1016/j.geomorph.2021.107836

Magirl, C.S., Hilldale, R.C., Curran, C.A., Duda, J.J., Straub, T.D., Domanski, M., et al. (2015) Large-scale dam removal on the Elwha River, Washington, USA: Fluvial sediment load. *Geomorphology*, 246, 669–686. Available from: https://doi.org/10.1016/j.geomorph.2014.12.032

Major, J.J., East, A.E., O'Connor, J.E., Grant, G.E., Wilcox, A.C., Magirl, C.S., et al. (2017) Geomorphic responses to dam removal in the United States – a two-decade perspective. In: Tsutsumi, D. & Laronne, J.B. (Eds.) *Gravel-Bed Rivers*. Chichester: Wiley, pp. 355–383 https://doi.org/10.1002/9781118971437.ch13

Major, J.J., Mosbrucker, A.R. & Spicer, K.R. (2018) Sediment erosion and delivery from Toutle River basin after the 1980 eruption of Mount St. Helens: A 30-year perspective. In: Crisafulli, C.M. & Dale, V.H. (Eds.) *Ecological Responses at Mount St. Helens: Revisited 35 Years After the 1980 Eruption*. New York: Springer, pp. 19–44 https://doi.org/10.1007/978-1-4939-7451-1_2

Major, J.J., O'Connor, J.E., Podolak, C.J., Keith, M.K., Grant, G.E., Spicer, K. R., Pittman, S., Bragg, H.M., Wallick, J.R., Tanner, D.Q., Rhode, A., & Wilcock, P.R. (2012) Geomorphic response of the Sandy River, Oregon, to removal of Marmot Dam. U.S. Geological Survey Professional Paper 1792.

Masteller, C.C. & Finnegan, N.J. (2017) Interplay between grain protrusion and sediment entrainment in an experimental flume. *Journal of Geophysical Research - Earth Surface*, 122(1), 274–289. Available from: https://doi.org/10.1002/2016JF003943

Maxwell, C., Tyler, P., Brock, M., Davies, P., Graddon, D., Blundy, S., et al. (2021) Lagoon of Islands, Tasmania: Ecosystem response to dam wall removal. *Ecological Management and Restoration*, 22(1), 22–31. Available from: https://doi.org/10.1111/emr.12446

Meyer, D.F. & Martinson, H.A. (1989) Rates and processes of channel development and recovery following the 1980 eruption of Mount St. Helens, Washington. *Hydrological Sciences*, 34(2), 115–127. Available from: https://doi.org/10.1080/02626668909491318

Moody, J.A. (2017) Residence times and alluvial architecture of a sediment superslug in response to different flow regimes. *Geomorphology*, 294, 40–57. Available from: https://doi.org/10.1016/j.geomorph.2017.04.012

O'Connor, J.E., Duda, J.J. & Grant, G.E. (2015) 1000 dams down and counting. *Science*, 348(6234), 496–497. Available from: https://doi.org/10.1126/science.aaa9204

Orescanin, M.M. & Scooler, J. (2018) Observations of episodic breaching and closure at an ephemeral river. *Continental Shelf Research*, 166, 77–82. Available from: https://doi.org/10.1016/j.csr.2018.07.003

Papangelakis, E., MacVicar, B.J., Montakhab, A.F. & Ashmore, P. (2022) Flow strength and bedload sediment travel distance in gravel bed rivers. *Water Resources Research*, 58(7), e2022WR032296. Available from: https://doi.org/10.1029/2022WR032296

Pearson, A.J., Snyder, N.P. & Collins, M. (2011) Rates and processes of channel response to dam removal with a sand-filled impoundment. *Water Resources Research*, 47(8), W08504. Available from: https://doi.org/10.1029/2010WR009733

Perry, M., McCormick, B., Cuthbertson, S., Bennington, P., & Lopez, P. (2020) The Cucharas #5 Dam removal: A story of determination, persistence, and partners. In Proceedings of the Association of State Dam Safety Officials Annual Conference on Dam Safety, vol 1, pp. 174–194.

Pess, G.R., Quinn, T.P., Gephard, S.R. & Saunders, R. (2014) Re-colonization of Atlantic and Pacific rivers by anadromous fishes: Linkages between life history and the benefits of barrier removal. *Reviews in Fish Biology and Fisheries*, 24(3), 881–900. Available from: https://doi.org/10.1007/s11160-013-9339-1

Piantini, M., Gimbert, F., Bellot, H. & Recking, A. (2021) Triggering and propagation of exogenous sediment pulses in mountain channels: Insights from flume experiments with seismic monitoring. *Earth Surface Dynamics*, 9(6), 1423–1439. Available from: https://doi.org/10.5194/esurf-9-1423-2021

Ralston, D.K., Yellen, B. & Woodruff, J.D. (2021) Watershed suspended sediment supply and potential impacts of dam removal for an estuary. *Estuaries and Coasts*, 44, 1195–1215. Available from: https://doi.org/10.1007/s12237-020-00873-3

Randle, T.J., Bounty, J.A., Ritchie, A. & Wille, K. (2015) Large-scale dam removal on the Elwha River, Washington, USA: Erosion of reservoir sediment. *Geomorphology*, 246, 709–728. Available from: https://doi.org/10.1016/j.geomorph.2014.12.045

Ravot, C., Laslier, M., Hubert-Moy, L., Dufour, S., Le Coeur, D. & Bernez, I. (2020) Large dam removal and early spontaneous riparian vegetation recruitment on alluvium in a former reservoir: Lessons learned from the pre-removal phase of the Selune River Project (France). *River Research and Applications*, 36(6), 894–906. Available from: https://doi.org/10.1007/s12237-020-00873-3

Reid, S.B. & Goodman, D.H. (2020) Natural recolonization by Pacific lampreys in a southern California coastal drainage: Implications for their biology and conservation. *North American Journal of Fisheries Management*, 40(2), 335–341. Available from: https://doi.org/10.1002/nafm.10412

Ritchie, A.C., Warrick, J.A., East, A.E., Magirl, C.S., Stevens, A.W., Bountry, J.A., et al. (2018) Morphodynamic evolution following sediment release from the world's largest dam removal. *Scientific*

Reports, 8(1), 13279. Available from: https://doi.org/10.1038/s41598-018-30817

Sawaske, S.R. & Freyberg, D.L. (2012) A comparison of past small dam removals in highly sediment-impacted systems in the U.S. *Geomorphology*, 151–152, 50–58. Available from: https://doi.org/10.1016/j.geomorph.2012.01.013

Smith, D.P., Kortman, S.R., Caudillo, A.M., Kwan-Davis, R.L., Wandke, J.J., Klein, J.W., et al. (2020) Controls on large boulder mobility in an 'auto-naturalized' constructed step-pool river: San Clemente reroute and dam removal project, Carmel River, California, USA. *Earth Surface Processes and Landforms*, 45(9), 1990–2003. Available from: https://doi.org/10.1002/esp.4860

Smith, D.P., Schneiders, J., Marshall, L., Melchor, K., Wolfe, S., Campbell, D., et al. (2021) Influence of a post-dam sediment pulse and post-fire debris flows on steelhead spawning gravel in the Carmel River, California. *Frontiers in Earth Science*, 9, 802825. Available from: https://doi.org/10.3389/feart.2021.802825

Swain, D.L., Langenbrunner, B., Neelin, J.D. & Hall, A. (2018) Increasing precipitation volatility in twenty-first-century California. *Nature Climate Change*, 8(5), 427–433. Available from: https://doi.org/10.1038/s41558-018-0140-y

Tang, L., Mo, K., Zhang, J., Wang, J., Chen, Q., He, S., et al. (2021) Removing tributary low-head dams can compensate for fish habitat losses in dammed rivers. *Journal of Hydrology*, 598, 126204. Available from: https://doi.org/10.1016/j.jhydrol.2021.126204

Tonra, C.M., Sager-Fradkin, K., Morley, S.A., Duda, J.J. & Marra, P.P. (2015) The rapid return of marine-derived nutrients to a freshwater food web following dam removal. *Biological Conservation*, 192, 130–134. Available from: https://doi.org/10.1016/j.biocon.2015.09.009

Trimble, S.W. (1981) Changes in sediment storage in the Coon Creek basin, Driftless Area, Wisconsin, 1853 to 1975. *Science*, 214(4517), 181–183. Available from: https://doi.org/10.1126/science.214.4517.181

Tucker, G.E. & Slingerland, R. (1997) Drainage basin responses to climate change. *Water Resources Research*, 33(8), 2031–2047. Available from: https://doi.org/10.1029/97WR00409

Tullos, D.D., Collins, M.J., Bellmore, J.R., Bountry, J.A., Connolly, P.J., Shafroth, P.B., et al. (2016) Synthesis of common management concerns associated with dam removal. *Journal of the American Water Resources Association*, 52(5), 1179–1206. Available from: https://doi.org/10.1111/1752-1688.12450

Tullos, D.D., Finn, D.S. & Walter, C. (2014) Geomorphic and ecological disturbance and recovery from two small dams and their removal. *PLoS ONE*, 9(9), e108091. Available from: https://doi.org/10.1371/journal.pone.0108091

Tunnicliffe, J., Brierley, G., Fuller, I.C., Leenman, A., Marden, M. & Peacock, D. (2018) Reaction and relaxation in a coarse-grained fluvial system following catchment-wide disturbance. *Geomorphology*, 307, 50–64. Available from: https://doi.org/10.1016/j.geomorph.2017.11.006

U.S. Geological Survey. (1981) *Guidelines for determining flood flow frequency*. Bulletin #17B of the Hydrology Subcommittee, Interagency Advisory Committee on Water Data. http://water.usgs.gov/osw/bulletin17b/bulletin_17B.html

U.S. Geological Survey. (2022) National Water Information System: U.S. Geological Survey web interface. https://doi.org/10.5066/F7P55KJN (last accessed 1 February 2023).

Vahedifard, F., Madani, K., AghaKouchak, A. & Thota, S.K. (2020) Preparing for proactive dam removal decisions. *Science*, 369(6500), 150. Available from: https://doi.org/10.1126/science.abc9953

Wang, H.W. & Kuo, W.C. (2016) Geomorphic responses to a large check-dam removal on a mountain river in Taiwan. *River Research and Applications*, 32, 1094–1105.

Warrick, J.A., Bountry, J.A., East, A.E., Magirl, C.S., Randle, T.J., Gelfenbaum, G., et al. (2015) Large-scale dam removal on the Elwha River, Washington, USA: Source-to-sink sediment budget and synthesis. *Geomorphology*, 246, 729–750. Available from: https://doi.org/10.1016/j.geomorph.2015.01.010

Warrick, J.A., Hatten, J.A., Pasternack, G.B., Gray, A.B., Goñi, M.A. & Wheatcroft, R.A. (2012) The effects of wildfire on the sediment yield of a coastal California watershed. *Bulletin of the Geological Society of America*, 124(7–8), 1130–1146. Available from: https://doi.org/10.1130/B30451.1

Wilcox, A.C., O'Connor, J.E. & Major, J.J. (2014) Rapid reservoir erosion, hyperconcentrated flow, and downstream deposition triggered by breaching of 38 m tall Condit Dam, White Salmon River, Washington. *Journal of Geophysical Research - Earth Surface*, 119(6), 1376–1394. Available from: https://doi.org/10.1002/2013JF003073

Wildman, L.A.S. & MacBroom, J.G. (2005) The evolution of gravel bed channels after dam removal: Case study of the Anaconda and Union City dam removals. *Geomorphology*, 71(1–2), 245–262. Available from: https://doi.org/10.1016/j.geomorph.2004.08.018

Wohl, E. (2015) Legacy effects on sediments in river corridors. *Earth-Science Reviews*, 147, 30–53. Available from: https://doi.org/10.1016/j.earscirev.2015.05.001

Wohl, E., Brierley, G., Cadol, D., Coulthard, T.J., Covino, T., Fryirs, K., et al. (2019) Connectivity as an emergent property of geomorphic systems. *Earth Surface Processes and Landforms*, 44(1), 4–26. Available from: https://doi.org/10.1002/esp.4434

Wolman, M.G. (1954) A method of sampling coarse river-bed material. *American Geophysical Union*, 35(6), 951–956. Available from: https://doi.org/10.1029/TR035i006p00951

Yellen, B., Woodruff, J.D., Cook, T.L. & Newton, R. (2016) Historically unprecedented erosion from tropical storm Irene due to high antecedent precipitation. *Earth Surface Processes and Landforms*, 41(5), 677–684. Available from: https://doi.org/10.1002/esp.3896

Young, H.H. & Hilley, G.E. (2018) Millennial-scale denudation rates of the Santa Lucia Mountains, California: Implications for landscape evolution in steep, high-relief, coastal mountain ranges. *Geological Society of America Bulletin*, 130(11–12), 1809–1824. Available from: https://doi.org/10.1130/B31907.1

Zarfl, C., Lumsdon, A.E., Berlekamp, J., Tydecks, L. & Tockner, K. (2015) A global boom in hydropower dam construction. *Aquatic Sciences*, 77(1), 161–170. Available from: https://doi.org/10.1007/s00027-014-0377-0

Zarri, L.J., Palkovacs, E.P., Post, D.M., Therkildsen, N.O. & Flecker, A.S. (2022) The evolutionary consequences of dams and other barriers for riverine fishes. *Bioscience*, 72(5), 431–448. Available from: https://doi.org/10.1093/biosci/biac004

Zunka, J.P.P., Tullos, D.D. & Lancaster, S.T. (2015) Effects of sediment pulses on bed relief in bar-pool channels. *Earth Surface Processes and Landforms*, 40(8), 1017–1028. Available from: https://doi.org/10.1002/esp.3697

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: East, A.E., Harrison, L.R., Smith, D.P., Logan, J.B. & Bond, R.M. (2023) Six years of fluvial response to a large dam removal on the Carmel River, California, USA. *Earth Surface Processes and Landforms*, 1–15. Available from: https://doi.org/10.1002/esp.5561