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Central Coast Watershed Studies

CCoWS

San Clemente Dam Removal Sediment Impacts: Year One Report

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Executive Summary

This study was conducted as part of a class project by students in the Advanced Watershed Science and Policy (ENVS 660) course at California State University at Monterey Bay (CSUMB).

Many dams in the United States have outlived their designed lifespan and are no longer serving intended purposes of water storage, energy production, and flood control. Dam removal is one economically viable option for these ineffectual dams. However, resultant changes in flow intensity and sediment transport may severely affect lower reaches including damage to endangered fish species spawning grounds and degradation of water quality.

The San Clemente Dam was removed in 2015 after 94 years of impairment to natural fluvial processes on the Carmel River in Monterey County, California. We identified possible sources of sediment and estimated the total volume that accumulated downstream of the former dam. We quantified ten substantial sediment deposits by measuring spatially referenced deposit thickness with an iron rod, pocket rod, tape and pocket transit. ArcGIS was used to interpolate deposit thickness from field measurements; the interpolated thickness grid was used to determine the volume of each deposit. We estimated the dimensions and volumes of smaller deposits in the field using a meter tape and pocket rod. Sediment samples were collected from most deposits to analyze grain size distribution and shape.

We estimated approximately 4,560 cubic meters (5,900 cubic yards) of sediment were deposited in the Carmel River along 3.5 km of channel immediately below the former San Clemente Dam during the 2016 water year. The largest deposits occurred in low-gradient reaches and pools. The sediment wave tapered at the upstream and downstream ends creating an overall bell shape. Deposit particle size was highly variable spatially.

Potential sources of sediment included the Carmel Watershed above the Carmel River Reroute and Dam Removal (CRRDR) project site, the San Clemente Creek Watershed, erosion within the CRRDR, as well as colluvial processes and construction activities downstream of the former SCD. Sediment input downstream of the CRRDR appeared minimal while the contribution of the upstream sources and the CRRDR site itself could potentially contribute more than a thousand cubic meters of sediment each.

Our results serve as a baseline for evaluating the impact of the 2016 Soberanes Fire to the Carmel Watershed which could release the same magnitude of sediment as the 2016 winter.

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1 Introduction

1.1 Background

Dams impede natural fluvial processes of rivers both upstream and downstream of an impoundment. Built for water storage, energy, and flood control, dams have supported the growth of numerous cities worldwide. In the United States, accelerated dam construction in the twentieth century led to an inventory of roughly 79,000 dams, as listed by the US Army Corps of Engineers (FEMA 2009). Dams are now exceeding their designed lifespan, becoming less economically viable and, in some cases, detrimental to surrounding riverine ecosystems through alteration of natural flow regimes and native species habitat (Poff and Hart 2002). To mitigate these effects, resource managers plan and carry out dam removal projects.

Dam removal can have both positive and negative effects downstream by modification of flow intensity and increased sediment supply (Pizzuto 2002). Redistribution of sediment following dam removal could be favorable to aquatic species by increasing variation in grain size. On the other hand, previous studies on dam removal note an immediate negative side effect is the large downstream sediment influx following the disturbance (Bednarek 2001). Fine sediment biologically impairs rivers; in particular, they influence fish migration, food source and reproduction (Berkman and Rabeni 1987, Everest *et al.* 1987, Suttle *et al.* 2004). However, these problems are typically short-lived, as rivers eventually flush out accumulated sediment (Higgs 2002).

Many studies discuss sedimentation and sediment transport from dam removal by case studies or modelling, but have no empirical data to verify consequential impacts (Doyle *et al.* 2000, Bednarek 2001, Higgs 2002, Cui and Wilcox 2008). In this report, we quantify the accumulation of sediment downstream of a major dam removal project using field observations.

1.2 Study Area: Carmel Watershed

This study took place in the reach below the former San Clemente Dam (SCD) on the Carmel River in Monterey County, California (Fig. 1). The Carmel River is 57.9 kilometers (36 miles) long and the watershed encompasses 660 square kilometers (255 square miles). Various agencies and organization monitor and manage the watershed intensively since it is a key freshwater resource to the Monterey Peninsula.

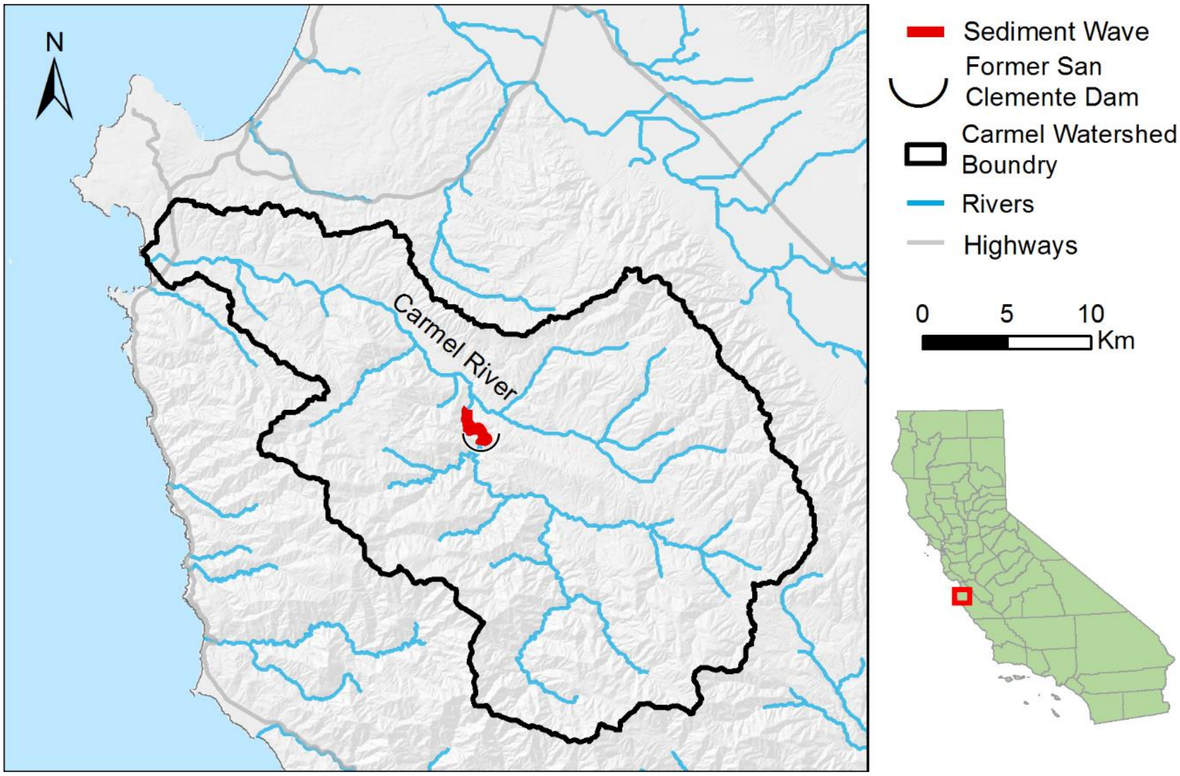


Figure 1. Location of the former San Clemente Dam and sediment impact area in the Carmel Watershed, Monterey County, CA.

1.3 Regional Geology

Active faults continuously fracture bedrock, controlling the geomorphology of the watershed (Fig. 2). Ongoing uplift of the Santa Lucia and Sierra de Salinas Ranges led to "v"-shaped canyons in the headwaters, contributing to high sediment transport rates (Smith *et al*. 2004). High transport rates generate enough gravel, sand, and silt to maintain the floodplains of the Carmel River (Rosenberg 2001). Fractured granitic rocks from the upper Carmel Watershed supply a significant source of bedload, which provides vertical channel stability. Construction of the SCD in 1921 eliminated transport of bedload downstream. Any substantial increase or decrease in bedload could cause channel morphology to change, including downcutting and development of coarse boulder armor downstream, and could reduce overall habitat quality (Dettman 1989, Kondolf and Curry 1986).

Sediment transport is inconsistent year-to-year in the Carmel River because flow depends on highly variable precipitation (Fig. 3). Precipitation in the Carmel Watershed ranges from 14 inches near the mouth of the Carmel River to 41 inches in the upper tributaries of the watershed (Rosenberg 2001). In the 2016 water year, the highest peak flow occurred in March at 1,110 cfs with a recurrence interval of 2.4 years (Tetra Tech 2016). During low to normal flow years, sediment is retained until high-flow events wash it downstream (Smith *et al.* 2004). Sediment yield can be especially high during strong El Niño winters and after intense fires. The winter of 1982 provides a good example of a very rainy wet season: 1.9 million tons of sediment were mobilized in the Carmel River, including 418,000 tons of bedload (Krebs 1983).

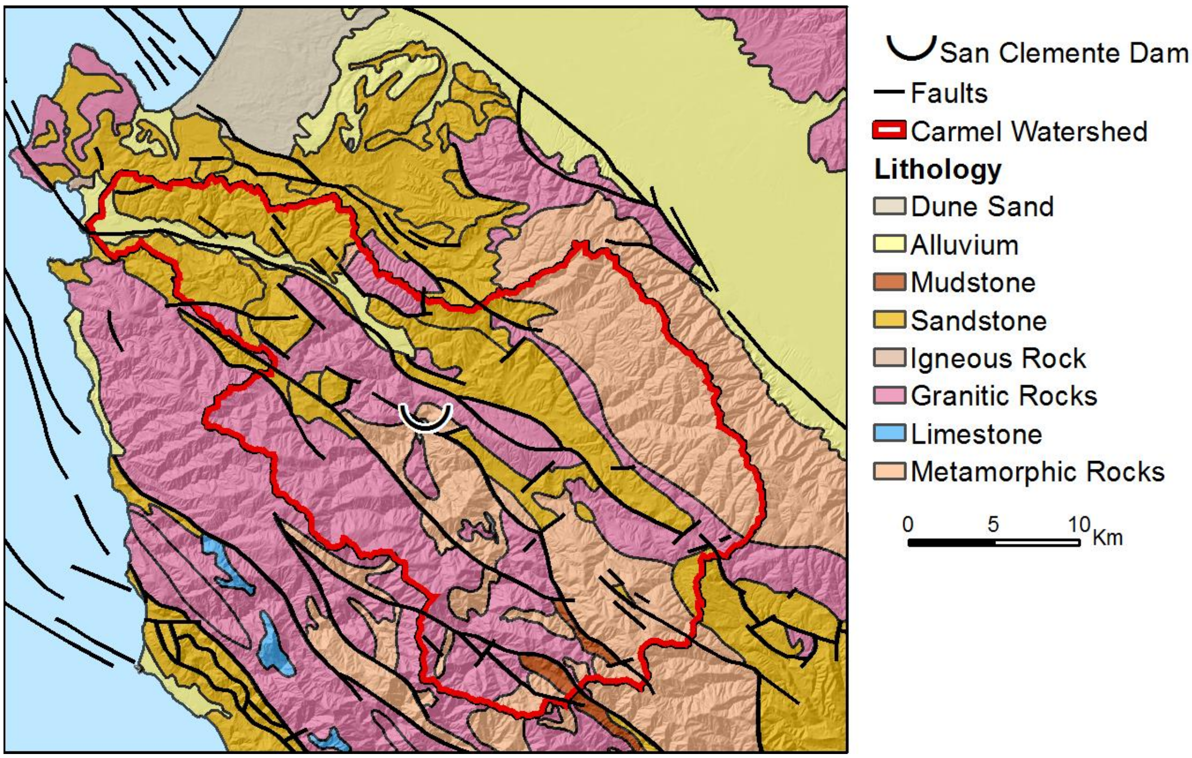


Figure 2. Carmel Watershed geologic map including dominant rock types and faults near the former San Clemente Dam in the Carmel Watershed (geologic data from Jennings *et al.* 1977).

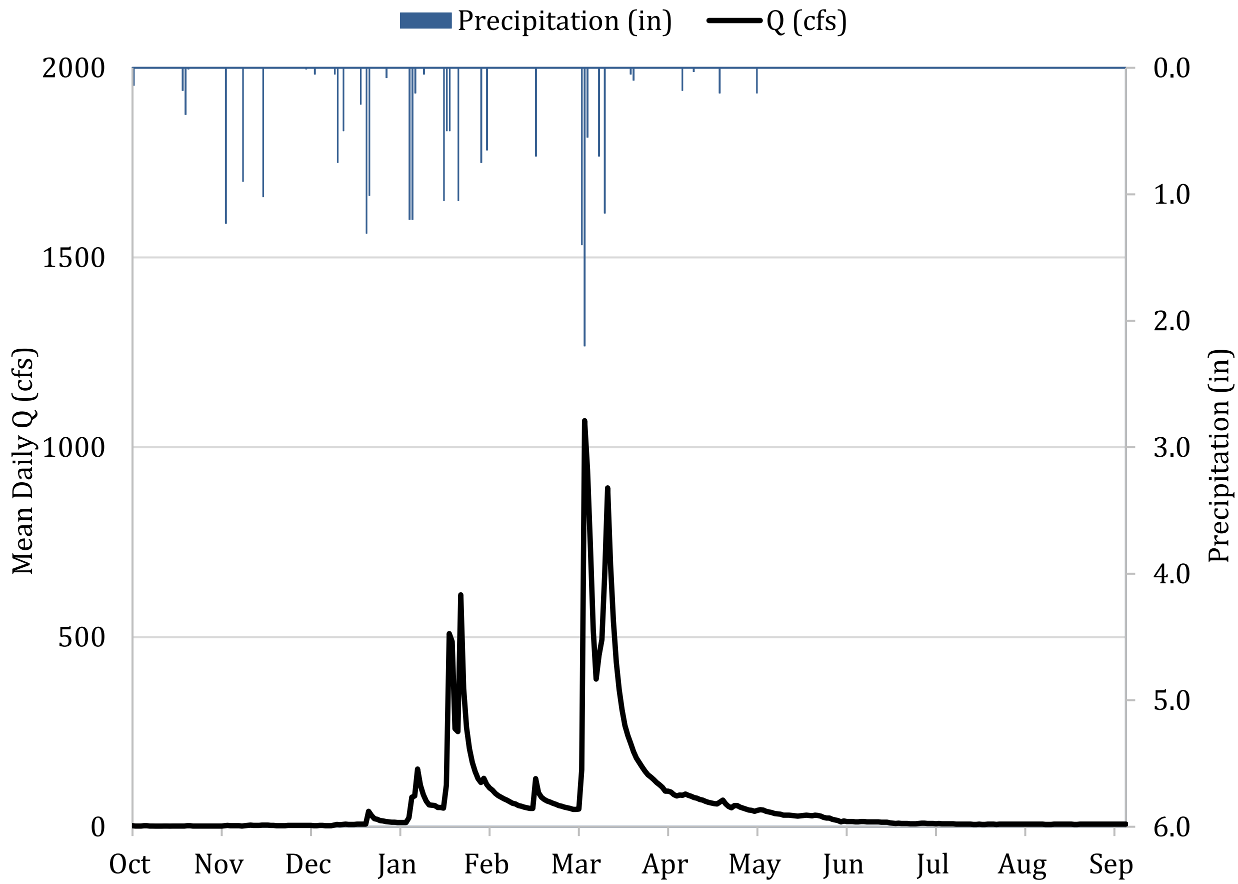


Figure 3. Water year 2016 mean daily flow from Monterey Peninsula Water Management District's Sleepy Hollow gauge and Granite Construction's daily precipitation gauge downstream of the former San Clemente Dam.

1.4 Fire History

Wildfires have played an integral role in Carmel Watershed history. Pre-1990 fire frequency was once every 21 years in the upper Carmel Watershed (Mathews 1989). Intensity of wildfires in California is projected to increase as temperatures rise and drought persists (Westerling *et al.* 2006). Wildfires act as catalysts for surface erosion and sediment transport on burned landscapes. Areas of intense burning are susceptible to landslides and debris flows during post-fire rain events.

Two historic fires in Monterey County show variability in fire-related sediment yield: the Marble Cone Fire (1977) and Basin Complex Fire (2008). The Basin Complex Fire had virtually no sediment impacts (Richmond 2009), but intense rains following the Marble

Cone Fire caused a sediment wave to move through the Carmel River (Hecht 1981). Habitats affected by the increase in sediment recovered after three years (Hecht 1981).

The Basin Complex Fire burned approximately 28,664 acres of the upper Carmel Watershed, of which 13,700 acres were considered moderate to high burn severity (Smith *et al.* 2009) and were at high risk of generating significant debris flows, but they did not materialize because the following winter did not produce any intense rain events (Kelly 2012).

The Soberanes Fire was first reported on July 22, 2016. The fire was started by an unattended campfire on Soberanes Canyon Trail in Garrapata State Park. The fire approached the upper Carmel Watershed on August 5, 2016 (Fig. 4). The Soberanes Fire continues to burn actively as of September 23, 2016. The fire has consumed approximately 121,000 acres to date, including 2,085 acres in the upper Carmel Watershed (USDA-FS 2016).

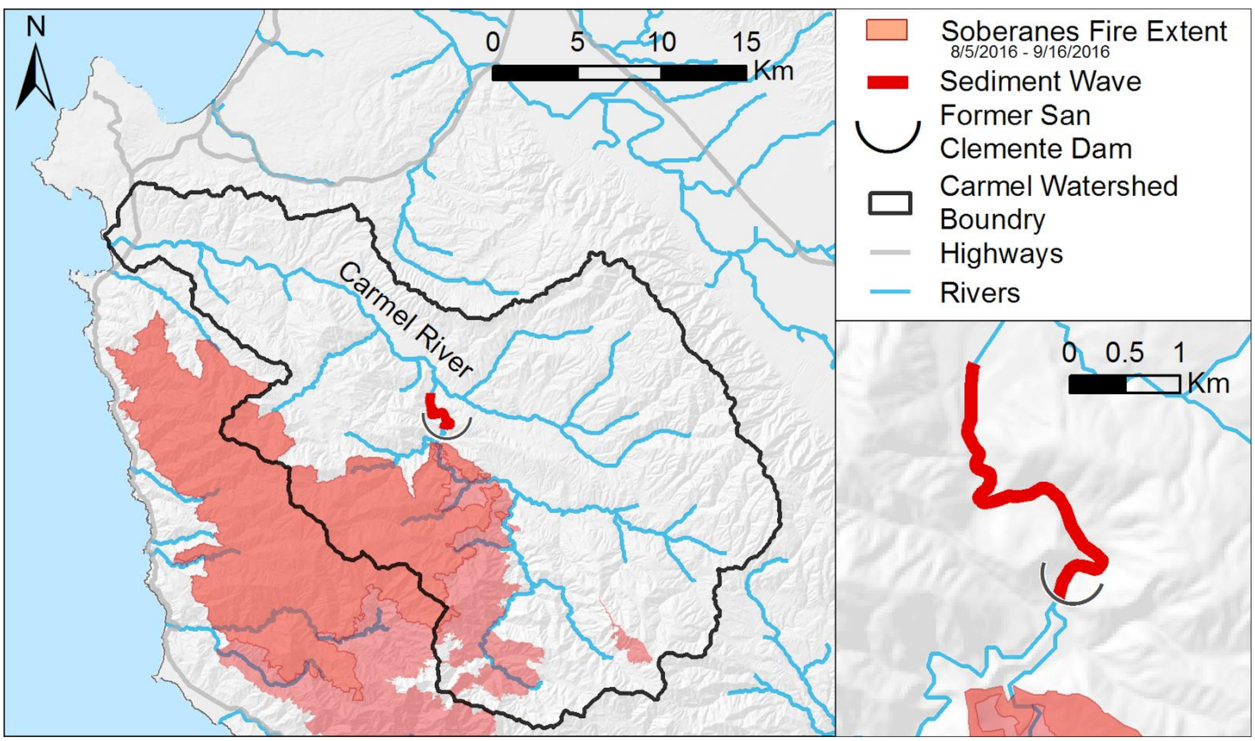


Figure 4. Extent of the Soberanes Fire in Carmel Watershed when it approached the San Clemente Dam Removal site on 8/5/16, and 9/16/2016 (data provided by the U.S. Forest Service).

1.5 San Clemente Dam Removal

The SCD impacted the flows, habitats, and geomorphology of the Carmel River from 1921to 2015 (Boughton *et al.* 2016). The dam rose 106 feet from the river floor and had an initial water capacity of 1,425 acre-feet. The combination of highly erodible bedrock in the upper watershed and a history of high-intensity fires led to a build-up of over 2.5 million cubic yards of sediment behind the dam, reducing reservoir capacity by 95% prior to its removal (EIR 2008).

The Carmel River Reroute and San Clemente Dam Removal Project (CRRDR) in 2011 included rerouting the river through San Clemente Creek and stabilizing the accumulated sediment in the older channel (EIR 2008). The CRRDR is the first project to attempt to stabilize the stockpile of sediment, rather than destroying the dam and allowing the sediment to move downstream. Stabilizing the sediment decreased possible downstream impacts (EIR 2008).

The Carmel River reroute channel design is divided into three general reaches (Fig. 5). The Upper Carmel Reach, located upstream of the reservoir, is a 960-foot long section of the river excavated through relatively unconsolidated sediments. Downstream of the Upper Carmel Reach, the Reroute Reach cut through a mountain ridge previously separating the Carmel River from the San Clemente Creek. The Reroute Reach connected the Upper Carmel Reach to the Combined Flow Reach, a junction where flows from the upper Carmel River merged with the San Clemente Creek and flowed to the main channel below the former SCD site (Tetra Tech 2016).

Planners selected the CRRDR design because it would protect downstream residence from the seismically unsafe SCD, allow unimpaired steelhead migration, provide riparian habitat for native species, restore the natural sediment flow of the Carmel River, and replenish beach erosion. The other alternatives included no action, dam notching, and dam strengthening. While the long-term positive results of dam removal might take time to achieve, the anticipated short-term impacts of the CRRDR included degradation to the downstream habitat, reduction in water quality, increased traffic around the construction site, increased sedimentation, and higher flooding frequency (EIR 2008). We evaluated the downstream sediment impacts on the Carmel River following the first post-dam runoff events of the 2016 water year.

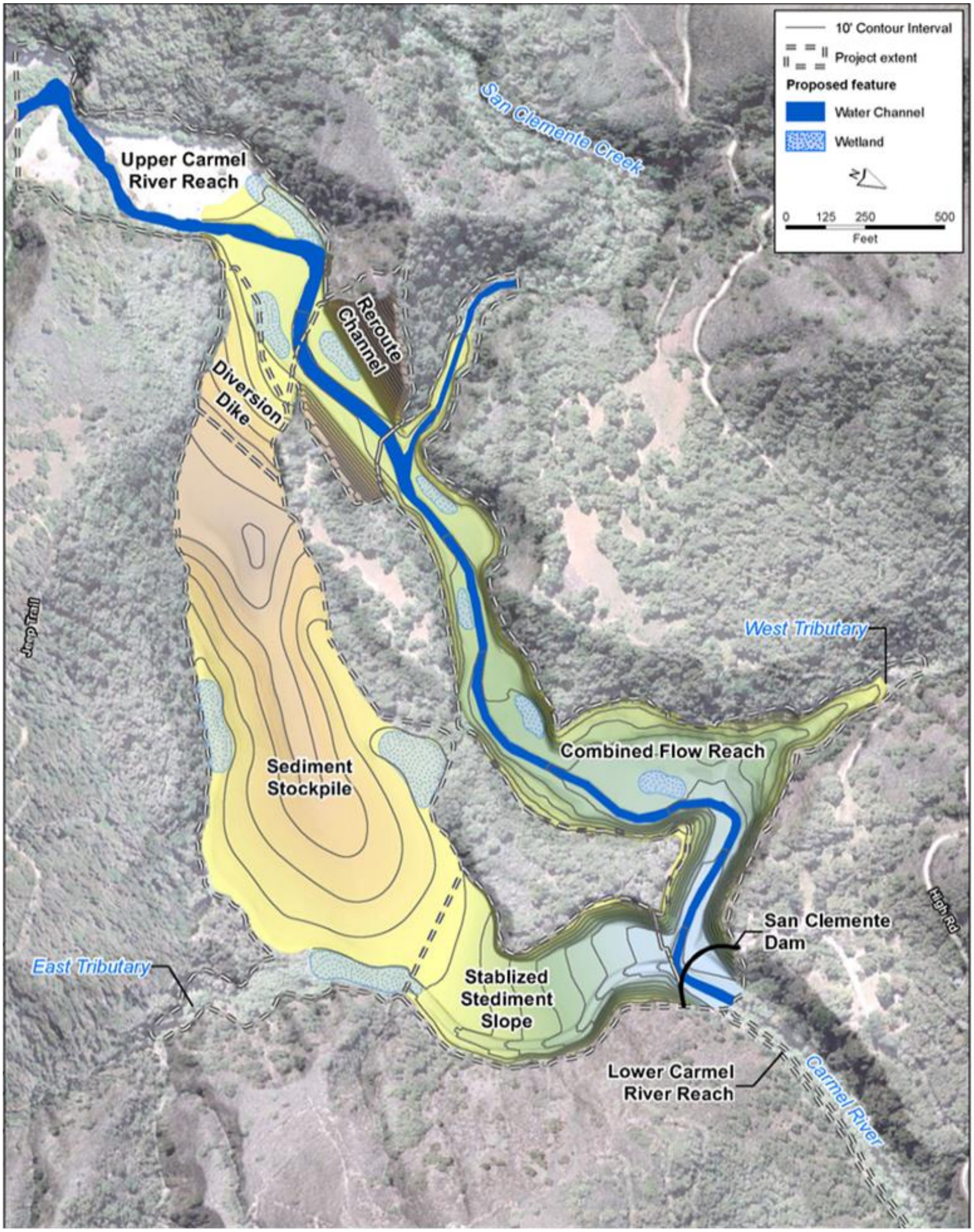


Figure 5. Map of the Carmel River Dam Removal and Reroute Project shows the Upper Carmel Reach, Reroute Reach, and Combined Flow Reach (URS 2012).

1.6 Project Goals

The purpose of this study was to quantify total volume and grain size parameters of sediment accumulated downstream from the former SCD, identify possible sources of sediment, and provide a timeline for any post-dam impacts we found. This study provides a baseline of in-channel sediment storage in advance of potential Soberanes Fire impacts.

2 Methods

2.1 Sediment Volume Quantification

2.1.1 Data Collection

We evaluated sediment located directly downstream of the former SCD that was deposited in water year 2016, the first runoff season immediately following dam removal. During reconnaissance work, we recorded locations of sediment deposits with a handheld GPS, and qualitatively described the deposit size and grain size. Sediment deposit volumes of less 20 m^3 were estimated by measuring the length and width with a tape measure and approximating the thickness with a pocket rod. We determined the full extent of the sediment wave by noting the point at which deeper, low gradient reaches of channel (pools and runs) were no longer storing post-dam removal sand and gravel. Post-dam sediment deposited in water year 2016 was easily identified because the pre-dam removal Carmel River channel along the same reach was armored with large cobble and boulders.

We quantified ten substantial sediment deposits by taking thickness measurements with a calibrated iron rod driven vertically into the deposit. The rod was hammered into the deposit until a change in resistance indicated the top of the pre-existing boulder substrate. We determined thickness measurement positions by recording polar coordinates from an arbitrary center point in each sediment deposit. Polar coordinates for each thickness measurement and boundary point were determined with a Brunton pocket transit and meter tape. We took thickness measurements at sporadic positions along the tape in a radial pattern until there were enough points to accurately model the volume of the deposit. We recorded an average of 58 thickness measurements for each deposit. We converted polar coordinates for each measurement to Cartesian coordinates through the following equation:

$$E = d \times \sin(\theta)$$

$$N = d \times \cos(\theta)$$

where d is the distance from an arbitrary center point in meters, θ is the compass bearing (true north) in degrees, E is easting, and N is northing. We used precise local positions for modeling volume. We shifted the local coordinates to approximate NAD83 UTM meters for general mapping illustration in ArcGIS.

One large deposit (Deposit 7) was in a construction zone; therefore, we were unable to quantify the sediment volume using the above methods. Instead, we obtained cross-sectional elevation data from the Monterey Peninsula Water Management District. Northwest Hydraulic Consultants surveyed the cross sections for the Federal Emergency Management Agency (FEMA) in 2006. Three cross sections from the data set had been surveyed at Deposit 7, located at the former Old Carmel River dam. Dr. Lee Harrison (NOAA) visually estimated that the sediment deposit at this site was one meter thick on average (personal communication). We calculated the cross-sectional area of the three cross sections at an average depth of one meter and multiplied the average area by the estimated length of the deposit (30 m) to derive an approximate volume of the sediment deposit.

2.1.2 Data Analysis

Thickness data for each pool were imported and interpolated in ArcGIS using the kriging spatial analyst tool. Kriging is a multistep process including exploratory statistical analysis, variogram modeling, and surface creation. The tool fits a mathematical function to nearby data points at each location to determine cell values. We used a field sketch and boundary points from the field survey to create a mask denoting the perimeter of the sediment deposit, which defined the analysis area. Rasters of each deposit were interpolated using ordinary kriging with a gaussian semivariogram model, default search radius settings, and a spatial resolution of one meter. To calculate volume, we created a constant raster with a thickness of zero, and used the cut and fit tool to calculate net volume between two surfaces.

2.2 Sediment Grain Size Analysis

2.2.1 Sample Collection and Processing

We collected representative samples of both large and smaller deposits. Smaller deposits were sampled at the tail end of the sediment wave. Samples included at least one estimate of fill material and one estimate of pavement, if present. Samples were oven-dried for 24 hours and then poured through a stack of nine brass sieves with a range of mesh sizes to develop grain size percentiles. The largest mesh (37.5 mm) was selected to be slightly smaller than that largest particles present in the samples. The smallest sieve (2 mm) was selected for sand and finer particles to be weighed as one grain size category. We shook the copper stack for 30 seconds to encourage particles to pass through the smallest possible perforation. The base pan collected particles smaller than 2 mm. Each sieve was weighed before (empty) and after (with collected sediment) to calculate a difference in mass. We then calculated the grain size percentiles of each sample, including the D50.

2.2.2 Data Analysis

Grain size percentiles for each deposit that included gravel were determined using Microsoft Excel and R Statistical package (R Core Team 2015). We generated histograms for each deposit to visually analyze grain size as a function of distance from the former SCD.

For sand only samples, we qualitatively described the overall sand size category and typical grain shape (angular or rounded) using a grain size comparator. We recorded the most common grain size and shape for each sample.

3 Results

3.1 Sediment Volume

Approximately 4,560 cubic meters (5,900 cubic yards) of sediment were deposited downstream of the former SCD (Fig. 6, Table 1). Very small deposits were found throughout the 3.5 km impact extent, but were not estimated due to their relatively low contribution to the overall sediment wave. The average gradient of the Carmel River underlying the sand wave was 1.7%; the gradient for the first 900 m below the former SCD was 4.4% and the rest of the reach was 0.7% (Fig. 7). The largest deposits occurred in reaches with both low gradient and large sediment accommodation space (pools and runs). Riffles were universally free of new deposits, except for sporadic thin patches of floodplain-mantling sand. Generally, a bell-shaped trend of deposit volume occurred with increased distance from the former SCD (Fig. 6). The largest deposits were in the first substantial pool downstream of the restoration site (Deposit 7) and upstream of the Sleepy Hollow ford (Deposit 16), and consisted of 21% and 34% of the total volume respectively (Fig. 7).

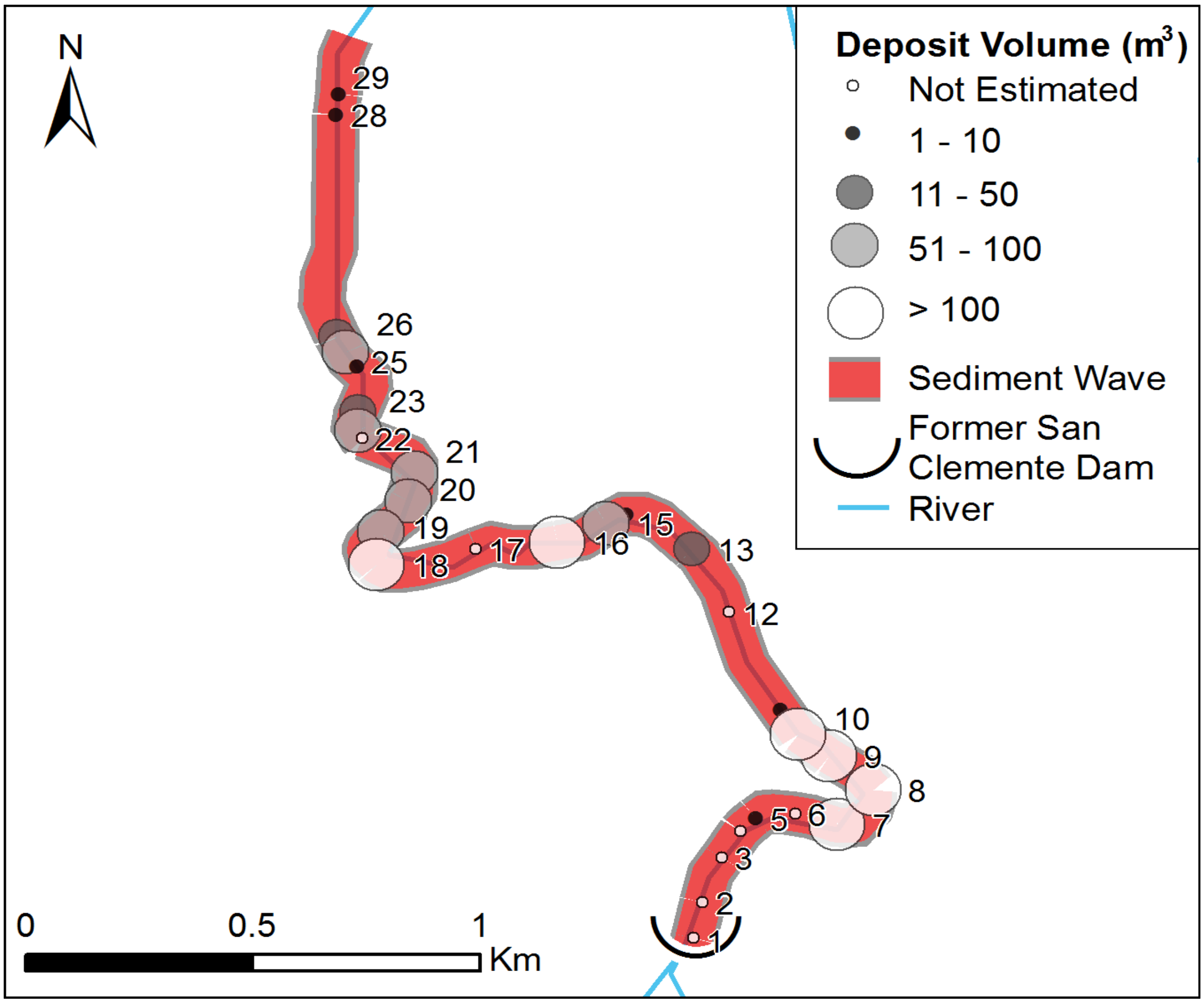


Figure 6. Sediment deposit extent, location, and volume downstream of the former San Clemente Dam.

Table 1. Sediment deposit summary downstream from the former San Clemente Dam including Deposit ID number, distance from the former SCD, approximate area, approximate volume, mean thickness, percentage of the entire deposit, and approximate UTM coordinates. An asterisk (*) next to the volume indicates a volume estimate rather than modeled volume. A dash (---) indicates the deposit volume was small and not estimated.

Deposit #	Distance from Dam (km)	Area (m^2)	Volume (m^3)	Avg Thickness (m)	Percentage	E	N
1	0.02	---	---			615764	4033129
2	0.11	---	---			615785	4033213
3	0.22	---	---			615827	4033318
4	0.30	---	---			615868	4033381
5	0.34	18	10 *	0.6	0.2%	615900	4033411
6	0.44	---	---			615989	4033421
7	0.53	970	970	1.0	21.3%	616081	4033396
8	0.67	357	140	0.4	3.1%	616159	4033478
9	0.79	324	190	1.0	4.2%	616063	4033559
10	0.88	663	400	0.6	8.8%	615995	4033609
11	0.95	---	< 3 *		0.0%	615956	4033667
12	1.21	---	---			615843	4033896
13	1.38	42	11 *	0.3	0.2%	615760	4034046
14	1.55	---	1 *		0.0%	615616	4034127
15	1.60	217	85	0.4	1.9%	615572	4034104
16	1.72	1,916	1570	0.7	34.4%	615466	4034060
17	1.90	---	---			615286	4034045
18	2.13	670	740	1.1	16.2%	615068	4034008
19	2.23	200	90	0.5	2.0%	615077	4034087
20	2.33	274	85	0.8	1.9%	615137	4034158
21	2.40	134	110	0.8	2.4%	615152	4034223
22	2.55	---	---			615037	4034307
23	2.57	148	80	0.5	1.8%	615026	4034323
24	2.62	27	11 *	0.4	0.2%	615026	4034368
25	2.75	---	15 *		0.3%	615024	4034475
26	2.79	---	20 *		0.4%	614999	4034509
27	2.83	150	30 *	0.2	0.7%	614981	4034546
28	3.36	0.5	0.25 *	0.5	0.0%	614979	4035067
29	3.41	0.5	0.08 *	0.2	0.0%	614984	4035117
Total		**6,111**	**4,560**		**100%**		

3.2 Grain Size

Grain size was spatially variable (Fig. 7, Fig. 8). There was channel pavement at four of the upstream deposits including Deposits 16 and 18. The sample with the largest median grain size (d_{50} = 16 mm) was from a volumetrically smaller deposit (Deposit 5), located closest to the former SCD (Fig. 7). The downstream tail of the sediment wave comprised five ancillary sand deposits (Fig. 8). The farthest downstream deposit was 0.5 m wide, 1 m long and 0.15 m thick.

Sand particles were angular due to being first cycle sediment derived directly from granitic and metamorphic sources. Pebble-sized particles were mostly granitic and metamorphic, with a small percent derived from the Tertiary Monterey Formation. The five most downstream sediment samples consisted of gravel-free sand (Fig. 8).

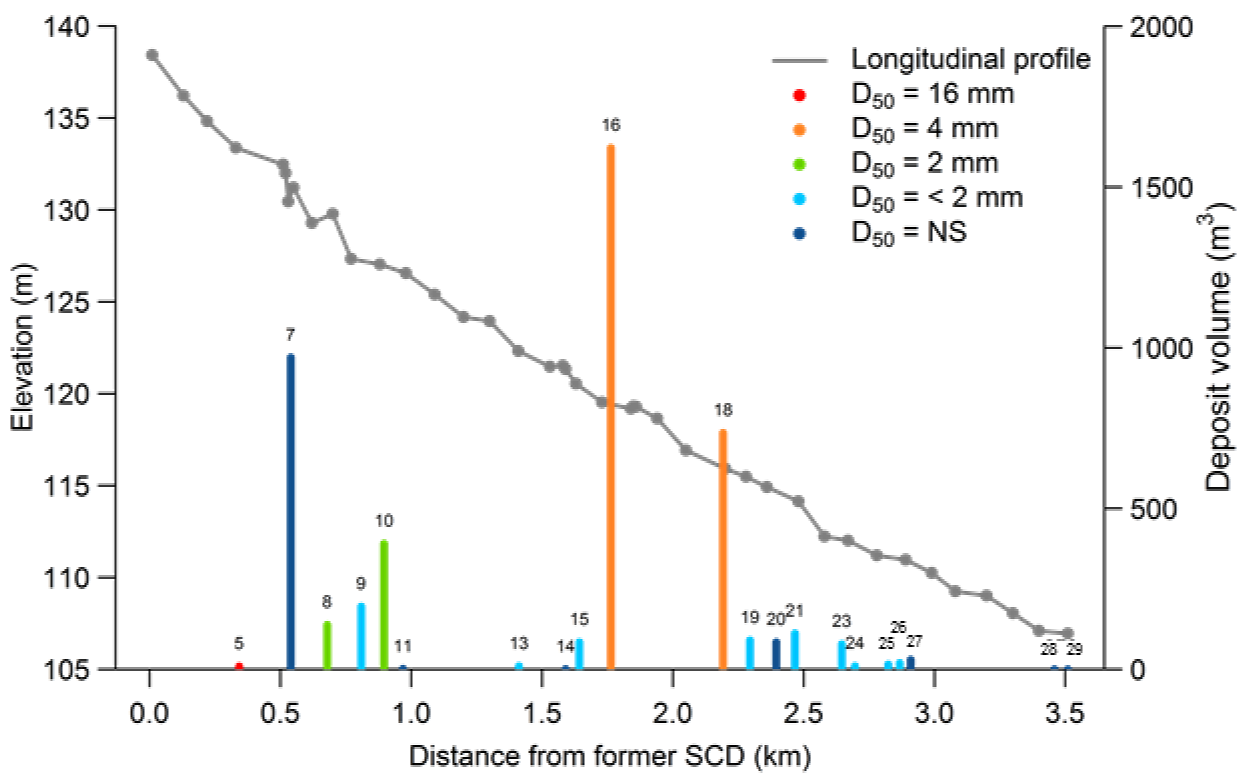


Figure 7. Longitudinal profile of the study area on the Carmel River, CA, derived from FEMA cross sections (2006), including location, volume, and D_{50} for significant sediment deposits; NS indicates that the deposits were not sampled for sediment size.

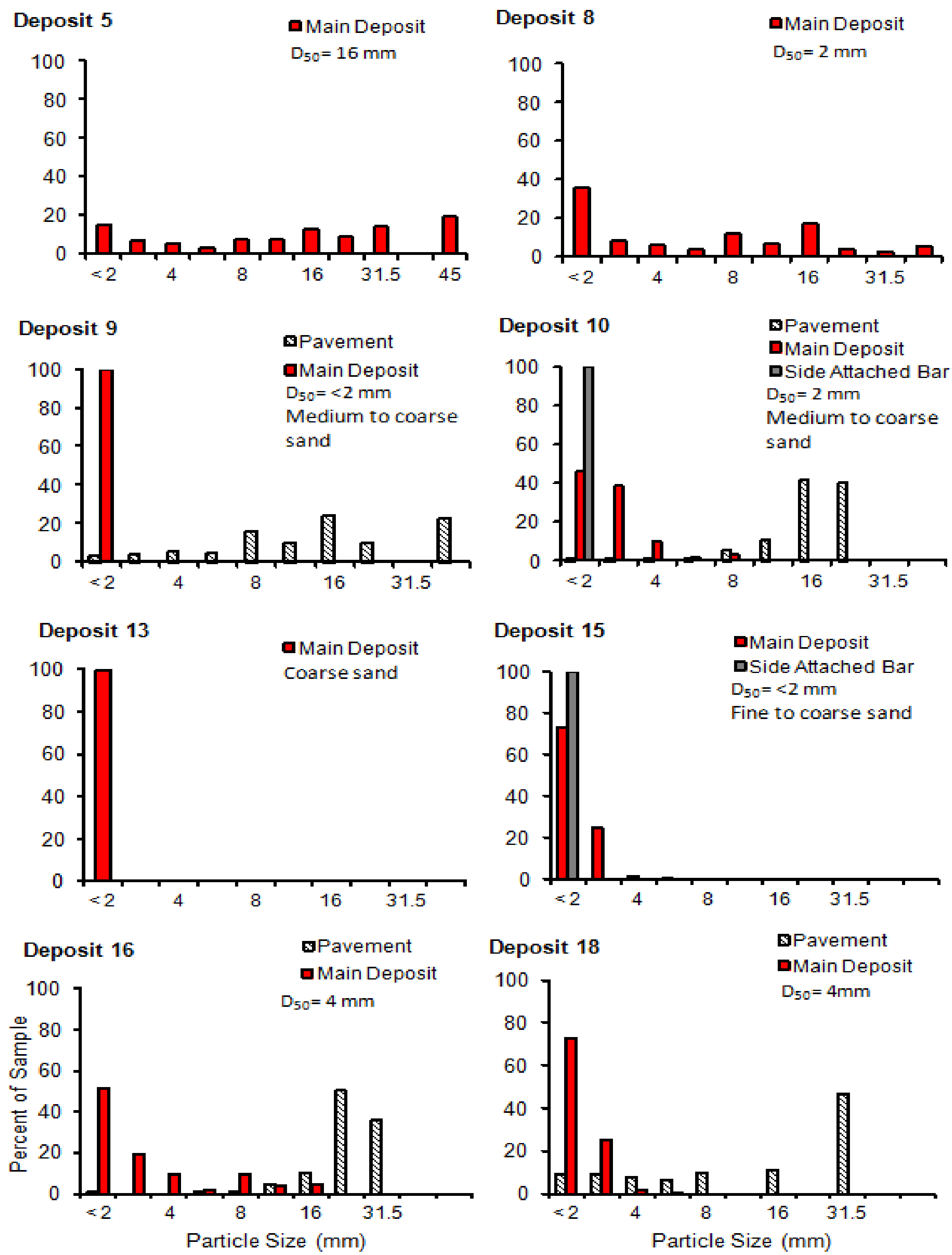


Figure 8. Particle size distribution histograms and sample descriptions for sampled deposits, continued on next page.

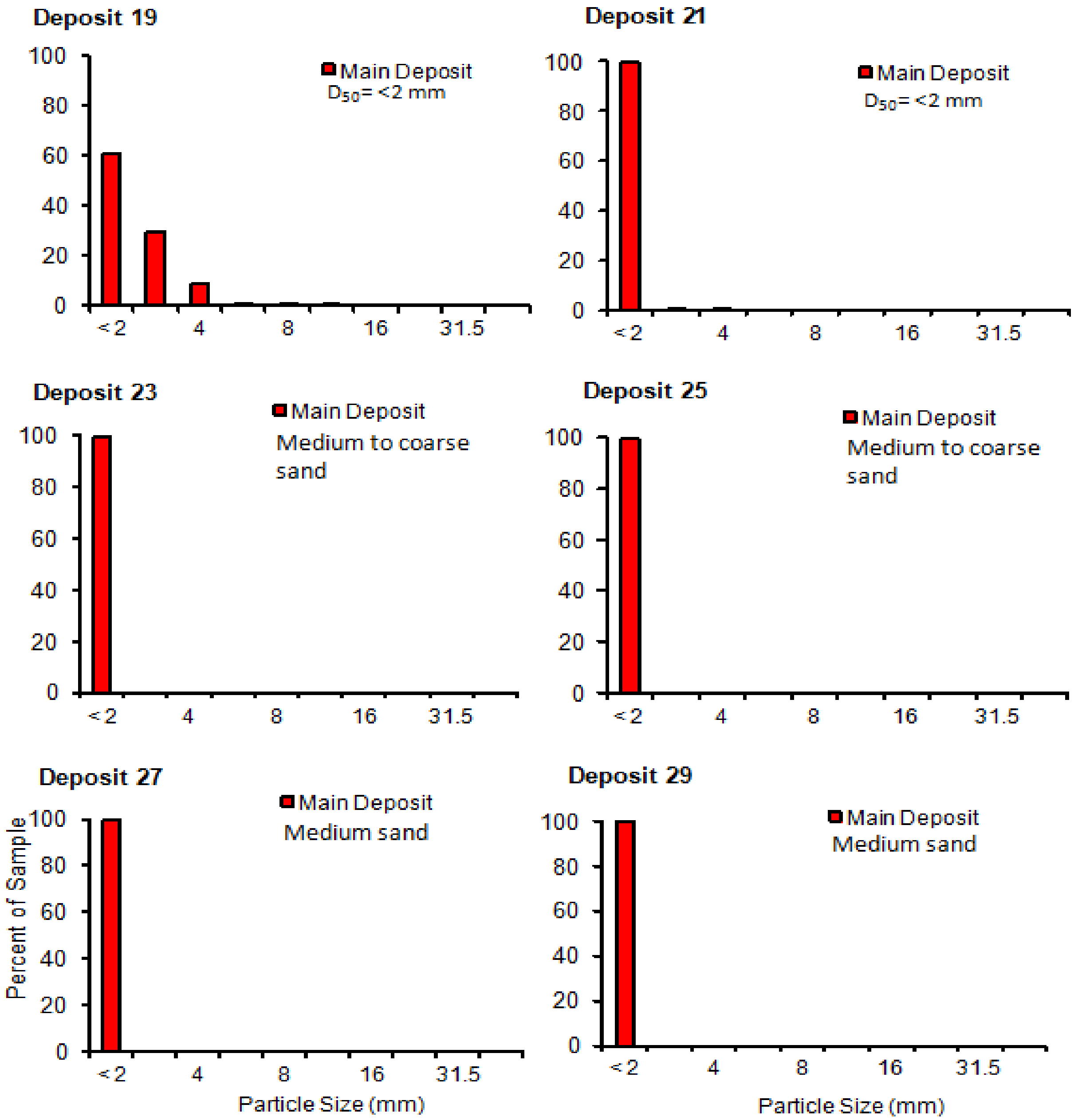


Figure 8 (continued). Particle size distribution histograms and sample descriptions for sampled deposits.

4 Discussion

We attempted to quantify post-dam-removal sediment impacts and provide pre-fire baseline conditions for future studies. A 3.5 km-long, 4,560 m^3 sand and gravel sediment wave was deposited in lower gradient reaches below the former SCD. The deposit is discontinuous with long reaches of steeper, sediment-free channel separating both minor and major sediment deposits. The wave tapers at both upstream and downstream ends, and gradually diminishes in grain size and volume within the downstream tail. Deposits farther downstream from the former SCD dwindled in size and filled gaps between large cobbles, but did not completely cover pre-existing substrate. Our volume estimate is almost certainly an underestimate, given that we did not measure 8 small mapped deposits that we estimate did not exceed 4 m^3 each (80 m^3 total volume), and discontinuous, thin sandy floodplain deposits that were not estimated.

The sediment wave progressed past the former SCD during the largest flow events occurring in January and March 2016, when the highest mean daily discharges reached 611 cfs (cubic-feet per second) and 1070 cfs, respectively. Smaller flow events occurred but did not exceed 152 cfs. Granite Construction staff working in the study area recalled that sand began to fill major pools following major storm events (David Hamblin, personal communication 2016).

4.1 Sediment Sources

Sediment deposits in the 3.5 km stretch of river directly below the former SCD were new deposits attributable to sediment transport following dam removal. Potential major sources of sediment included the Carmel Watershed above the CRRDR, San Clemente Creek, erosion within the CRRDR, colluvial processes and construction activities downstream of the former SCD.

Annual bedload rates from the Carmel Watershed are only poorly constrained, even for water years like 2016 when there were no fire impacts, landslides or extreme floods. By averaging reservoir capacity changes during unexceptional time-periods, upper and lower estimates of bedload during water year 2016 could be as high as five acre-feet per year (AFY) and as low as one AFY. Upper estimates were derived and from reservoir sedimentation rates and storage capacity measurements recorded in 1960 and 1970 and averaged (MPWMD 1995). A similar methodology was used to estimate the lower annual bedload yield calculated between 1984 and 1993 (MPWMD 1995). Therefore, the bedload contribution from the upper Carmel Watershed could account for between 1,200 to 6,200 m^3 of sediment. San Clemente Creek may have contributed 1,200 to 2,500 m^3 of sediment (Matthews 1989). Particle sizes from the upper Carmel Watershed are primarily cobble and gravel, with minimal sand input from Pine and Cachagua Creeks (ASCE 1992). This grain size is incompatible with the deposits we found below the former SCD.

Erosion from within the CRRDR was documented, but not quantified by Marson *et al.* (2016). Tetra Tech (2016) estimated the volume of sediment eroded from the unconfined Upper Carmel Reach of the CRRDR to be approximately 4,000 m^3. This estimate was comparable in scale to the total sediment volume (4,560 m^3) we measured below the former SCD. The grain size distribution in the deposits (generally gravelly sand and sandy gravel) is similar to the material eroded from the Upper Carmel Reach as well.

Visual assessment indicated that there were no significant contributions from colluvial processes downstream of the former SCD. Construction activities were well constrained behind silt fence installations, and thus did not provide excess sediment to the channel.

The total available source sediment ranged from 6,400 m^3 to 12,700 m^3 (Table 2). However, the only directly estimated source was 4,000 m^3 from the CRRDR (Tetra Tech 2016), leaving only approximately 560 m^3 of the sediment wave to have come either from other erosion sites within the CRRDR (Marson *et al.* 2016) or from very sparse inputs from the Carmel Watershed and San Clemente Creek.

Table 2. Sediment source location and annual volume estimates for the Carmel River up and downstream of the CRRDR.

Location from CRRDR	Source	Acre-feet	Cubic meters	Literature Source
Upstream	Carmel Watershed	1 – 5	1200 – 6200	MPWMD 1995
	San Clemente Creek	1 – 2	1200 – 2500	MPWMD 1995
CRRDR	CRRDR erosion	3	4000	Tetra Tech 2016
Downstream	Colluvial processes	0	0	Field Recon
	Construction	Minimal	Minimal	Field Recon

4.2 Biological Impacts

The sediment wave will likely have a complex impact on local biological conditions, where a short-term negative impact is followed by general improvement over pre-SCD removal conditions. Heterogeneity in streambed particle size is critical for maintaining trophic stability and providing prey base and life cycle habitat for many species found in the Carmel River (Merz and Chan 2005; USFWS 2002; Everest *et al.* 1987). Historically, fine grains and cobbles were absent from SCD to Tularcitos Creek resulting in an armored streambed (MPWMD 2004).

Sudden influx of sand and gravel to the study reach could affect the benthic macroinvertebrate (BMI) populations of the surveyed reach. Increased abundance of fine sediments in the channel commonly depletes taxonomic diversity and impedes BMI productivity by accumulating in interstitial spaces of the streambed where BMI's are most abundant (Cover *et al.* 2008). Conversely, high gradient armored streambeds, like those present before the sediment wave arrived, increase BMI drift propensity resulting in reduced taxonomic richness (Wilcox *et al.* 2008).

Annual Carmel River BMI surveys completed by Monterey Peninsula Water Management District (MPWMD) suggest substrate size is only a single factor contributing to healthy BMI populations. Sediment deprivation and streambed armoring resulted in less diverse and abundant BMI populations from the SCD to the confluence with Tularcitos Creek. However, BMI populations improved downstream near Robinson Canyon Road (MPWMD 2010) likely through the addition of mobile sediment.

Recent sandy-gravel deposits downstream of the former SCD may continue to degrade BMI productivity in the near term, but impacts are likely to attenuate over time. Once the sand fraction is flushed downstream, the remaining gravel will enhance habitat for BMI, and productivity might rise above pre dam-removal conditions. This is important as two federally threatened species in the Carmel River, south-central California coast steelhead (Oncorhynchus mykiss) and California red-legged frogs (Rana draytonii) depend on BMI populations as a major food source (NMFS 2013; USFWS 2002).

Steelhead utilize pool habitat for both summer refuge and spawning grounds (Nielsen and Lisle 1994; Spina 2005). Deep pools retain cooler temperatures and provide habitat through prolonged hot, dry summers. The sediment wave accumulated in areas of the channel with low stream flow velocity, such as deep pools, that were historically maintained because the SCD prevented bedload from reaching the site. The accretion of sediments in pools dramatically reduced the cool water habitat available to steelhead and eliminated a major source of sustained cold-water flows to the lower Carmel River. Salmonids prefer medium fist sized particles (25-150mm) for red nest formation, typically found in pool glides (Merz and Chan 2005). We observed fine sand substrates dominating pool glides with a pavement veneer. Prior to dam removal riffle and pool habitat demonstrated minimal variability in substrate size and armoring resulted in virtually unsuitable steelhead spawning habitat (MPWMD 2004). Therefore sand wave sediments accumulated in glides are unlikely to degrade spawning habitat beyond pre-existing conditions.

Over time, improved sediment transport resulting from the CRRDR project will benefit the lower Carmel River ecosystem by encouraging establishment of riparian vegetation and reconnecting the river to the historic floodplain. Stratified layering of sand and clay deposits carried downstream will accrete in eddies and slow water formed by large woody debris accumulations. These deposits are hotspots for plant growth and will propagate riparian vegetation along the streambanks, reducing bank erosion and channel incision (URS 2012).

4.3 Fire Impacts

Increased sediment transport downstream of the former SCD is anticipated during the subsequent rainy seasons as a result of the 2016 Soberanes Fire. Sediment liberated by the fire and mobilized by runoff causes concern for Carmel Watershed. The fire approached the former SCD on 8/5/16 (Cal-Am 2016; Fig. 4). Predicted effects of the fire on the Carmel River include increased sediment flow and sedimentation. The Soberanes Phase I Burned-Area Report estimated sediment contribution from the fire to Carmel River to be 2-7 tons/acre from 2-10 year storms. We estimate that anywhere from 2,400 – 8,500 m^3 of sediment could be released from the Carmel Watershed from the Soberanes Fire by multiplying the amount of burned area (2,085 acres as of September 2016), the estimated sediment yield (2 – 7 tons/ acre), converting to mass (2,650 kg/ m^3 for quartzo-feldspathic material), and accounting for 35% porosity. The estimated fire impact in the 2017 winter might be similar in magnitude to the 2016 sediment wave.

4.4 Comparison to Other Dam Removals

Past studies of dam removals highlighted the short-term ecological impacts of dam removal such as sediment releases (Pizzuto 2002). After removal, it took a week to flush the contents of the former Lewiston dams on the Clearwater River in Idaho 6.5 km downstream to the confluence of the Snake River (Winter 1990). The Muskegon River is expected to take anywhere from 50-80 years to transport formerly detained sediment (Simons and Simons 1991). Following the phased removal of two dams on the Elwha River in Washington, 7.1 million cubic meters of sediment was released. Despite the sand wave, the Elwha River's morphology did not change in the first year post dam removal. In the second year, sand deposited on riffle crests creating a shift from pool-riffle to braided morphology (East *et al.* 2015), supporting the idea that river morphology shifts to a new equilibrium to transport supplied sediment (Schumm 1981). The scale at which a sediment wave impact lasts depends on the volume of sediment, river velocity, channel gradient, distance to the river mouth, and the technique of dam removal (Bendarek 2001).

Given the flashy nature of the Carmel River flows, most of the sand wave propagated during the winter storms. In a single, slightly above average winter flow the centroid of the sediment wave was transported approximately 1.7 km downstream. Future studies on the movement of this sand wave will provide more insight to the rate and magnitude of sand transport after a dam removal with minimal expected downstream impact such as the CRRDR project.

5 References

[ASCE] American Society of Civil Engineers Task Committee on Sediment Transport and Aquatic Habitat. 1992. Sediment and aquatic habitat in river systems. Journal of Hydraulic Engineering 118(5): 669-687.

Bednarek AT. 2001. Undamming rivers: A review of the ecological impacts of dam removal. Environmental Management 27(6): 803 – 814.

Berkman HE. And Rabeni CF. 1987. Effects of siltation on stream fish communities. Environmental Biology of Fishes 18:285-294

Bowie C. 2012. San Clemente Dam Removal Project [Internet]. California American Water. Available from: http://www.sanclementedamremoval.org/

[Cal-Am] California American Water. 2016. Upper Carmel River Basin daily reservoir storage values: August 2016.

Cover MR, May CL, Dietrich WE, Resh VH. 2008. Quantitative linkages among sediment supply, streambed fine sediment, and benthic macroinvertebrates in northern california streams. Journal of the North American Benthological Society 27:135-149.

Cui Y, Wilcox A. 2008. Development and application of numerical models of sediment transport associated with dam removal. Sedimentation Engineering: pp. 995-1020

Dettman DH. 1989. The quantity of Steelhead spawning habitat inundated or blocked by alternative water supply projects in the carmel river basin: MPWMD Technical Memorandum 89-03, 15 pp.

East AE, Pess GR, Bountry JA, Magirl CS, Ritchie AC, Logan JB, Randle TJ, Mastin MC, Minear JT, Duda JJ., Liermann MC., McHenry ML., Beechie TJ., Shafroth PB. 2015. Large-scale dam removal on the Elwha River, Washington, USA: River channel and floodplain geomorphic change. Geomorphology 246: 687-708.

[EIR] Environmental Impact Report. 2008. Final Environmental Impact Report/ Statement, San Clemente Dam Seismic Safety Project. Prepared for: California Department of Water Resources and U.S. Army Corps of Engineers. SCH #997042007. pp. 563.

Everest FH., Beschta RL, Scrivener JC., Koski KV., Sedell JR., Cederholm CJ. 1987. Fine sediment and salmonid production: a paradox. Pages 98-142 in E. O. Salo and T. W. Cundy (editors). Streamside management: forestry and fishery interactions. Contribution No. 57. Institute of Forest Resources, University of Washington, Seattle.

[FEMA] Federal Emergency Management Agency. 2009. Dam Safety in the United States: A Progress Report on the National Dam Safety Program. Fiscal years 2006 and 2007. FEMA P-759, Washington, DC.

[FEMA] Federal Emergency Management Agency. 2006. Hydrologic and hydraulic analyses (cross-sectional data) performed by Northwest Hydraulic Consultants for FEMA under contract no. EMF-2001-CO-0015.

Hecht B. 1981. Sequential changes in bed habitat conditions in the upper Carmel River following the marble-cone fire of august 1977: California Riparian Systems Conference University of California, Davis, September, 17-19, p.134-141.

Higgs S, Maclin E, Bowman M, Bednarek A. 2002. The ecology of dam removal a summary of benefits. American Rivers pp. 15.

Jennings CW, Strand RG, Rogers TH. 1977. Geologic map of California: California Division of Mines and Geology, scale 1:750,000.

Kelly SA. 2012. Geomorphic change in the upper Carmel River, CA: Effects of the 2008 Basin Complex Fire. Senior Capstone Research Project at California State University Monterey Bay.

Kondolf MG, Curry RR. 1986. Channel erosion along the Carmel River, Monterey County, California. Earth Surface Processes and Landforms v. 11, p. 307-319.

Krebs F. 1983. Computation of Total Sediment Load of the Carmel River, CA: Report to the Monterey Peninsula Water Management District.

Marson L, Besson J, Biordi C, Conlen A, DeWolf K, Gravelle M, Hubbard H, MacSween L, Santos R, Sosa M, Thompson K, Trejo-Arce J, Smith D. 2016. First Year Assessment of the Carmel River Reroute and Dam Removal Project. Division of Science and Environmental Policy. Senior Thesis Report, 101 pp.

Matthews G. 1989. Evaluation of reservoir sedimentation rates in the upper Carmel River Watershed. Monterey Peninsula Water Management District, Technical Memorandum 88-03.

Merz JE, Ochikubi Chan LK. 2005. Effects of gravel augmentation on macroinvertebrate assemblages in a regulated california river. River Research and Applications 21: 61-74.

[MPWMD] Monterey Peninsula Water Management District. 1995. Hydrologic evaluation of the Carmel River at the Los Padres Reservoir reference site and at the San Clemente reservoir mitigation site: Technical Memorandum 95-01, 30 pp.

[MPWMD] Monterey Peninsula Water Management District. 2004. Environmental and biological assessment of portions of the Carmel River Watershed, Monterey California.

[MPWMD] Monterey Peninsula Water Management District. 2010. Ten-year summary of the Monterey peninsula water management district's bioassessment program on the Carmel River.

Nicol CL, Smith DP, Watson FGR. 2015. Exploring particle density effects on partial mobility of steelhead spawning gravels. River Res. Appl. 31:62-69.

Nielsen JL, Lisle TE. 1994, Thermally stratified pools and their use by steelhead in northern California streams. Transactions of the American Fisheries Society 123: 613-626.

[NMFS] National Marine Fisheries Service. 2013. South-central california coast steelhead recovery plan. West Coast Region, california coastal area office, Long Beach, California.

Pizzuto J. 2002. Effects of dam removal on river form and process. BioScience 52(8): 683-691.

Poff NL, Hart DD. 2002. How dams vary and why it matters for the emerging science of dam removal. BioScience 52: 659-668.

R Core Team.2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/

Richmond S. 2009. Post-fire channel response: A comparison between the 1977 Marble Cone Fire and 2008 Basin Complex Fire on the upper Carmel River. Master's Thesis Dissertation

Rosenberg L. 2001. Geologic resources and constraints, Monterey County, California: A technical report for the Monterey County 21st Century general plan update program. Prepared for County of Monterey Environmental Resource Policy Department. pp. 91.

Schumm, S.A., 1981. Evolution and Response of the Fluvial System, Sedimentologic Implications. Society of Economic Paleontologists and Mineralogists Special Publication 31:19-29.

Simons RK and DB Simons. 1991. Sediment problems associated with dam removal-Muskegon River, Michigan. Pages 680-685 in Hydraulic engineering, Proceedings of the 1991 national conference of the American Society of Civil Engineers, 29 July-2 August. American Society of Civil Engineers, Nashville, Tennessee.

Smith DP, Newman WB, Watson FGR, Hameister J. 2004. Physical and hydrologic assessment of the Carmel River watershed, California. The Watershed Institute, California State University Monterey Bay, Publication No. WI-2004-05/2 88 pp.

Smith DP, Kvitek R, Aiello I, Iampietro P, Quan C, Paddock E, Endris C, and Gomez K, 2009. Fall 2008 Stage-Volume Relationship for Los Padres Reservoir, Carmel Valley, California: Prepared for the Monterey Peninsula Water Management District. The Watershed Institute, California State University Monterey Bay, Publication no. WI-2009-2, 30 pp.

Spina AP. 2005. Downstream migration, rearing abundance, and pool habitat associations of juvenile steelhead in the lower main stem of a south-central California stream. North American Journal of Fisheries Management 25: 919- 930.

Suttle KB, Power ME, Levine JM, McNeely C. 2004. How fine sediment in riverbeds impairs growth and survival of juvenile salmonids. Ecological Applications 14:969-974.

Tetra Tech. 2016. Post-Construction CRRRDR Weir Boulder Movement Analysis Based Upon Surveys/Visual Observations and Remedial Recommendations.

Tetra Tech. 2015. Initial design report for the Carmel River reroute and San Clemente Dam Removal (CRRDR) project.

[URS] United Research Services. 2012. Final supplement to the EIR, No. 2. Old Carmel River dam removal.

[URS] United Research Services. 2012. Project number 26818107. Project base map. http://www.sanclementedamremoval.org/wp-content/uploads/2011/08/CRRDRProposed-Project.jpg. Last accessed: May 19, 2016.

[USDA-FS] United States Department of Agriculture-Forest Service. 2016. Soberanes Phase I Burned-Area Report. Reference FSH 2509.13.

[USFWS] United States Fish and Wildlife Service. 2002. Recovery Plan for the California Red-legged Frog (Rana aurora draytonii). U.S. Fish and Wildlife Service, Portland, Oregon. Viii. 173 pp.

Westerling AL, Hidalgo HG, Cayan DR, Swetman TW. 2006. Warming and earlier spring increase Western U.S forest wildfire activity. Science 313(5789): 940 – 943.

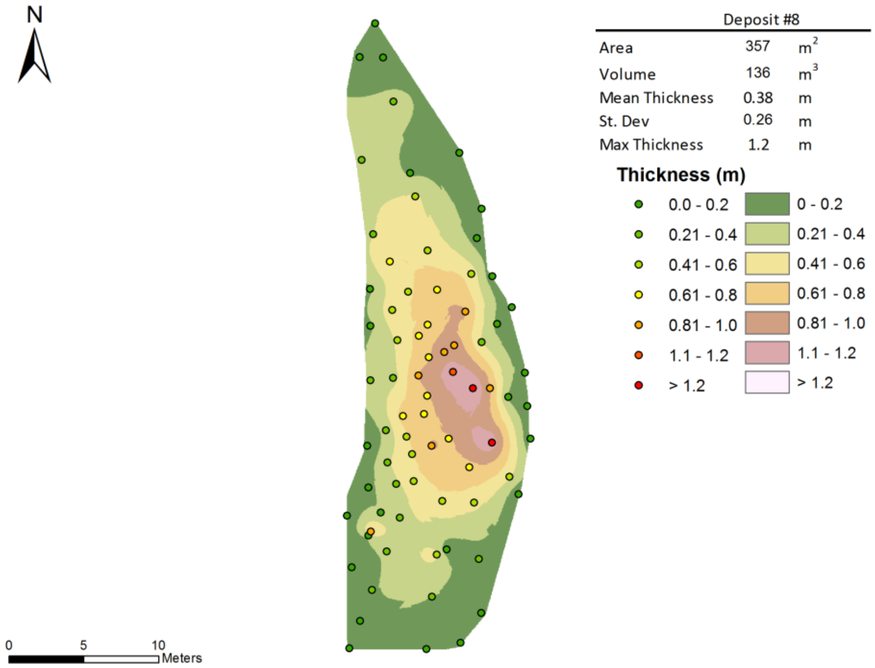
Wilcox AC, Peckarsky BL, Taylor BW, Encalada AC. 2008. Hydraulic and geomorphic effects on mayfly drift in high-gradient streams at moderate discharges. Ecohydrology 1(2): 176-186.

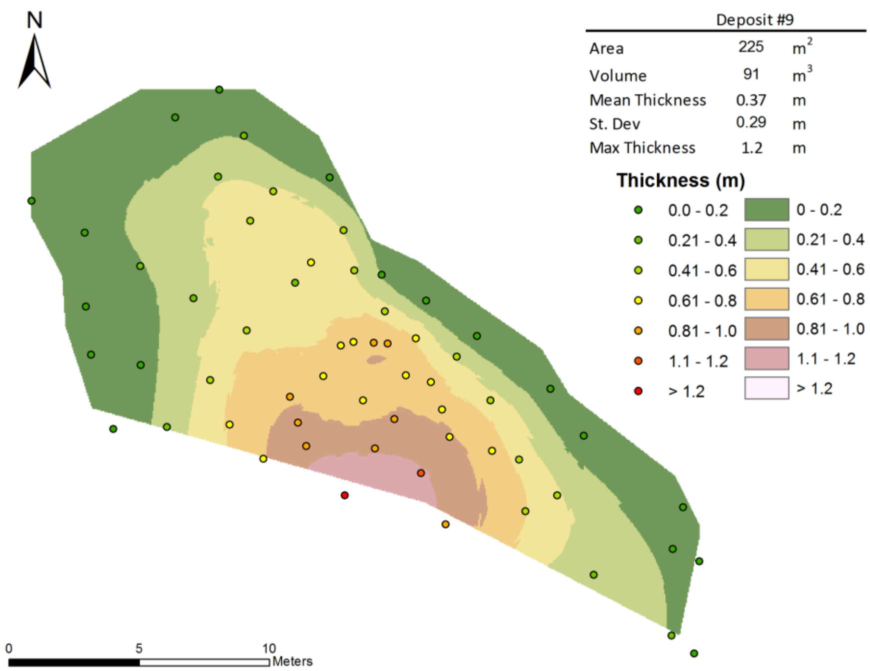
Winter BD. 1990. A brief review of dam removal efforts in Washington, Oregon, Idaho, and California. US Department of Commerce, NOAA Tech. Memo. NMFS F/NWR-28, 13 pp.

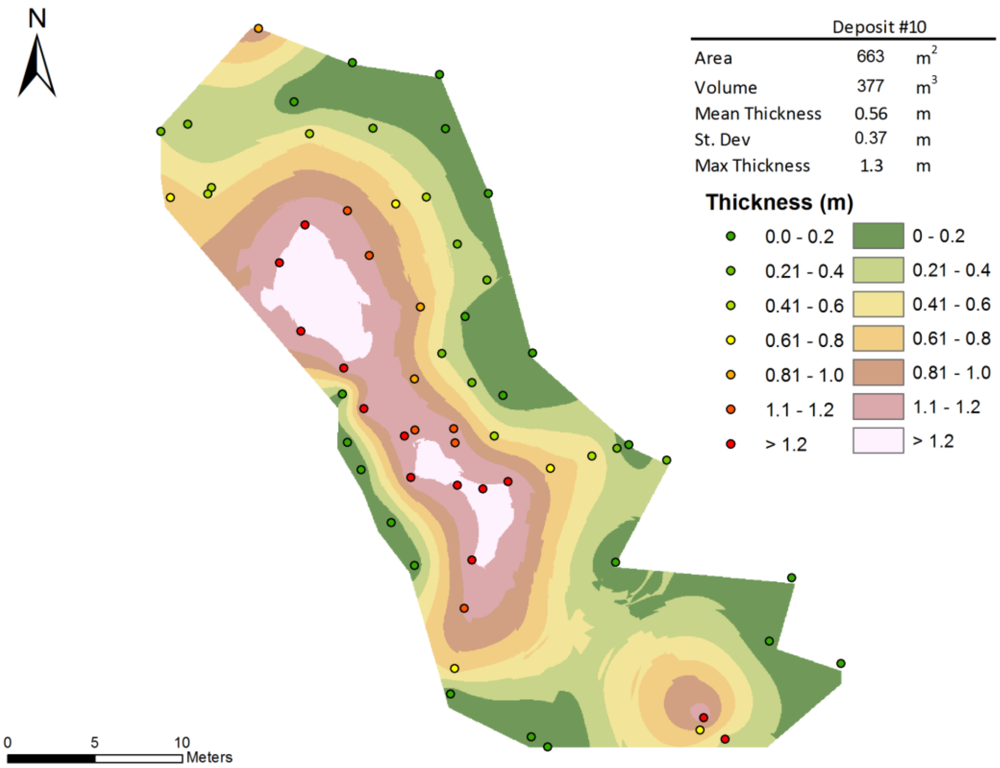
6 Appendix

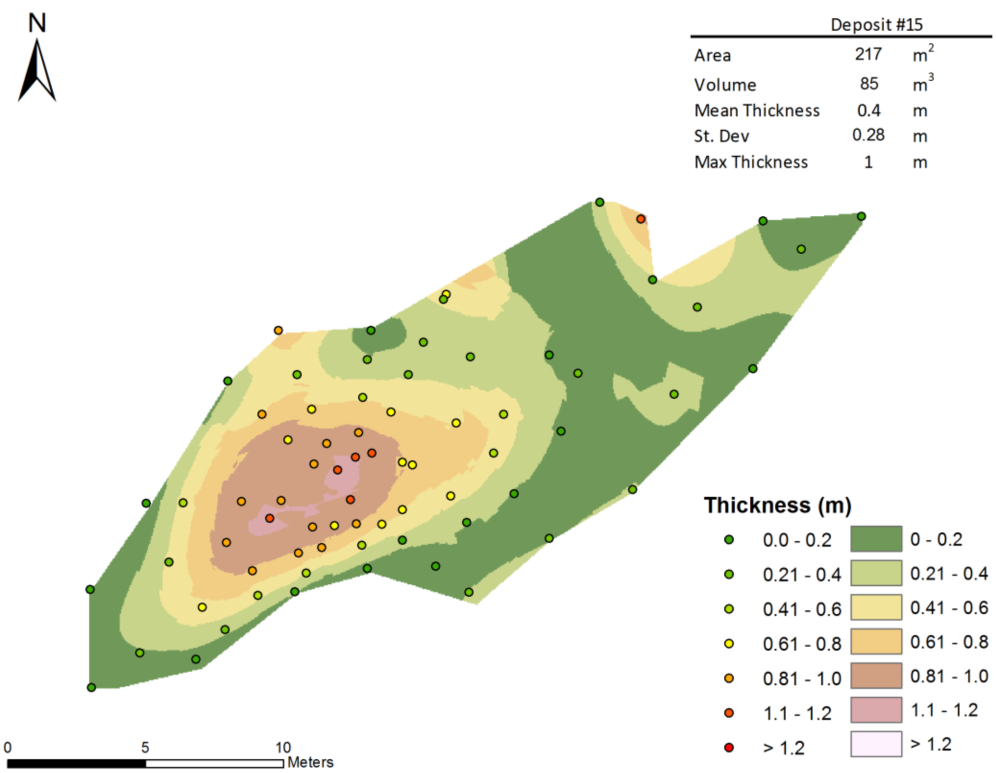
6.1 Appendix A: Pool Images

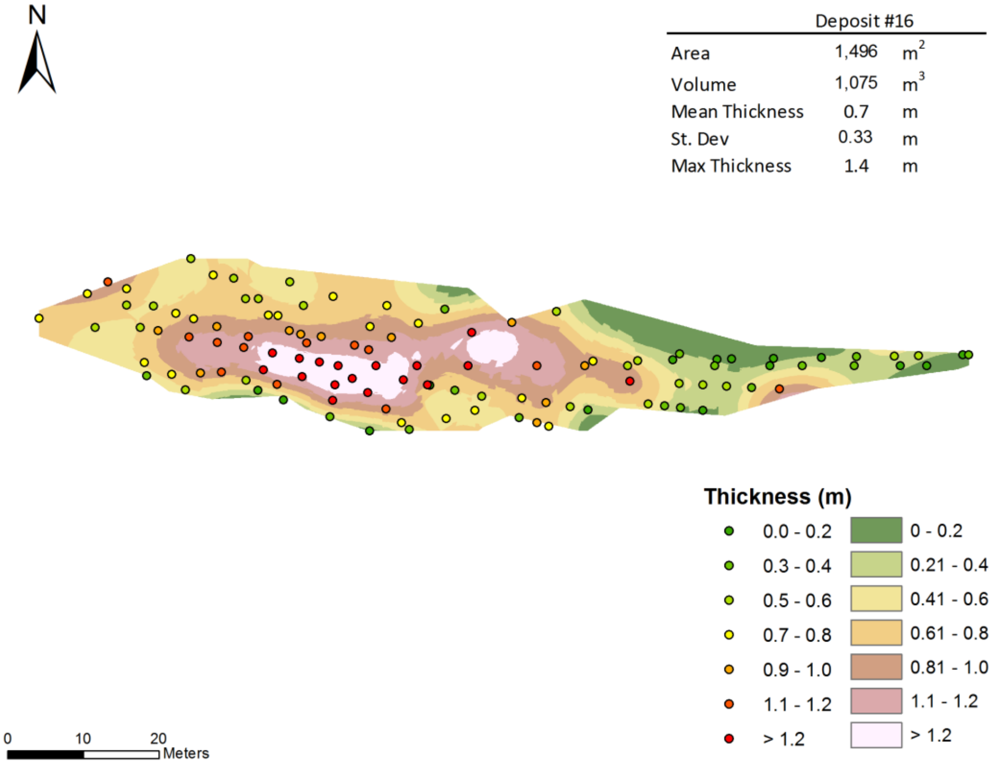
Below is each pools spatially interpolated deposit thicknesses and their manually measured points.

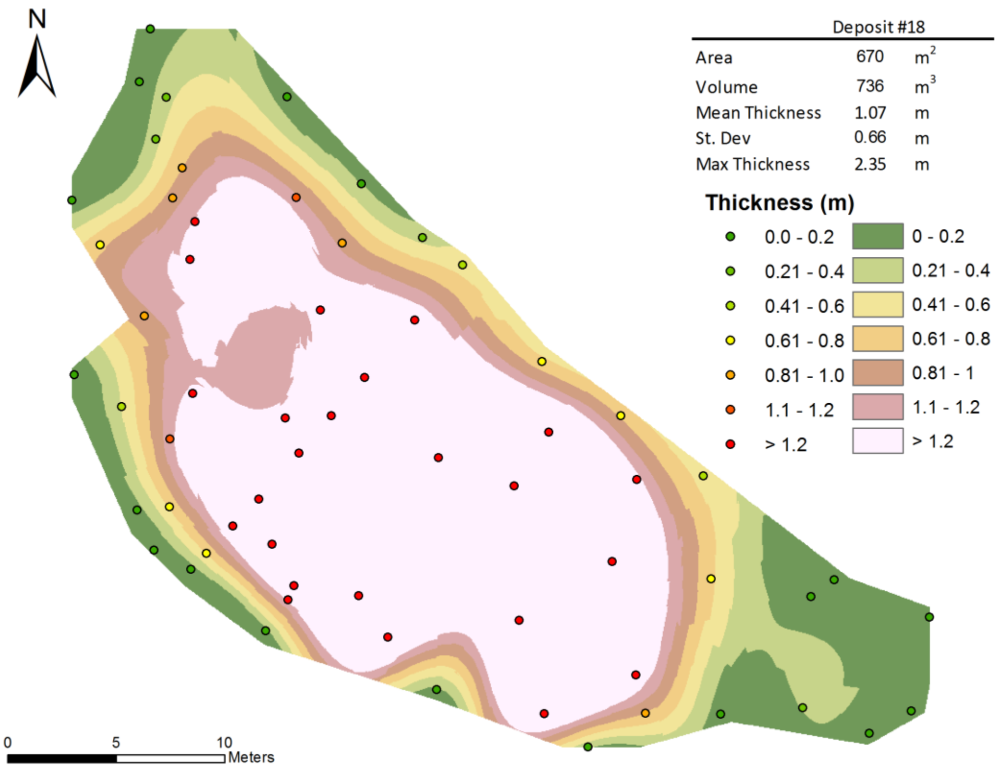


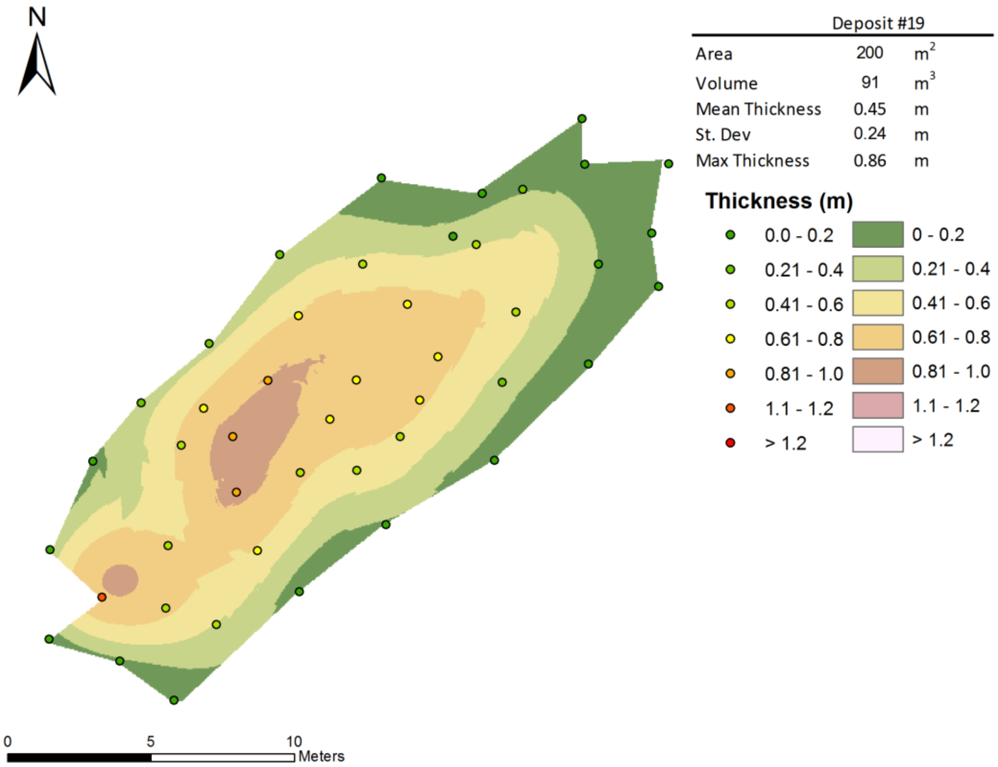


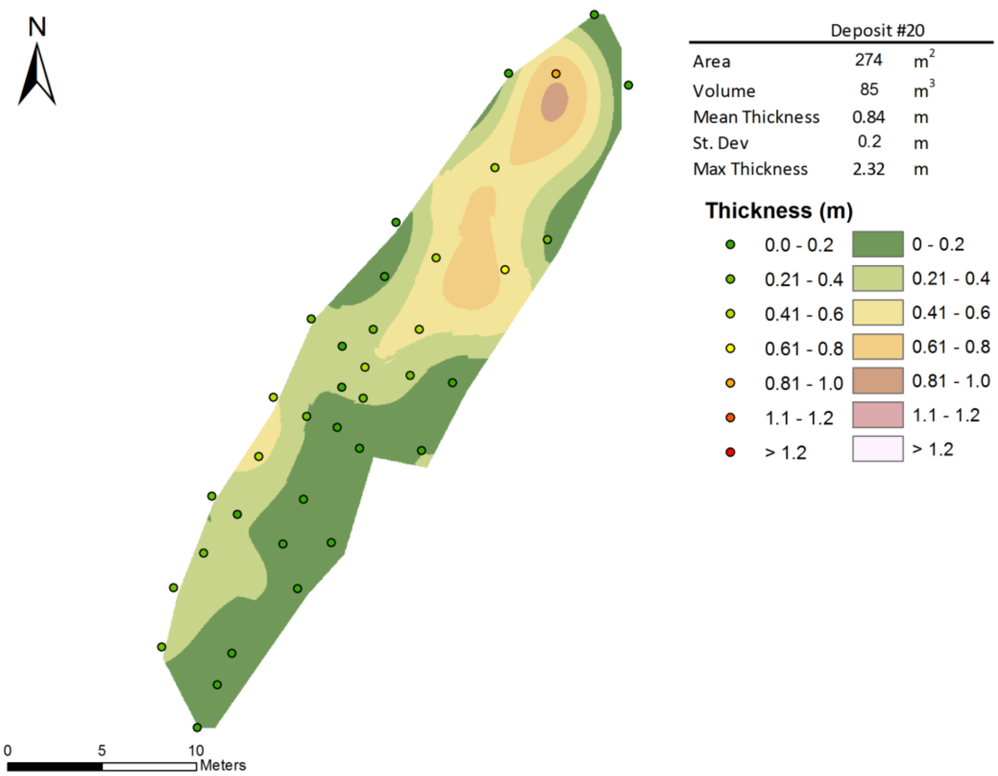

N
Deposit #10
Area 663 m2
Volume 377 m3
Mean Thickness 0.56 m
St. Dev 0.37 m
Max Thickness 1.3 m
Thickness (m)
0.0 - 0.2
0.21 - 0.4
0.41 - 0.6
0.61 - 0.8
0.81 - 1.0
1.1 - 1.2
> 1.2
0 - 0.2
0.21 - 0.4
0.41 - 0.6
0.61 - 0.8
0.81 - 1.0
1.1 - 1.2
> 1.2
0 5 10
Meters


N
Deposit #15
Area 217 m2
Volume 85 m3
Mean Thickness 0.4 m
St. Dev 0.28 m
Max Thickness 1 m
Thickness (m)
0.0 - 0.2
0.21 - 0.4
0.41 - 0.6
0.61 - 0.8
0.81 - 1.0
1.1 - 1.2
> 1.2
0 - 0.2
0.21 - 0.4
0.41 - 0.6
0.61 - 0.8
0.81 - 1.0
1.1 - 1.2
> 1.2
0 5 10
Meters


N
Deposit #16
Area 1,496 m2
Volume 1,075 m3
Mean Thickness 0.7 m
St. Dev 0.33 m
Max Thickness 1.4 m
Thickness (m)
0.0 - 0.2
0.3 - 0.4
0.5 - 0.6
0.7 - 0.8
0.9 - 1.0
1.1 - 1.2
> 1.2
0 - 0.2
0.21 - 0.4
0.41 - 0.6
0.61 - 0.8
0.81 - 1.0
1.1 - 1.2
> 1.2
0 10 20
Meters


N
Deposit #18
Area 670 m2
Volume 736 m3
Mean Thickness 1.07 m
St. Dev 0.66 m
Max Thickness 2.35 m
Thickness (m)
0.0 - 0.2
0.21 - 0.4
0.41 - 0.6
0.61 - 0.8
0.81 - 1.0
1.1 - 1.2
> 1.2
0 - 0.2
0.21 - 0.4
0.41 - 0.6
0.61 - 0.8
0.81 - 1
1.1 - 1.2
> 1.2
0 5 10
Meters


N
Deposit #19
Area 200 m2
Volume 91 m3
Mean Thickness 0.45 m
St. Dev 0.24 m
Max Thickness 0.86 m
Thickness (m)
0.0 - 0.2
0.21 - 0.4
0.41 - 0.6
0.61 - 0.8
0.81 - 1.0
1.1 - 1.2
> 1.2
0 - 0.2
0.21 - 0.4
0.41 - 0.6
0.61 - 0.8
0.81 - 1.0
1.1 - 1.2
> 1.2
0
5
10
Meters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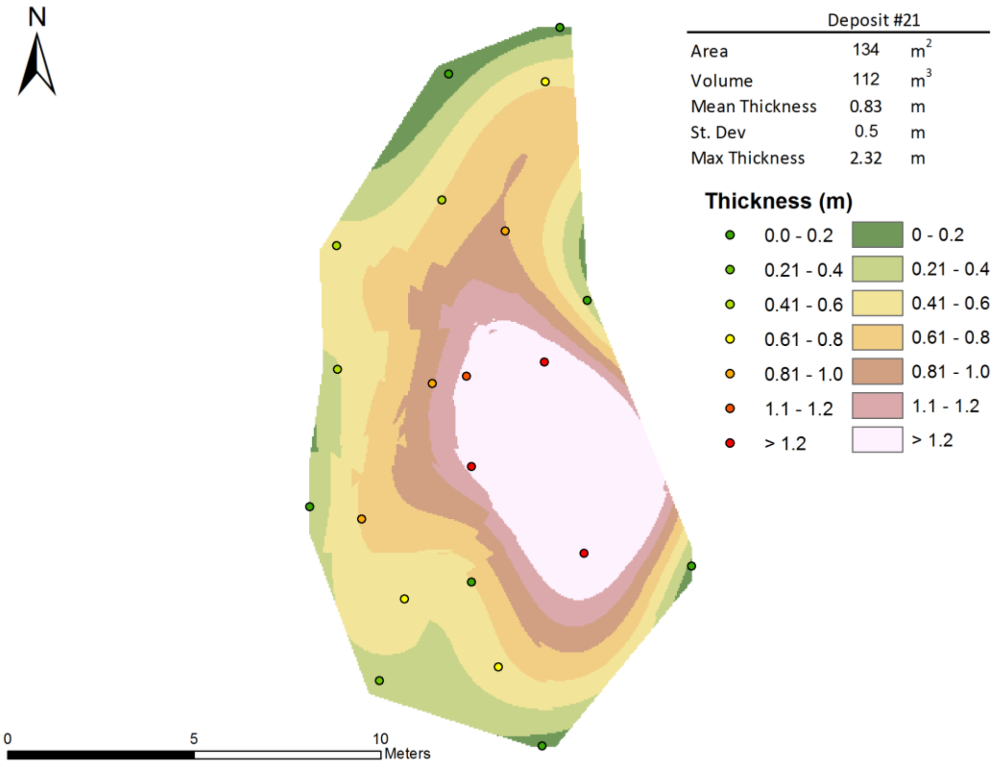
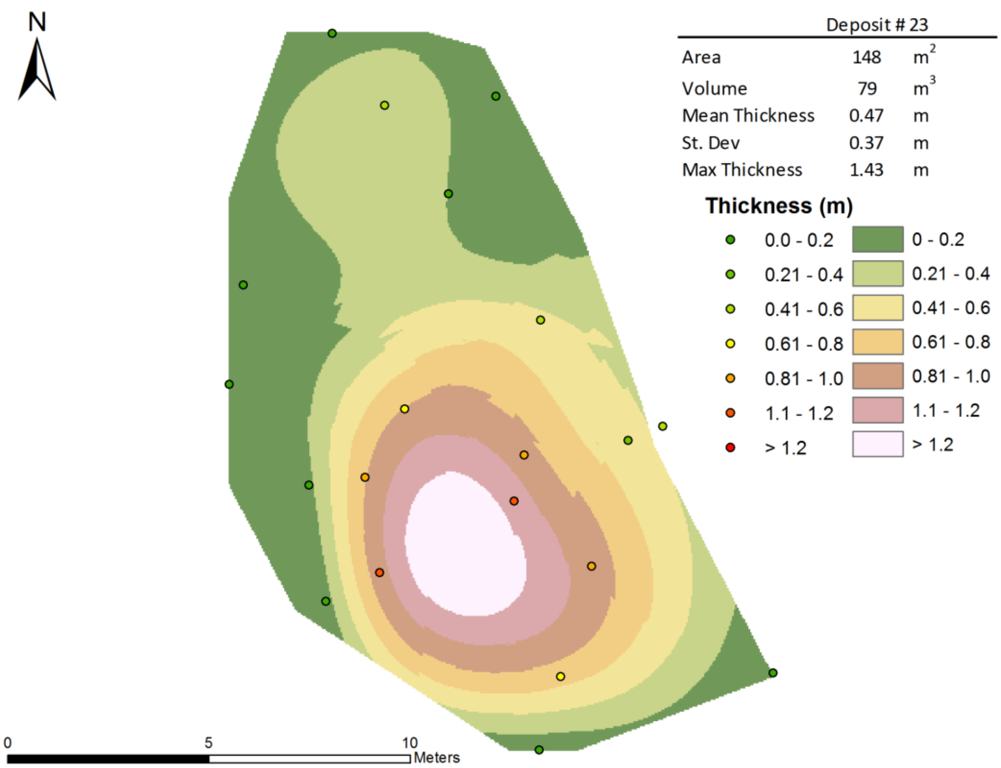
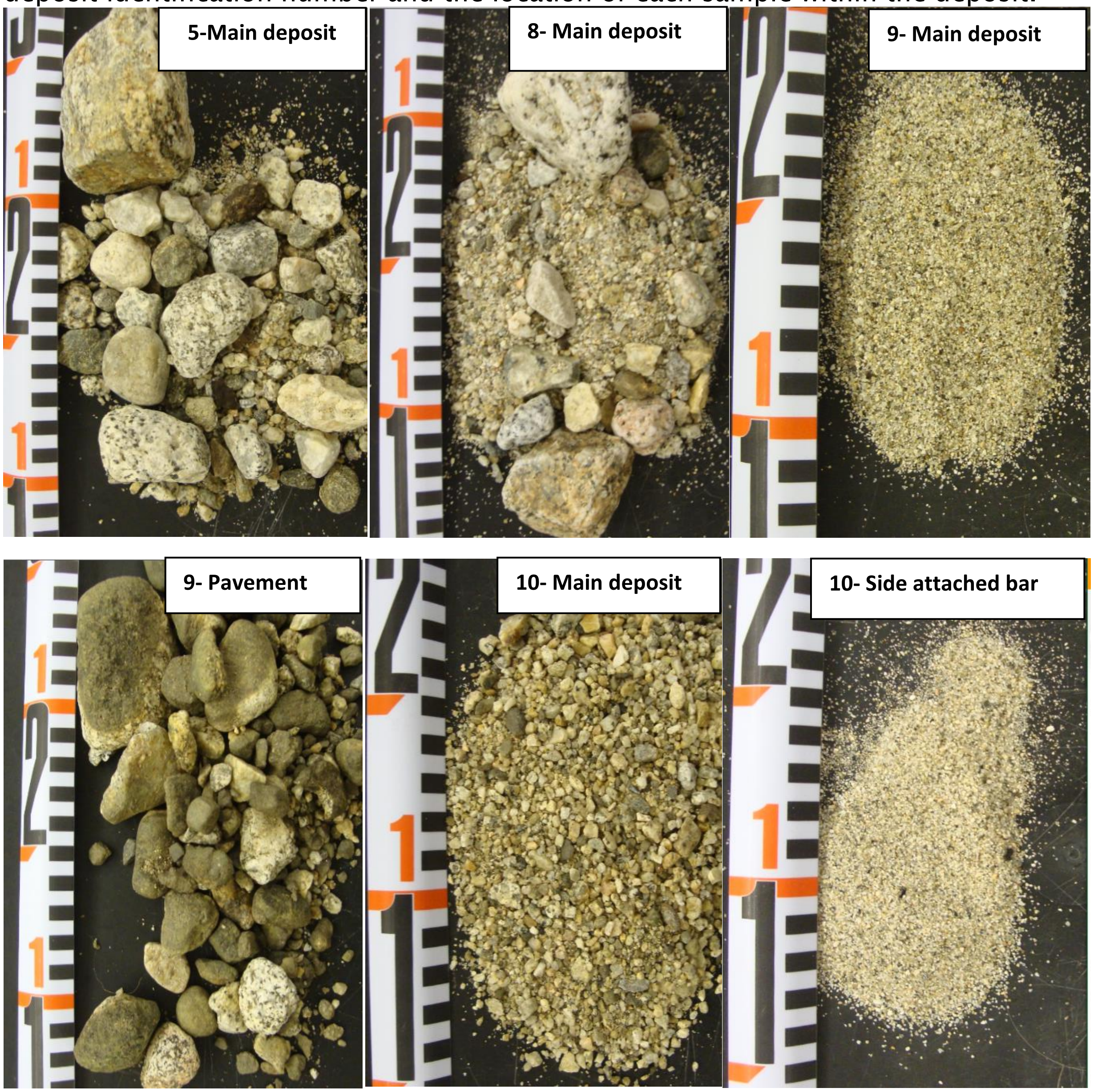
Deposit #20
Area 274 m2
Volume 85 m3
Mean Thickness 0.84 m
St. Dev 0.2 m
Max Thickness 2.32 m
Thickness (m)
0.0 - 0.2
0.21 - 0.4
0.41 - 0.6
0.61 - 0.8
0.81 - 1.0
1.1 - 1.2
> 1.2
0 - 0.2
0.21 - 0.4
0.41 - 0.6
0.61 - 0.8
0.81 - 1.0
1.1 - 1.2
> 1.2
0
5
10
Meters

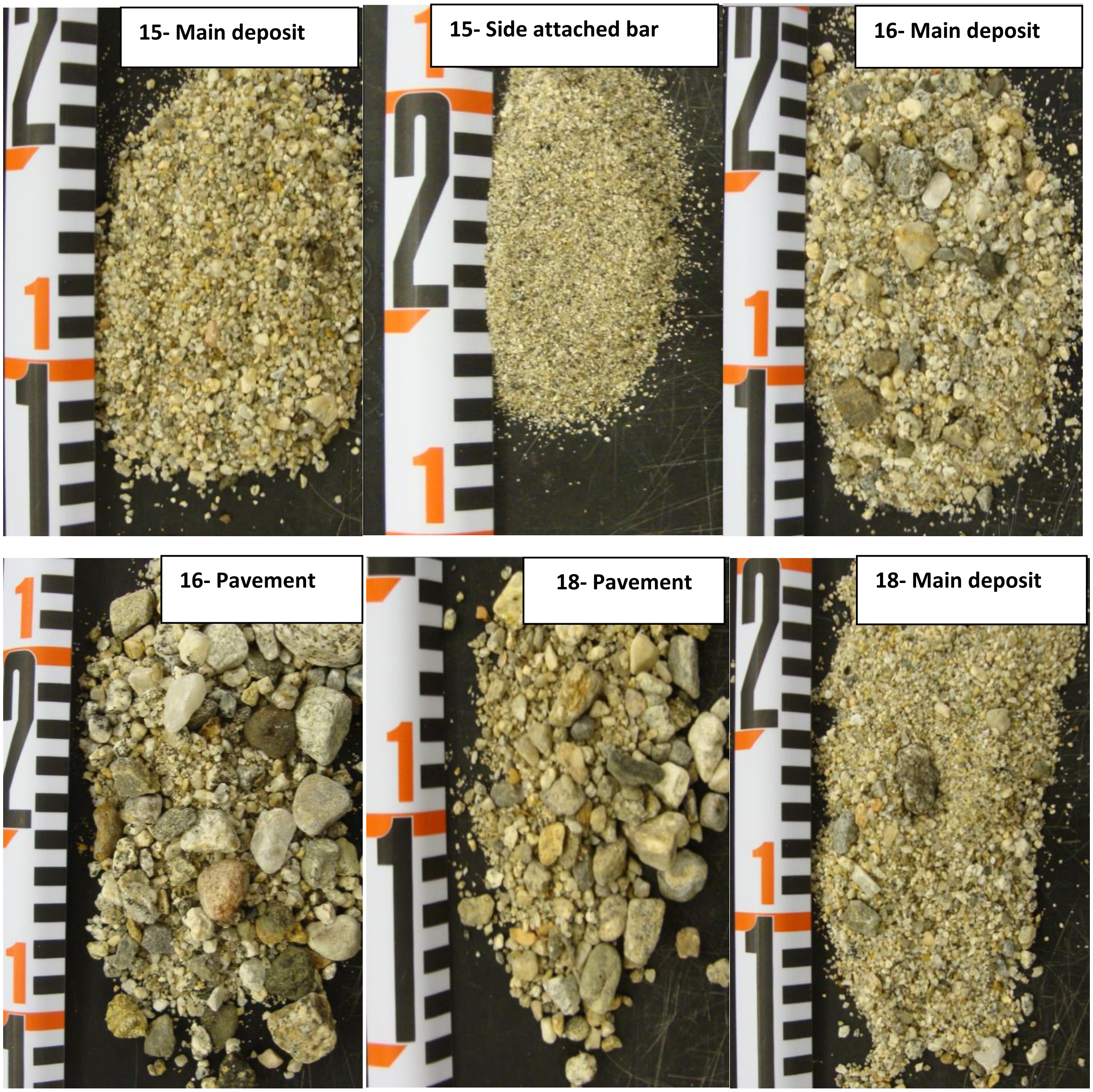

N
Deposit #21
Area 134 m2
Volume 112 m3
Mean Thickness 0.83 m
St. Dev 0.5 m
Max Thickness 2.32 m
Thickness (m)
0.0 - 0.2
0.21 - 0.4
0.41 - 0.6
0.61 - 0.8
0.81 - 1.0
1.1 - 1.2
> 1.2
0 - 0.2
0.21 - 0.4
0.41 - 0.6
0.61 - 0.8
0.81 - 1.0
1.1 - 1.2
> 1.2
0
5
10
Meters

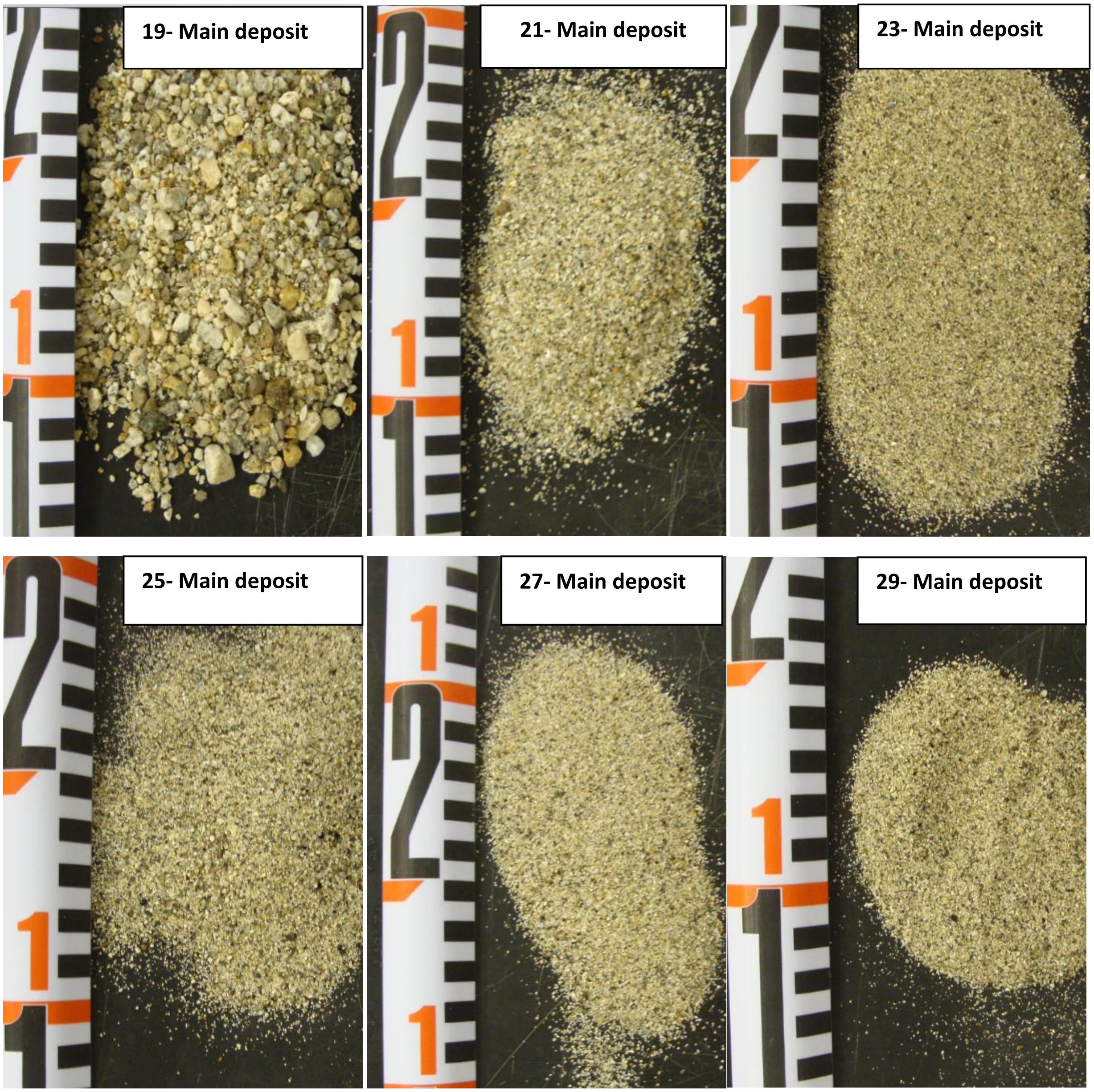

N
Deposit # 23
Area 148 m2
Volume 79 m3
Mean Thickness 0.47 m
St. Dev 0.37 m
Max Thickness 1.43 m
Thickness (m)
0.0 - 0.2
0.21 - 0.4
0.41 - 0.6
0.61 - 0.8
0.81 - 1.0
1.1 - 1.2
> 1.2
0 - 0.2
0.21 - 0.4
0.41 - 0.6
0.61 - 0.8
0.81 - 1.0
1.1 - 1.2
> 1.2
0
5
10
Meters

6.2 Appendix B: Sediment Images

Images of sand, pavement, and general pool fill sediment samples. Labels represent the deposit identification number and the location of each sample within the deposit.




15- Main deposit
15- Side attached bar
16- Main deposit
16- Pavement
18- Pavement
18- Main deposit


19- Main deposit
21- Main deposit
23- Main deposit
25- Main deposit
27- Main deposit
29- Main deposit