Central
Coast
Watershed
Studies

CCoWS

2017 Post-San Clemente Dam Removal Morphological Monitoring of the Carmel River Channel in Monterey County, California

Publication No. WI-2018-3
8 February 2018

Cory Steinmetz
Douglas Smith (Ph.D.)

The Watershed Institute

School of Natural Sciences
California State University Monterey Bay
http://watershed.csumb.edu

100 Campus Center, Seaside, CA, 93955-8001
831 582 4696 / 4431

Contact:
dosmith@csumb.edu

Executive Summary

The San Clemente Dam was removed from the Carmel River in 2015. Cross section and pebble count surveys were performed before (2013 and 2015) and after (2016 and 2017) dam removal to document dam removal impacts. This report presents surveys from 2017, the second year after dam removal. Data collection was preceded by the 2016 Soberanes Fire and several flooding events during the 2017 water year.

We found geomorphic changes at every reach in the study area, ranging from sand aggradation in the channel and floodplain to minor vertical erosion and several meters of lateral erosion. Grain size analysis indicates that high sand bedload and substantial fining observed in reaches below the dam in 2017 is likely because of erosion of reservoir sediments left in the path of the Carmel River (dam removal impacts) rather than unusually high flows of 2017 or fire impacts of 2016.

Acknowledgements

Funding and support for this long-term project has been provided at various times by Monterey Peninsula Water Management District, U.C. Santa Cruz and NOAA Fisheries Service's Southwest Fisheries Science Center, California American Water, and by the CSUMB Undergraduate Research Opportunity Center.

We are grateful for the assistance and collaboration of:

- Larry Hampson (MPWMD)
- David Boughton, Lee Harrison, Colin Nicol, and Lea Bond (NOAA Fisheries)
- Amy East and Josh Logan (USGS)
- Zane Mortenson, Jessica Williamson, and Megan Pentecost (CSUMB)

This report can be cited as:

Steinmetz C. and Smith D. 2018. 2017 Post-San Clemente Dam Removal Morphological Monitoring of the Carmel River Channel in Monterey County, California. The Watershed Institute, California State University Monterey Bay, Publication No. WI-2018-03, 51 pp.

Table of Contents

1 Introduction

In 2015, the San Clemente Dam was removed from the Carmel River in the northern Santa Lucia Range due to its seismic hazard, low storage capacity, and ecological impacts (Boughton et al. 2016; CCOWS 2012). The dam removal project was designed to minimize downstream impacts to fish habitat and flood frequency by sequestering all the stored sediment on site (SCDRP 2015). Sediment transport modeling of the dam removal project indicated that the river would not be significantly altered by the project (Mussetter 2005).

In collaboration with the U.S. Geological Survey and NOAA Fisheries Service, we established several study reaches in 2013 to monitor downstream impacts of the dam removal project (Fig. 1; Leiker et al. 2014). Monitoring includes cross sectional surveys to detect changes in channel morphology and pebble counts to detect changes in particle size of the river substrate. The study reaches include six "impact" reaches located downstream, and one "control" reach located upstream of the former dam. The "control" reach is located directly downstream from the currently operating Los Padres Dam, approximately 11 km upstream from the former San Clemente Dam.

The 2013 and 2015 surveys assessed the natural geomorphic variability in the Carmel River prior to dam removal (Leiker et al. 2014 and Chow et al. 2016). Those surveys were conducted during severe drought years. The first survey following the dam removal was conducted after the average 2016 water-year, and found minimal changes at the study reaches (Chow et al. 2017).

This report presents results from the surveys conducted after the 2017 water-year, the second year following the dam removal. In contrast to previous years, the 2017 water-year included flows reaching the 10-year flood on multiple occasions, and one storm peaking near the 25-year flood. High flows of 2017 were preceded by the late summer 2016 Soberanes Fire which extended into the southern Carmel Watershed above the former San Clemente Dam.

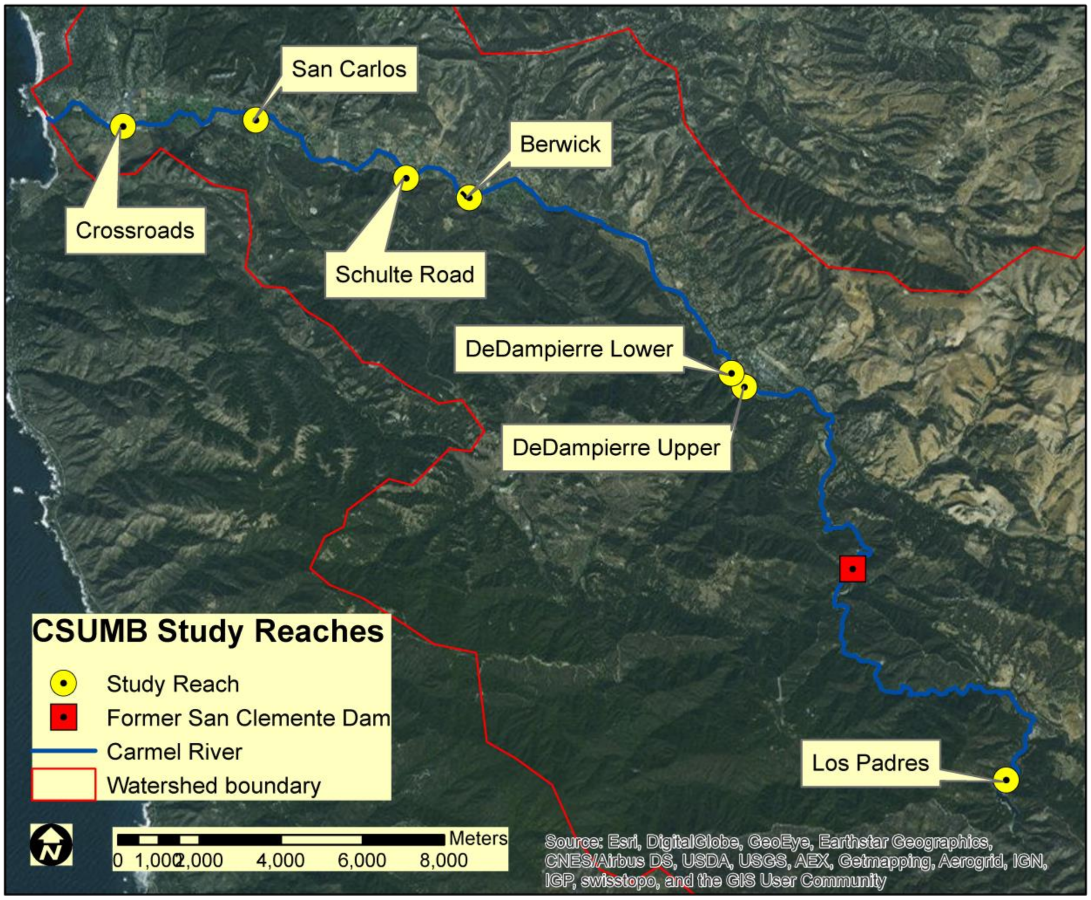


Figure 1. Location of study reaches upstream and downstream of the San Clemente Dam on the Carmel River.

2 Methods

Following the methods of the initial 2013 study (Leiker et al. 2014), we conducted geomorphic measurements of the Carmel River before the San Clemente Dam removal at seven diverse and representative reaches of the river that could change character following dam removal (Fig. 1). The cross sections were surveyed and pebble counts were performed at each site in the dry season when low flows provided easy access to the channel. Data were collected in the fall of 2016. Each study reach is described below:

- **Los Padres (LP)**: Located directly downstream from the Los Padres Dam, this reach is the most upstream reach established in 2015. This site spans a spawning gravel injection operation run by the Monterey Peninsula Water management District.
- **DeDampierre Upper (DDU)**: Located in the upper portion DeDampierre Park, the reach extends from the footbridge past the baseball fields. This reach contains several pieces of large wood installed for a restoration project by the Monterey Peninsula Water Management district.
- **DeDampierre Lower (DDL)**: This reach begins at the lower end of DeDampierre park and extends to the Carmel Valley Trail and Saddle Club downstream of the park.
- **Berwick (BW)**: Established in 2015, this reach is located on California American Water property.
- **Schulte Road (SR)**: Located upstream of the Schulte Road Bridge. This reach begins in land owned by the Big Sur Land Trust and extends to 100m upstream of the Schulte Bridge.
- **San Carlos (SC)**: Located just downstream of the San Carlos Road Bridge. The reach extends from the bridge to the California American Water San Carlos production well.

- **Crossroads (CR)**: Located adjacent to the Crossroads Shopping Center at the mouth of Carmel Valley. This is the most downstream reach included in this study.

Each reach was approximately 300 m in length and contained four to six benchmarked cross sections, approximately spaced at 60 m intervals. Cross sections were set in a variety of hydraulic settings, but mainly in riffles and pools. Using the previous benchmarks established in 2013 or 2015, we resurveyed each cross section using an autolevel, leveling rod, and 30-meter tape (Harrelson et al. 1994). At each cross section, a taut tape was set between the left and right benchmarks. Points along each transect were shot at one meter increments with additional shots to record breaks in slope. Surveys were opened and closed on the left benchmark. Cross section data were plotted and visually compared with the previous surveys. Cross sections were plotted as if looking downstream, with the left benchmark (LBM) set at a reference distance of zero. In several locations we were unable to locate the LBM, right benchmark (RBM), or both benchmarks of the cross section due to burial from sediment, vegetation, or removal from high flows. We did not obtain cross section data at locations where benchmarks were missing.

Pebble counts were performed along each cross section to determine average particle size distribution. Pebble counts included only particles within the active channel as indicated by recent substrate activity. We employed the sampling technique from Bunte and Abt (2001) that uses a 60 x 60 cm sampling quadrat. This method reduces serial correlation by adjusting the spacing between intersections on the frame to equal the dominant large particle size (≈D95). The 60 x 60 cm square sampling frame was constructed from 1" PVC pipe with notches every 10 cm. Elastic bands were then attached to notches according to the dominant large particle size of each transect. At locations where we did not collect cross sectional data due to missing benchmarks, pebble counts were obtained near the general UTM coordinates of the missing cross section.

The sampling grid was moved repeatedly across the estimated low flow channel at fixed intervals to achieve a sample size of ≥ 100. A gravelometer was used to measure particle sizes for pebble counts. Particle size histograms and cumulative frequency graphs were generated for each cross section, and averaged for each reach. Particle size percentiles were interpolated in R (R Core Team, 2017). The 2017 data were then compared to the previous data sets.

3 Results

The geomorphic and particle count data for all years of this study, including the additional 4 sites surveyed by collaborators at USGS and NOAA are archived at the following USGS digital repository: https://doi.org/10.5066/F74M93HF (East et al. 2017a).

3.1 Los Padres Reach

The Los Padres reach is located directly downstream of the Los Padres Dam (Fig. 1). This reach is upstream of the San Clemente Dam reroute site and serves as a control reach to be compared with the downstream reaches (Fig. 2). This reach also serves as the location for sporadic spawning gravel augmentation. The most recent augmentation occurred in late calendar year 2014, approximately 10 months before the first surveys. Through the 2016 survey, we witnessed the movement and sorting of augmented gravel in the Los Padres reach (Chow et al. 2016).

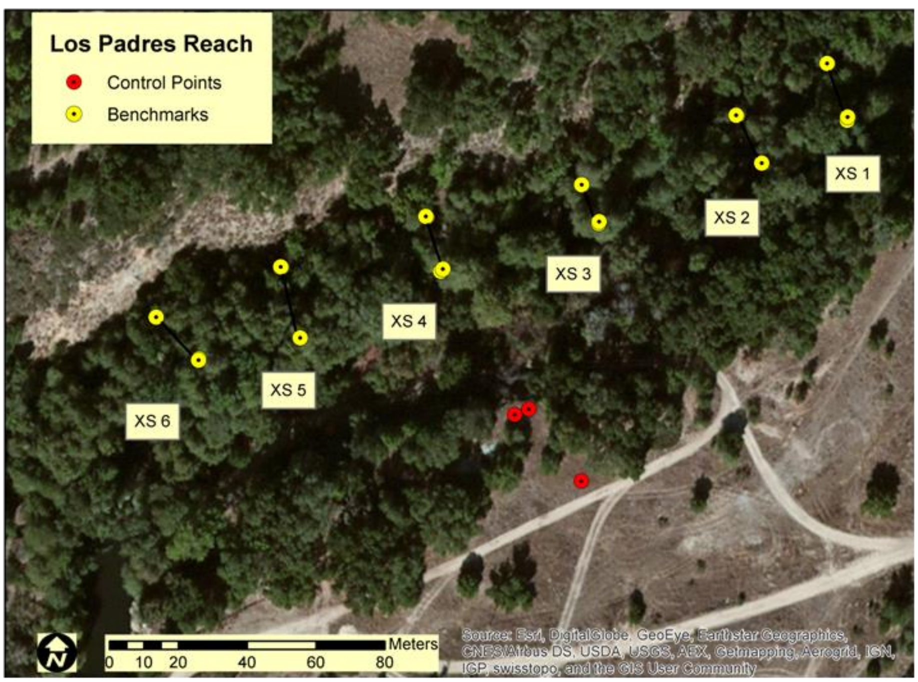


Figure 2. Location of georeferenced control points and cross sections within the Los Padres Reach.

After high 2017 flows, the substrate coarsened as the D50 increased from 147.1 mm in 2016 to 176.2 mm in 2017 (Table 1). The coarsening may be the result of augmented gravel being transported further downstream, leaving only the larger material. With the Los Padres Dam directly upstream, there is no source for sediment inputs other than adjacent banks. The 2017 increase in boulders >300 mm is likely the result of the removal of the upper layer of augmented gravel and cobbles (Fig. 3; Appendix B).

The removal of the generally thin upper most layer of substrate is evident in most of the Los Padres cross sections (Appendix A). Removal of smaller substrate increased the roughness of the stream bed by exposing large boulders, most evident in LP2 (Appendix A). LP4 is an exception, where depositional features coincide with erosional features, likely the result of shifting boulders (Appendix A).

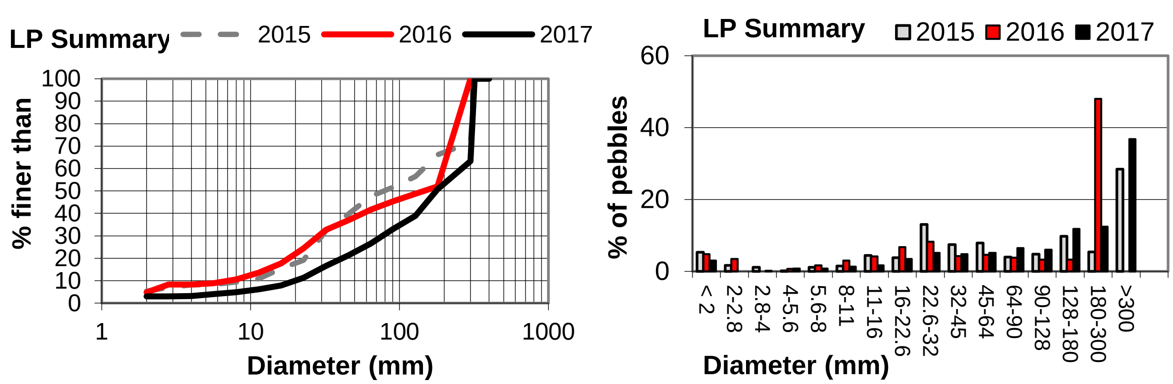


Figure 3. Summary pebble count distribution (LP 1 – LP 6) for the Los Padres reach displayed as cumulative percentiles (left) and individual bins (right) for 2015 to 2017.

Table 1. Summary grain size distribution among cross-sectional transects within the Los Padres Reach from 2015 to 2017.

Reach	Quantile	2015	2016	2017
LP	D5	2.0	2.1	8.4
	D16	17.0	13.9	31.1
	D50	78.9	147.1	176.2
	D84	300.0	233.1	300.0
	D95	300.0	249.0	300.0
	graphic mean	66.7	78.2	108.6

3.2 DeDampierre Upper Reach

The DeDampierre Upper Reach (Fig. 4) is the most upstream reach monitored by CSUMB that will see impacts of the San Clemente Dam removal. We obtained cross sectional data for DDU1, DDU3, and DDU6 and pebble counts at all locations.

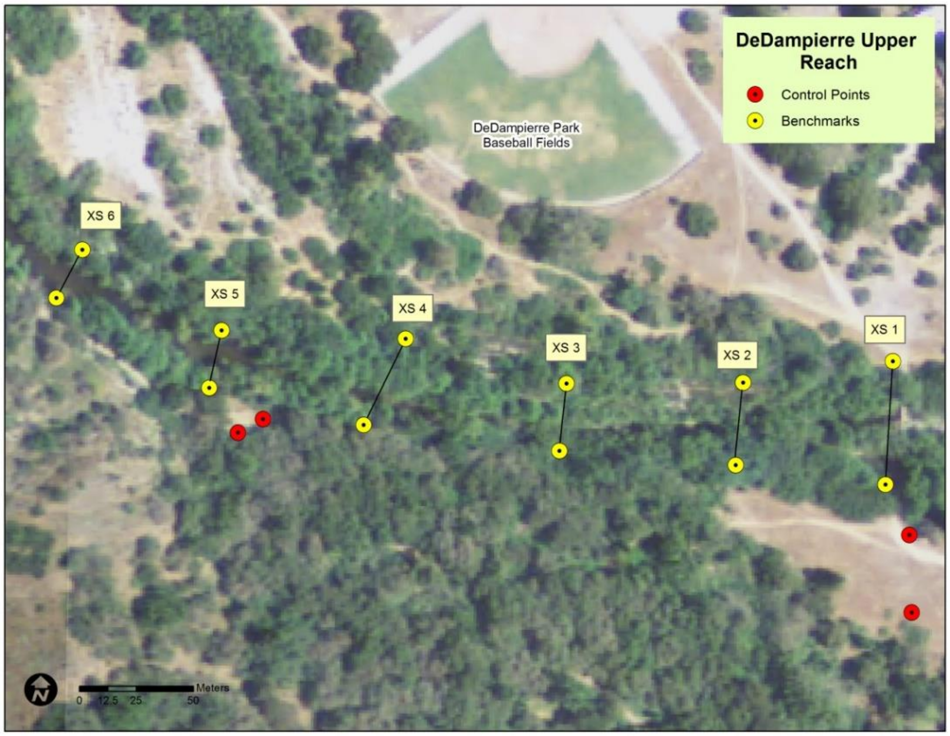


Figure 4. Location of georeferenced control points and cross sections within the DeDampierre Upper Reach.

Most of the geomorphic changes recorded at DDU cross sections were depositional (Appendix A). The most significant geomorphic change occurred at DDU3, where a 13.0 m wide, 0.7 m thick coarse pebble deposit was recorded on the right bank extending into the flood plain. At DDU1, 1.2 m of sediment filled the left side of the main channel, narrowing the channel by about 5 m. At DDU6, a 0.2 m thick deposit was recorded on the left side of the channel. Nearly the same thickness of material was removed from the right side of the channel.

The D50 of this reach decreased from 12.5 mm to 8.4 mm (Table 2). Histograms show that the percentage of sand (<2mm) increased at every cross section, with an overall increase in sand of nearly 30% (Appendix B; Fig. 5).

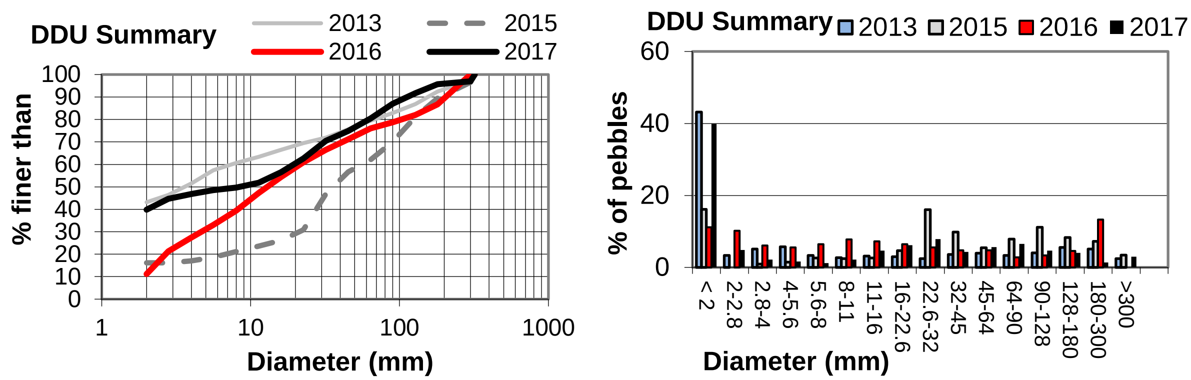


Figure 5. Summary pebble count distribution (DDU 1 – DDU 6) for the DeDampierre Upper reach displayed as cumulative percentiles (left) and individual bins (right) for 2013 to 2017.

Table 2. Summary grain size percentiles among cross-sectional transects within the DeDampierre Upper Reach from 2013 to 2017

Reach	Quantile	2013	2015	2016	2017
DDU	D5	2.0	2.0	2.0	2.0
	D16	2.0	2.0	2.4	2.0
	D50	3.6	39.7	12.5	8.4
	D84	92.9	152.4	147.7	77.1
	D95	201.9	220.2	225.7	170.2
	graphic mean	8.7	23.0	16.4	10.9

3.3 DeDampierre Lower Reach

The DeDampierre Lower reach is located directly downstream of the DeDampierre Upper Reach near the northern extent of DeDampierre Park (Fig. 3). The upstream portion of the reach is a wide and open channel with a pool and long run. The reach narrows downstream from cross section 3 and has a steeper gradient than Upper DeDampierre. We obtained cross sectional data for DDL1 and DDL2, and pebble counts at all cross section locations.

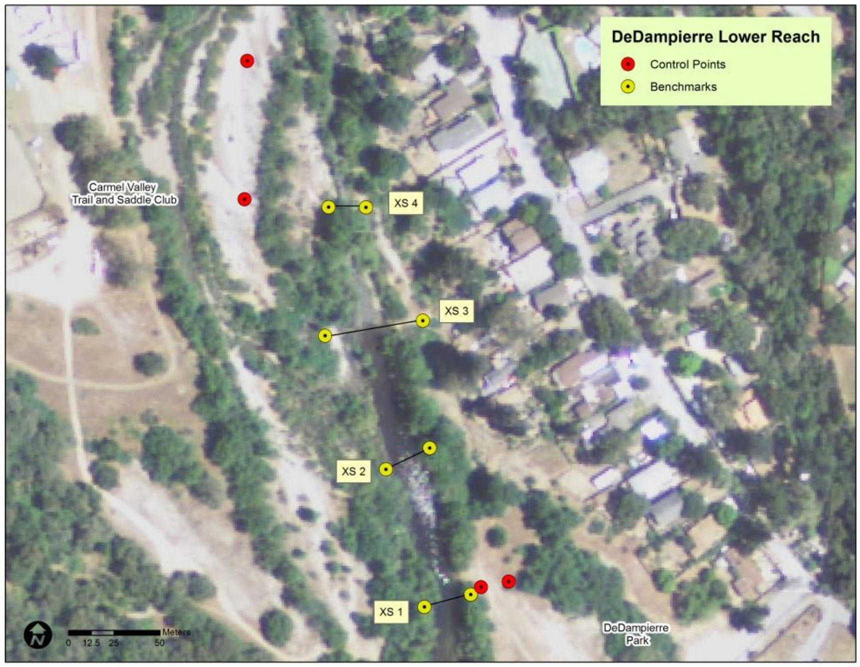


Figure 6. Location of georeferenced control points and cross sections within the DeDampierre Lower Reach.

Geomorphic changes occurred in DDL1 and DDL2 after the 2017 water year, in which the main channel at each cross section filled with up to 1.0 m of sand (Appendix A). In DDL2, the deposit extended onto the left bank. The tall feature on the right bank of DDL2 at distance 20-21.2 meters was a pile of woody debris.

The D50 for the Lower DeDampierre Reach shifted from 8.0 mm in 2016 to 5.1 mm in 2017 (Table 3). Although Figure 7 reflects relatively little change in the pebble size distribution of this reach from 2016, the individual cross section pebble counts in Appendix B show that there was significant fining of sediment in some sections, and coarsening in others depending on the channel style. The wide, low gradient sections (DDL1 and DDL2) showed an increase of sand and fine gravel (<2mm-8 mm) and were void of sediment greater than 16 mm (Appendix B). The narrow, steep gradient sections (DDL3 and DDL4) coarsened from 2016 due to the removal of existing sand and gravel (Appendix B).

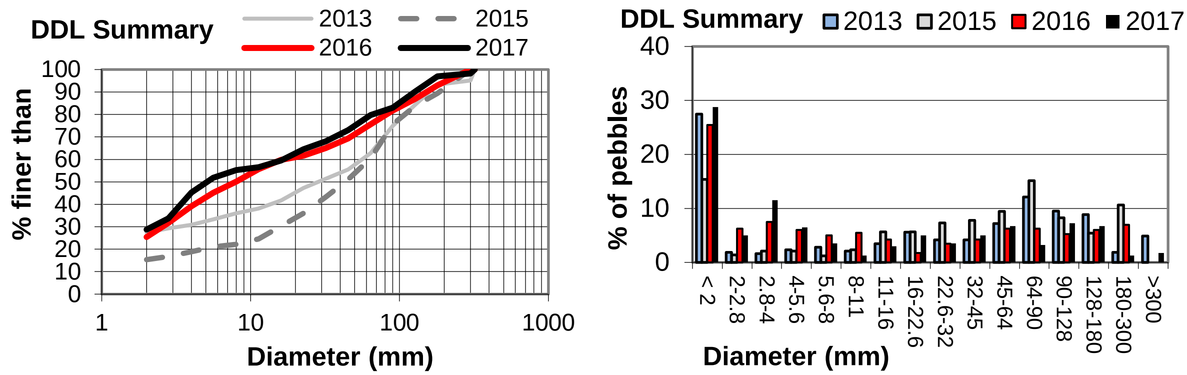


Figure 7. Summary pebble count distribution (DDL 1 – DDL 4) for the DeDampierre Lower reach displayed as cumulative percentiles (left) and individual bins (right) for 2013 to 2017.

Table 3. Summary grain size distribution among cross-sectional transects within the DeDampierre Lower Reach from 2013 to 2017.

Reach	Quantile	2013	2015	2016	2017
DDL	D5	2.0	2.0	2.0	2.0
	D16	2.0	2.5	2.0	2.0
	D50	28.1	43.7	8.0	5.1
	D84	127.3	132.2	104.4	94.6
	D95	200.9	219.2	197.4	163.1
	graphic mean	19.3	24.2	11.9	9.9

3.4 Berwick Reach

The Berwick reach was established in 2015 (Fig. 8). Cross sections were generally shorter in this reach (11-17m), as they included less of the flood plain than other reaches in this survey. We obtained cross sectional and pebble count data at all cross section locations.

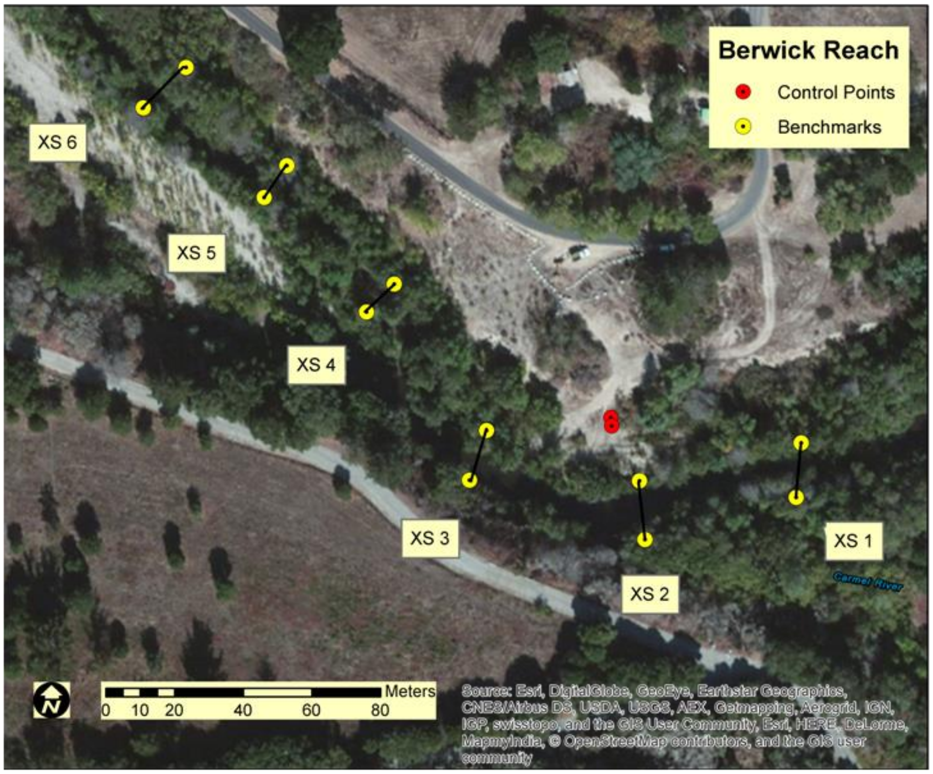


Figure 8. Location of georeferenced control points and cross sections within the Berwick Reach.

All the Berwick reaches showed some degree of aggradation in the main channel with deposition as thick as 0.6 m (Appendix A). Channel fill mostly consisted of sand and fine gravel (2mm-16mm), reflected in the D50 shift from 37.1 mm in 2016 to 4.4 mm in 2017 (Table 4; Appendix B). Figure 9 shows dominant substrate shift from cobble to sand and gravel. The tall feature in BW6 from distance 14-15 meters was a pile of woody debris (Appendix A).

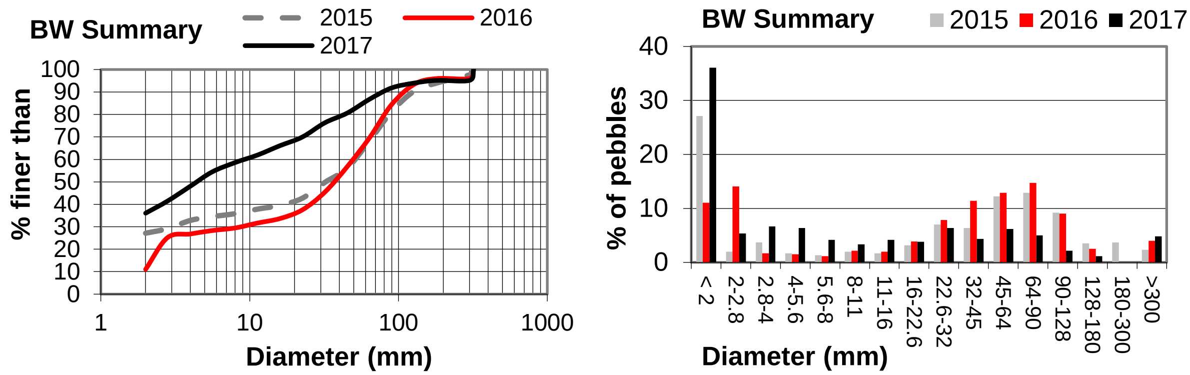


Figure 9. Summary pebble count distribution (BW 1 – BW 6) for the Berwick reach displayed as cumulative percentiles (left) and individual bins (right) for 2015 to 2017.

Table 4. Summary grain size distribution among cross sectional transects within the Berwick Reach from 2015 to 2017.

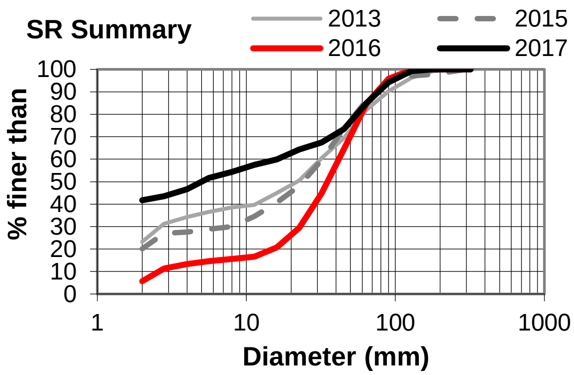
Reach	Quantile	2015	2016	2017
BW	D5	2.0	2.0	2.0
	D16	2.0	2.3	2.0
	D50	32.5	37.1	4.4
	D84	100.3	89.2	54.7
	D95	190.9	156.7	171.9
	graphic mean	18.7	19.7	7.9

3.5 Schulte Road Reach

The Schulte Road reach is located approximately 200 m upstream of the Schulte Bridge and extends above the 'Steinbeck Pool' which is located between cross sections 2 and 3 (Fig. 10). The reach spans a large northern bend in the river. We obtained cross sectional and pebble count data at every cross section location.

Figure 10. Locations of georeferenced control points and cross sections within the Schulte Road Reach.

The Schulte reach showed a variety of geomorphic changes from 2016 to 2017, both erosional and depositional (Appendix A). An overall fining of sediment along this reach in which the D50 shifted from 35.3mm to 6.0mm is mostly attributed to the increase in sand at sections upstream from the northern bend (SR1 and SR2) (Fig. 1; Table 5; Appendix B). SR1, the most upstream section, was filled with about 0.9 m of sediment along 8 meters of the active channel (Appendix A). Channel fill at SR1 mostly consisted of sand, which increased by 41% from 2016 (Appendix B). The channel at SR2 was widened by approximately 10 meters and filled with sand evident by an exposed sand bar at distance 8-12 meters in the active channel and the 80% increase in sand at this section (Appendix A; Appendix B). The most significant morphological change at SR3 was a 0.8 m deep scour along 5 meters on the left side of the main channel from distance 12.5-17.5 meters (Appendix A). The was an 25% increase in 64-128 mm cobbles at SR3 (Appendix B). Material was also scoured from SR4, where the channel widened by 2.0 m and deepened by 0.3 m (Appendix A).



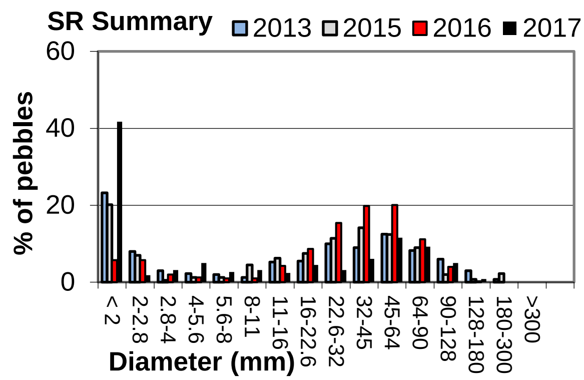


Figure 11. Summary pebble count distribution (SR 1 – SR 4) for the Schulte Road reach displayed as cumulative percentiles (left) and individual bins (right) for 2013 to 2017.

Table 5. Summary grain size distribution among cross-sectional transects within the Schulte Road Reach from 2013 to 2017.

Reach	Quantile	2013	2015	2016	2017
SR	D5	2.0	2.0	2.0	2.0
	D16	2.0	2.0	8.9	2.0
	D50	21.9	24.0	35.3	6.0
	D84	69.7	60.5	63.4	64.6
	D95	119.2	89.9	88.0	97.7
	graphic mean	14.5	14.3	27.1	9.2

3.6 San Carlos Reach

The San Carlos Reach is located downstream of the Rancho San Carlos Bridge (Fig. 12). We obtained cross sectional data from SC1, SC2, SC4, SC5, SC6 and pebble count data at all locations.

Figure 12. Locations of georeferenced control points and cross sections within the San Carlos Reach.

The most significant geomorphic change in the study area occurred at SC2, where 20 meters of the 5 meter tall left terrace eroded away during high 2017 flows (Appendix A). A similar erosional pattern was found at SC4, but at a much smaller scale. SC1 showed slight degradation in the main channel, with a 0.5 m thick deposit on the edge of the floodplain. The channel deepened in SC5 by about 0.3 m, and was raised 0.5 meters just downstream at SC6 (Appendix A). The overall D50 at San Carlos decreased from 19.1 to

6.3 after 2017 flows (Table 6). The fining of substrate is due to the increase in sand and fine-coarse gravels found at most of the cross sections (Fig. 13; Appendix B).

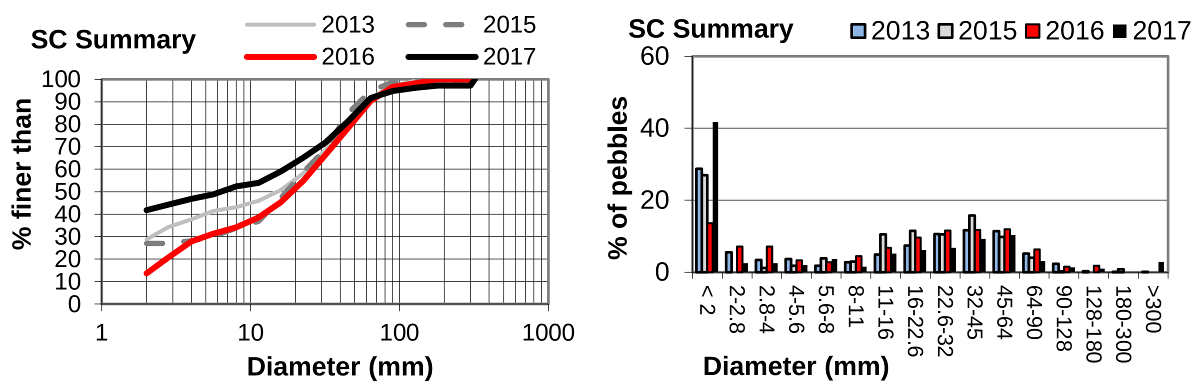


Figure 13. Summary pebble count distribution (SC 1 – SC 6) for the San Carlos reach displayed as cumulative percentiles (left) and individual bins (right) for 2013 to 2017.

Table 6. Summary grain size distribution among cross-sectional transects within the San Carlos Reach from 2013 to 2017.

Reach	Quantile	2013	2015	2016	2017
SC	D5	2.0	2.0	2.0	2.0
	D16	2.0	2.0	2.3	2.0
	D50	13.5	17.5	19.1	6.3
	D84	49.9	44.1	53.4	49.4
	D95	78.9	64.9	82.4	93.9
	graphic mean	11.0	11.6	13.2	8.6

3.7 Crossroads Reach

Crossroads was the lowermost monitored reach, located adjacent to the Crossroads shopping center near the mouth of Carmel Valley (Fig. 14). We obtained cross sectional data from CR1 and CR6 and pebble counts at all cross section locations.

Figure 14. Locations of georeferenced control points and cross sections within the Crossroads Reach.

Geomorphic changes at the Crossroads were mostly erosional. Sediment was removed from the main channel at both CR1 and CR6 (Appendix A). At CR1, over 7 meters of the channel deepened by 0.5-0.9 m. At CR6, ~3.5 meters of the left bank was removed, resulting in a wider channel (Appendix A).

The D50 shifted from 22.5mm to 7.5mm (Table 7). Most of the reach contained particles ranging from sand to coarse gravel, with every section showing an increase in sand from 2016, when coarse gravel and cobbles were the dominant substrate (Fig. 15; Appendix B).

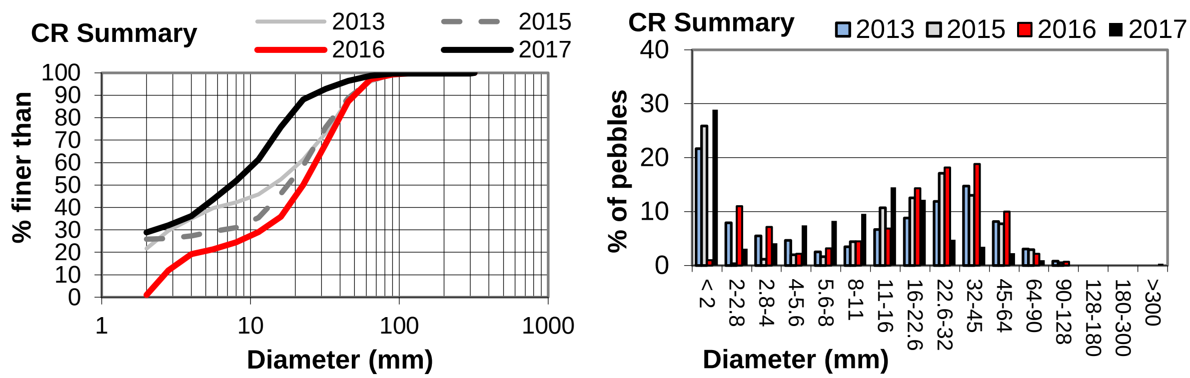


Figure 15. Summary pebble count distribution (CR 1 – CR 6) for the Crossroads reach displayed as cumulative percentiles (left) and individual bins (right) for 2013 to 2017.

Table 7. Summary grain size distribution among cross-sectional transects within the Crossroads Reach from 2013 to 2017. This reach is dominated by sand. It is the furthest downstream and has the smallest average grain size.

Reach	Quantile	2013	2015	2016	2017
CR	D5	2.0	2.0	2.5	2
	D16	2.0	2.0	3.5	2
	D50	15.0	17.9	22.5	7.5
	D84	41.9	39.9	42.7	20.3
	D95	61.5	59.9	59.5	39.5
	graphic mean	10.8	11.3	15.0	6.7

4 Discussion

This report is part of a multi-year effort to describe sediment transport and geomorphic changes in the Carmel River following the removal of the San Clemente dam in 2015. The 2017 survey found extreme changes in both channel morphology and substrate size below San Clemente Dam site when compared to above the dam site, and when compared to insignificant changes documented at all sites before dam removal. Every cross section in the study area showed some degree geomorphic change from 2016, with several significant changes that completely transformed the shape of the channel. Below the former San Clemente dam, in the upper reaches (DeDampierre Upper through Berwick), geomorphic changes were most often depositional with either fill in the main channel or aggradation on the banks and flood plain. The lower reaches (Schulte Road through Crossroads), on the other hand, mostly showed erosion from previous years, with the most significant erosion recorded downstream from the San Carlos Bridge at SC2 (Appendix A).

In general, sand and small gravel blanketed the Carmel channel below the dam site following the high runoff of 2017, and a rarely seen delta sand bar formed in the ocean at the Carmel River mouth. The grain size data can be interpreted in a before-after-control-impact (BACI) framework (fig. 16). The median grain size fell significantly in all sites located below the dam site especially near the dam, where 96 years of gravel starvation had had left a boulder substrate (Fig. 16). The 2017 fining is related to the dam removal, since the control sites upstream of the dam did not fine.

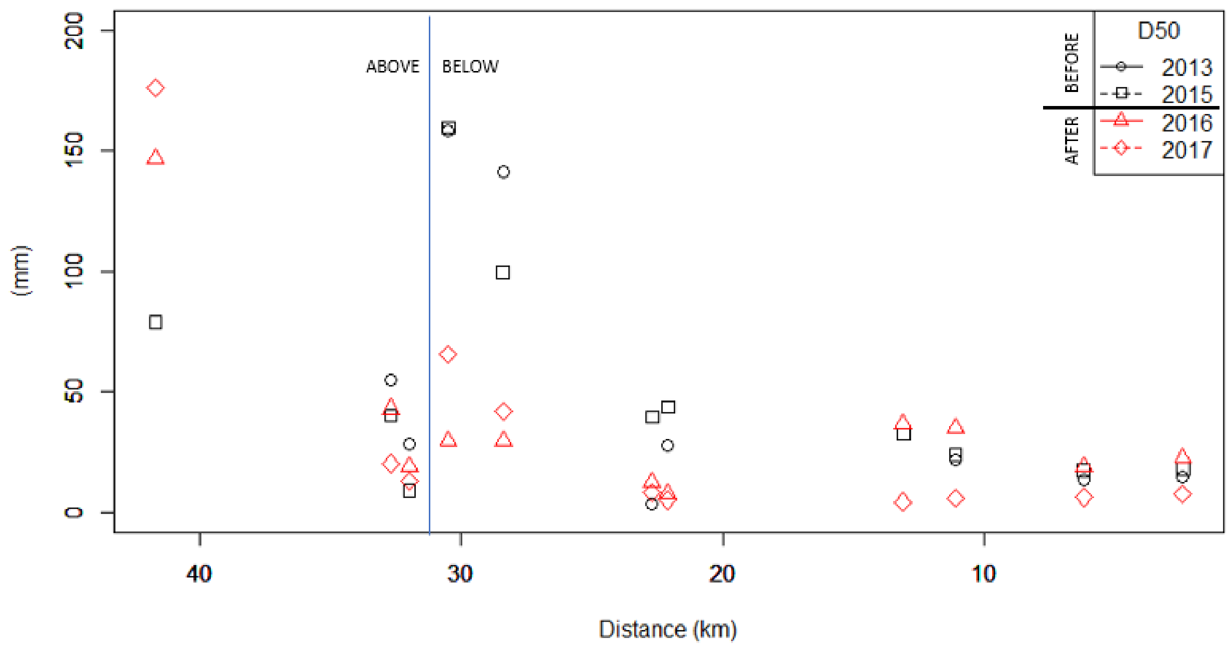


Figure 16. Median grain size (D50) of gran size as a function of year and distance upstream of the Carmel River mouth. Data are divided into before and after periods and above and below dam sites. Data from this study and East et al. (2017a)

Anecdotal accounts indicate that the tributaries were not the main source of fine sand this year. Rather, the sand was likely eroded from the unconsolidated reservoir sediment located upstream of the dam site. Three lines of evidence support that interpretation.

1) CSUMB (2016) reported that the volume of sand deposited downstream from the dam site in the first year after dam removal was the same order of magnitude as the volume calculated to have been eroded from the reservoir site.
2) Serial cross sections in the reservoir sediments show that extreme erosion continued into water-year 2017 (Fig. 17 and Harrison et al. 2017).

3) Analysis of suspended load hysteresis loops from a rated turbidimeter located downstream of the dam (East et al. 2017b) point to very local sediment sources (such as channel erosion in reservoir sediments) rather than fire impacts (upper watershed sources). Fire impacts were not a significant influence in the increased fine bedload found in 2017.

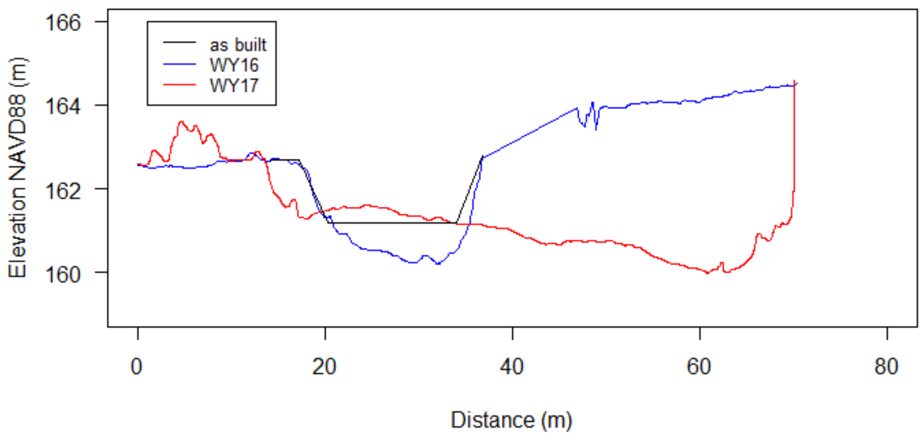


Figure 17. Cross-sectional change in the Carmel River channel between 2015 (as built) and 2017 in reservoir sediment located upstream from the former dam site.

5 References

Boughton DA, East A, Hampston L, Kiernan J, Leiker, S, Mantua N, Nicol C, Smith D, Urquhart K, Williams T, Harrison L. 2016. Removing a dam and re-routing a river: Will expected benefits for Steelhead materalize in Carmel River, California? NOAA Technical Memorandum, NOAA-TM-NMFS-SWFSC-553. US Department of Commerce. Southwest Fisheries Science Center, Santa Cruz, CA. 89 pp.

Bunte K., Abt S. 2001. Sampling Frame for Improving Pebble Count Accuracy in Coarse Gravel-bed Streams. Journal of the American Water Resources Association. Vol. 37, No. 4:1001-1014.

[CCOWS] Central Coast Watershed Studies. 2012. San Clemente Dam Removal and Carmel River Reroute Monitoring Plan: Carmel, CA. The Watershed Institute, Seaside, CA. Available from: http://ccows.csumb.edu/pubs/proj_pubs/2012/ENVS660_Carmel_Monitoring/CSUMB_ENVS660_ClassReport_DamRemovalMonitoring_121024.pdf

Chow K., Luna L., Delforge A. and Smith D. 2016. 2015 Pre-San Clemente Dam Removal Morphological Monitoring of the Carmel River Channel in Monterey County, California. The Watershed Institute, California State University Monterey Bay, Publication No. WI-2016-01, 50 pp.

[CSUMB] Class ENVS 660: Chow K, Fields J, Flores S, Hart K, Kleven A, Luna L, MacCarter L, and Smith D. 2016. San Clemente Dam Removal Sediment Impacts: Year One Report. Watershed Institute, California State University Monterey Bay, Publication No. WI-2016-10, 38 pp.

East, A.E., Harrison, L.R., Smith, D.P., Bond, R., Logan, J.B., Nicol, C., and Chow, K. 2017a, 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://doi.org/10.5066/F74M93HF

East, A., Harrison, L., Smith, D., Bond, R., Logan., J., Nicol, C., Williams, T., and Boughton, D. 2017b. Early geomorphic and fish-habitat response to a unique large-dam removal and subsequent major floods: Carmel River, California. GSA Annual Meeting, Seattle.

Harrelson C. Rawlins C. Potyondy J. 1994. Stream channel reference sites: an illustrated guide to field technique. Gem Tech. Per. RM-245. Fort Collins, CA: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, 61 pp.

Harrison, L., East, A., Smith, D., Bond, R., Logan., J., Nicol, C., Williams, T., Boughton, D., and Chow, C. 2017. Geomorphic and habitat response to a large-dam removal in a Mediterranean river. AGU Fall Meeting, New Orleans.

Leiker S. Delforge A. Geisler E. Smith D. 2014. Pre-San Clemente Dam Removal Morphological Monitoring of the Carmel River Channel in Monterey County, California. The Watershed Institute, California State University Monterey Bay, Publication No. WI-2014-07, 32 pp.

Mussetter Engineering, Inc., 2005. Hydraulic and Sediment-transport Analysis of the Carmel River Bypass Option, California. Prepared for California American Water. April 25, 2005. 74pp.

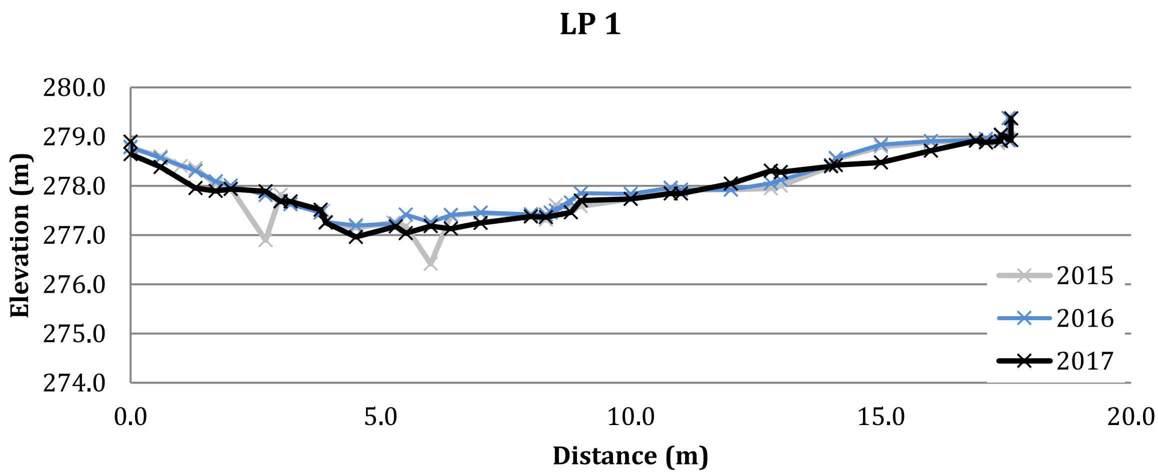
[NOAA] National Oceanic and Atmospheric Administration. Fisheries Staff and Collaborators. Nov 2012. DRAFT Conceptual Model of the Carmel River System. SW Fisheries Science Center, Santa Cruz, CA.

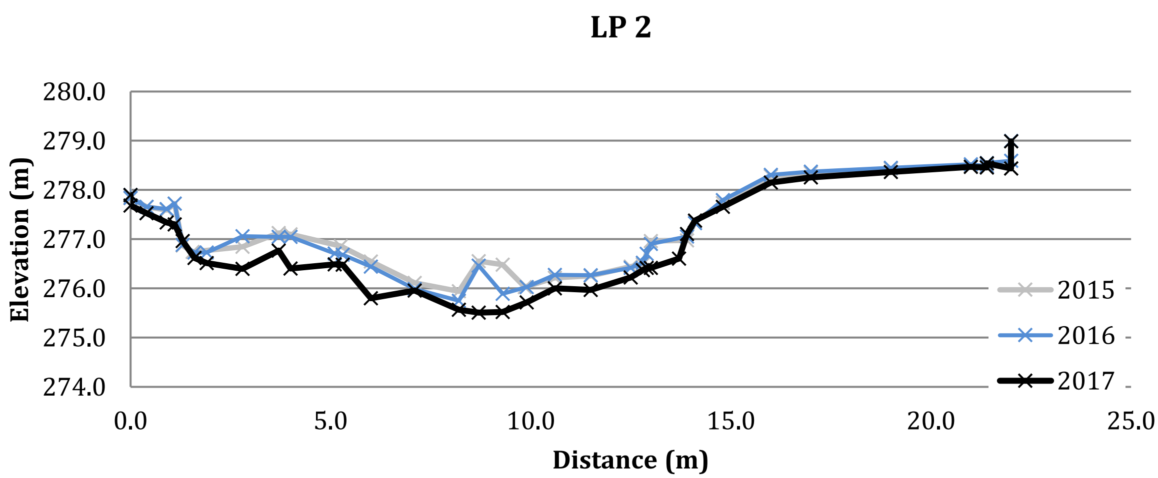
R Core Team (2017). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

[SCDRP] San Clemente Dam Removal Project. 2014. Project Overview. Available from: http://www.sanclementedamremoval.org/

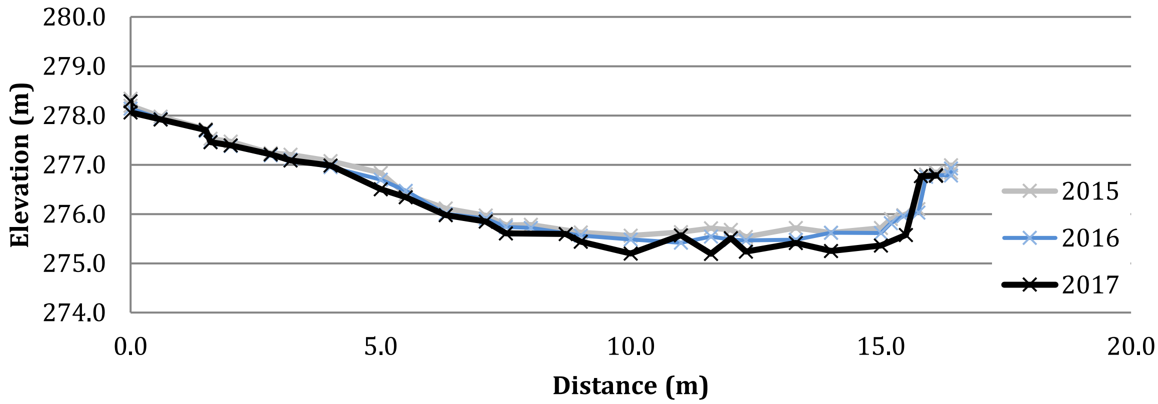
6 Appendix A: Cross Sections

Channel geometry for each cross section surveyed within each reach. Cross sections are denoted by their reach abbreviation (LP, DDU, DDL, BW, SR, SC, and CR) and transect number descending from upstream to downstream (1 to 4 or 6).

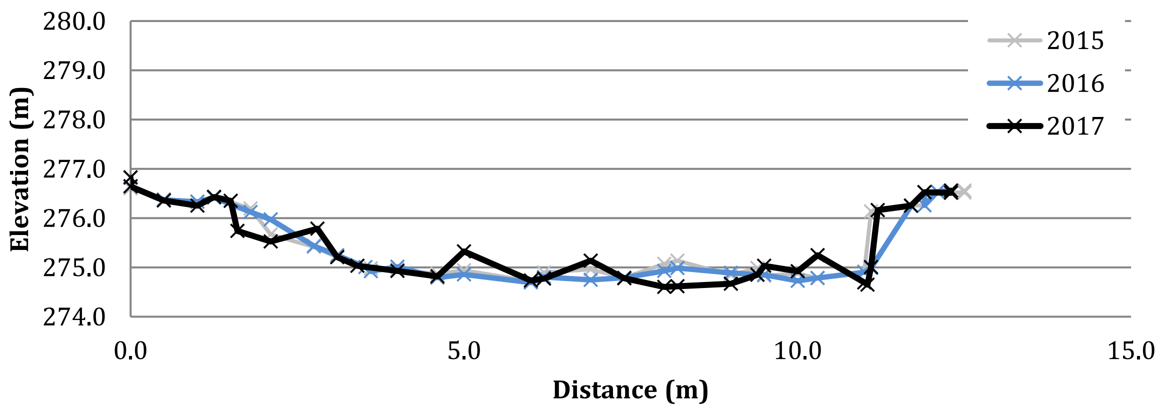




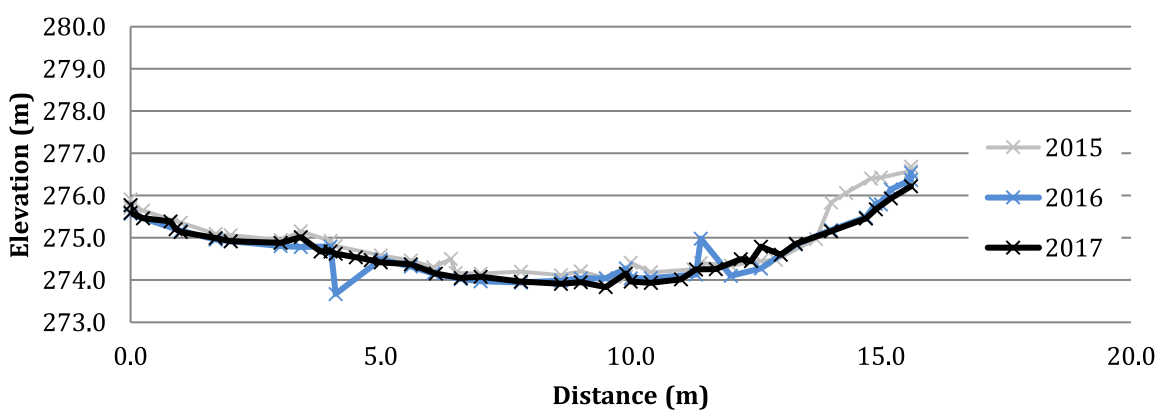
LP 3

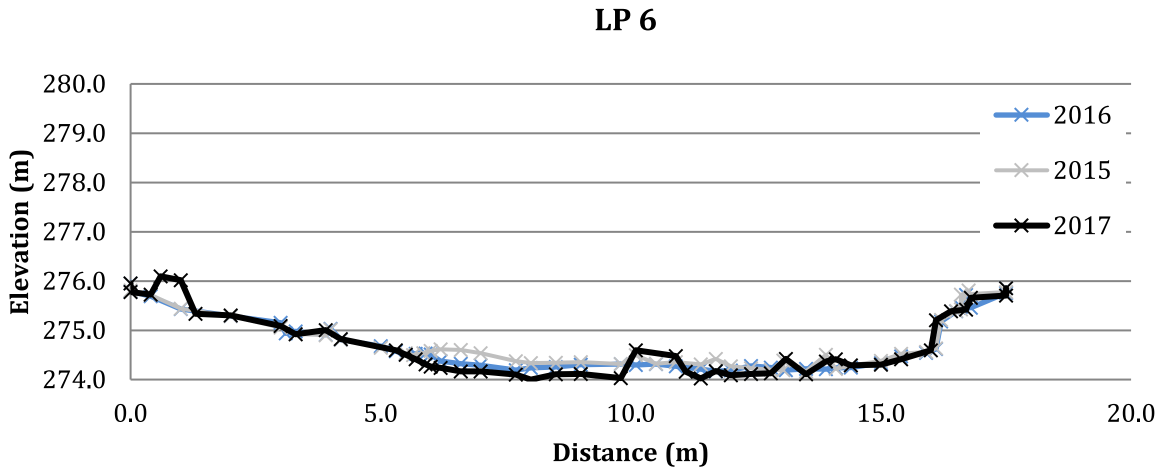

280.0
279.0
278.0
277.0
276.0
275.0
274.0
Elevation (m)
0.0
5.0
10.0
15.0
20.0
Distance (m)
2015
2016
2017

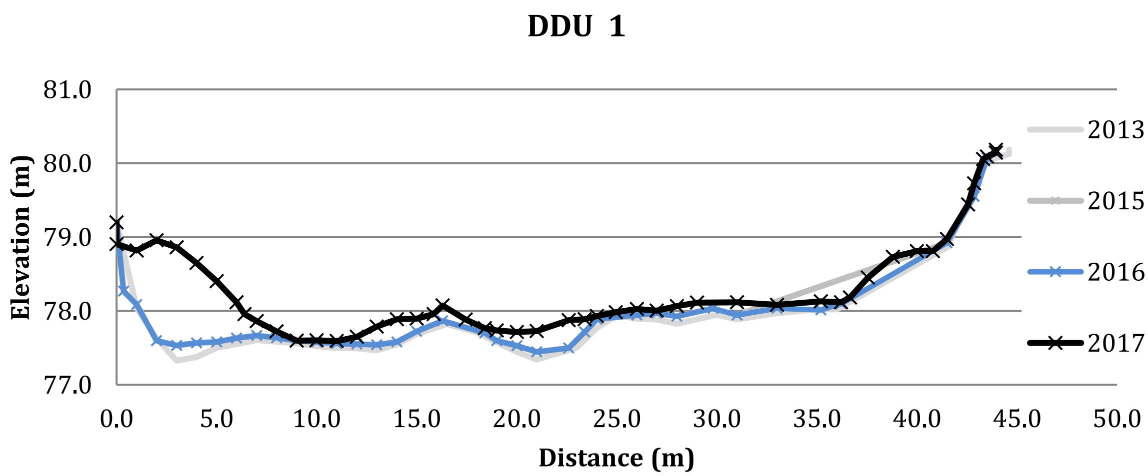
LP 4

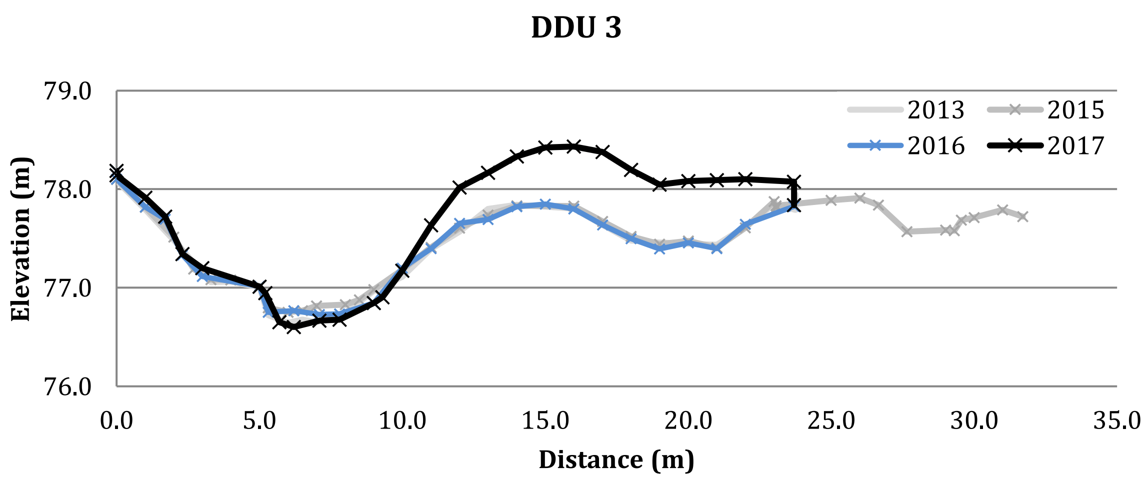

280.0
279.0
278.0
277.0
276.0
275.0
274.0
Elevation (m)
0.0
5.0
10.0
15.0
Distance (m)
2015
2016
2017

LP 5

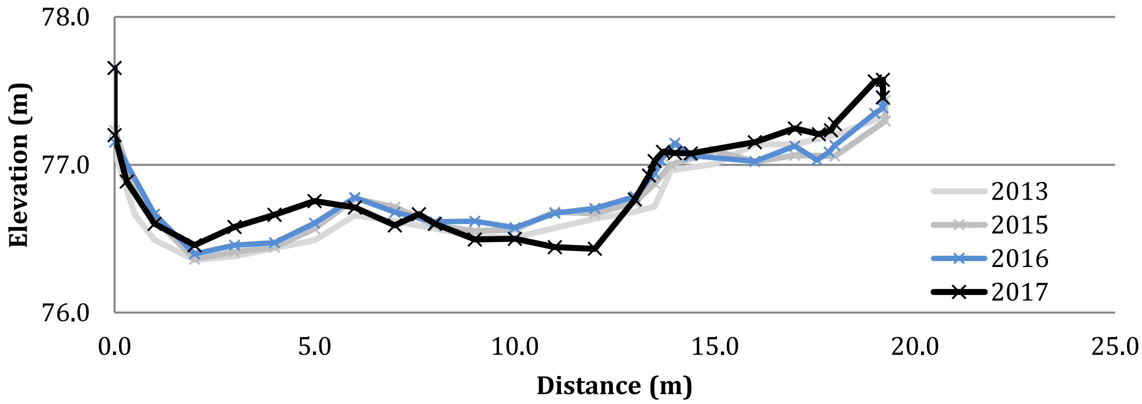

280.0
279.0
278.0
277.0
276.0
275.0
274.0
273.0
Elevation (m)
0.0
5.0
10.0
15.0
20.0
Distance (m)
2015
2016
2017


LP 6
280.0
279.0
278.0
277.0
276.0
275.0
274.0
Elevation (m)
0.0
5.0
10.0
15.0
20.0
Distance (m)
2016
2015
2017

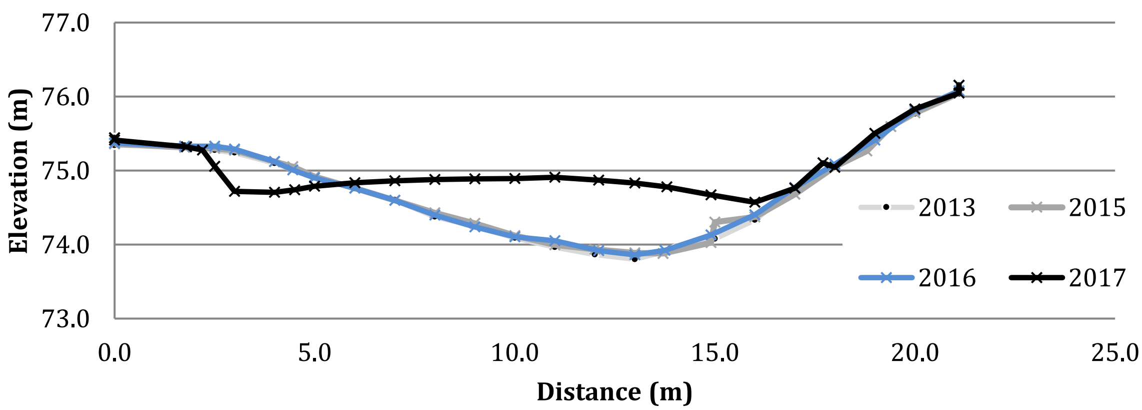

DDU 1
81.0
80.0
79.0
78.0
77.0
Elevation (m)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
Distance (m)
2013
2015
2016
2017


DDU 3
79.0
78.0
77.0
76.0
Elevation (m)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
Distance (m)
2013
2015
2016
2017

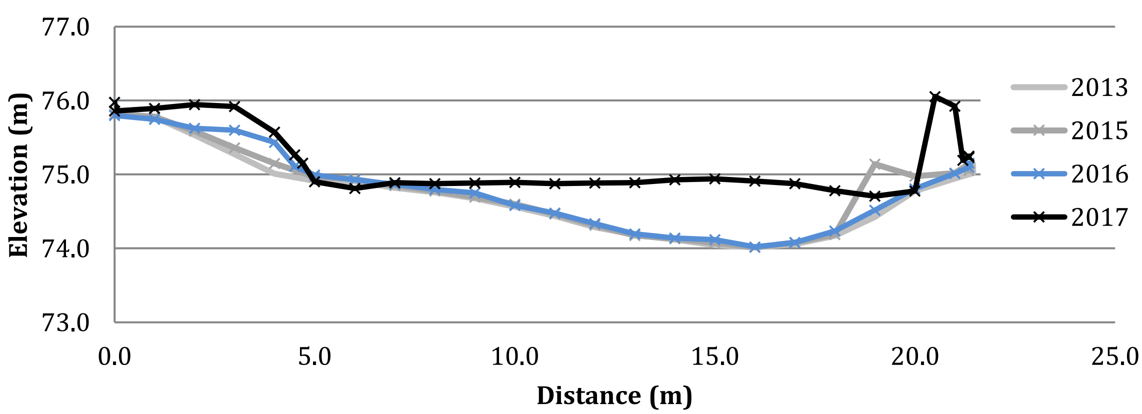
DDU 6

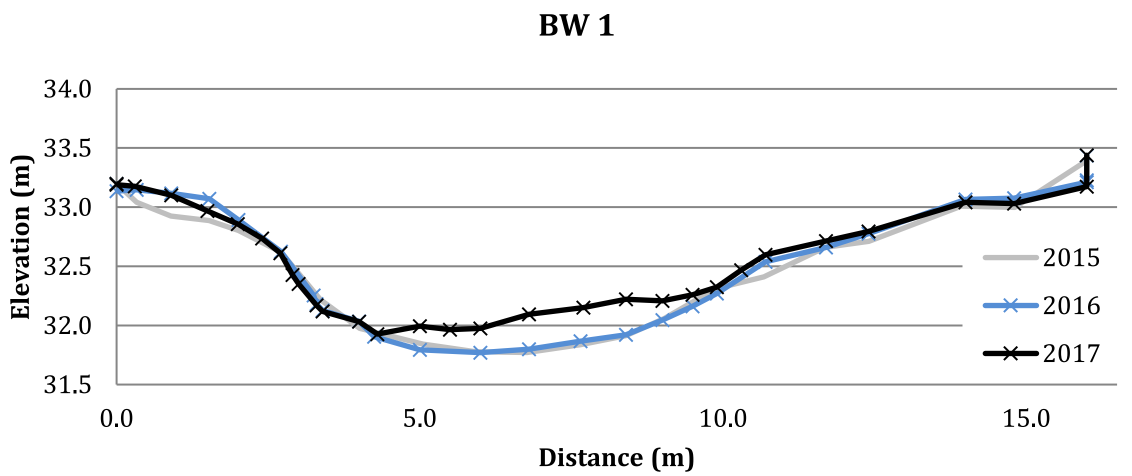


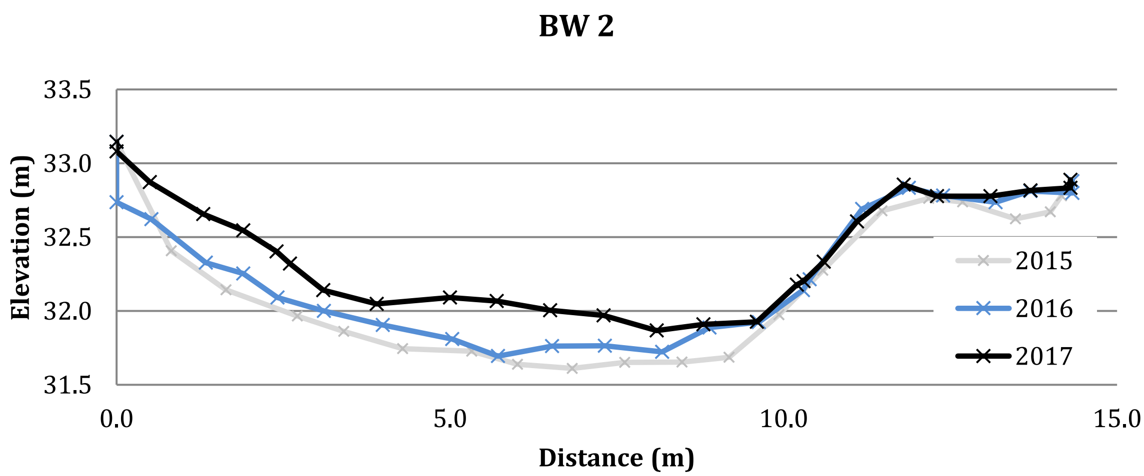
DDL 1

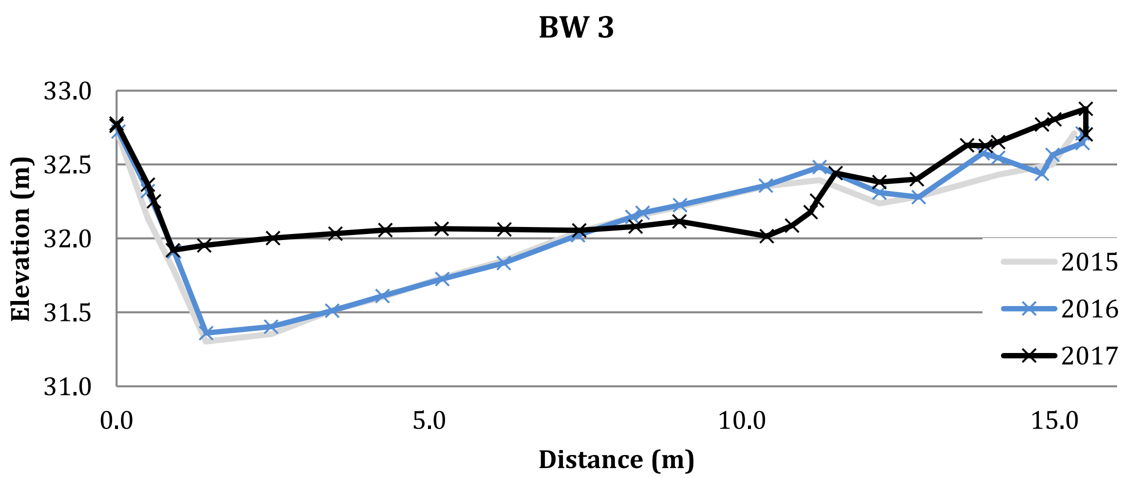


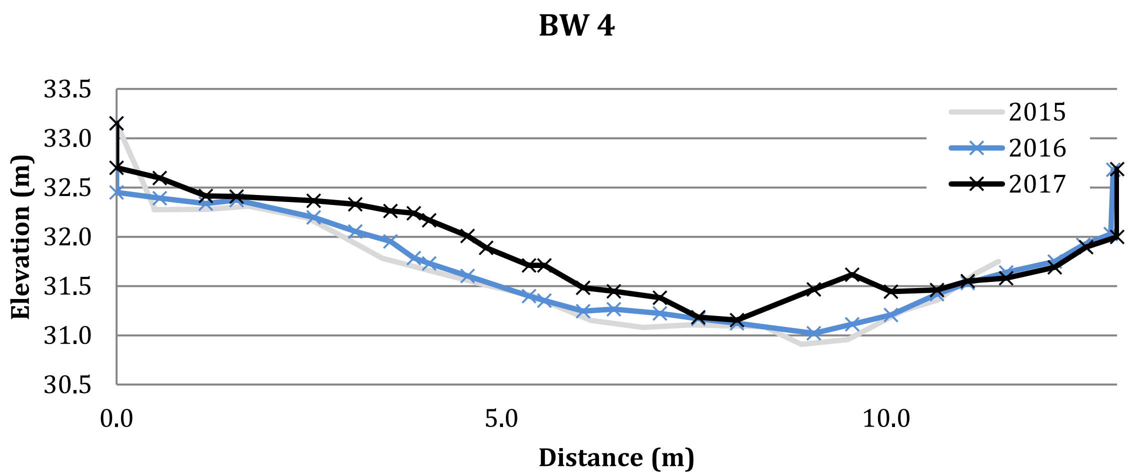
DDL 2

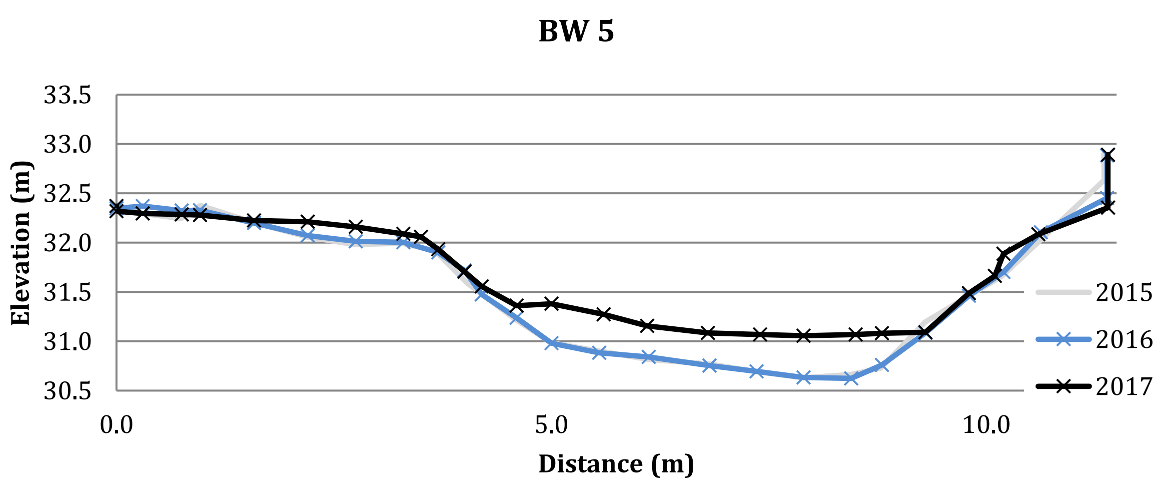


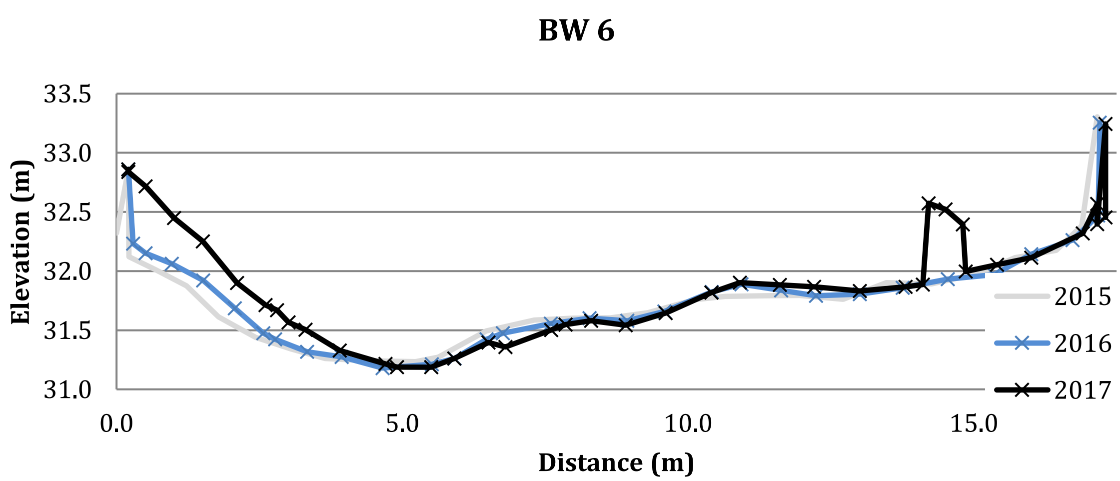

BW 1
34.0
33.5
33.0
32.5
32.0
31.5
Elevation (m)
0.0
5.0
10.0
15.0
Distance (m)
2015
2016
2017

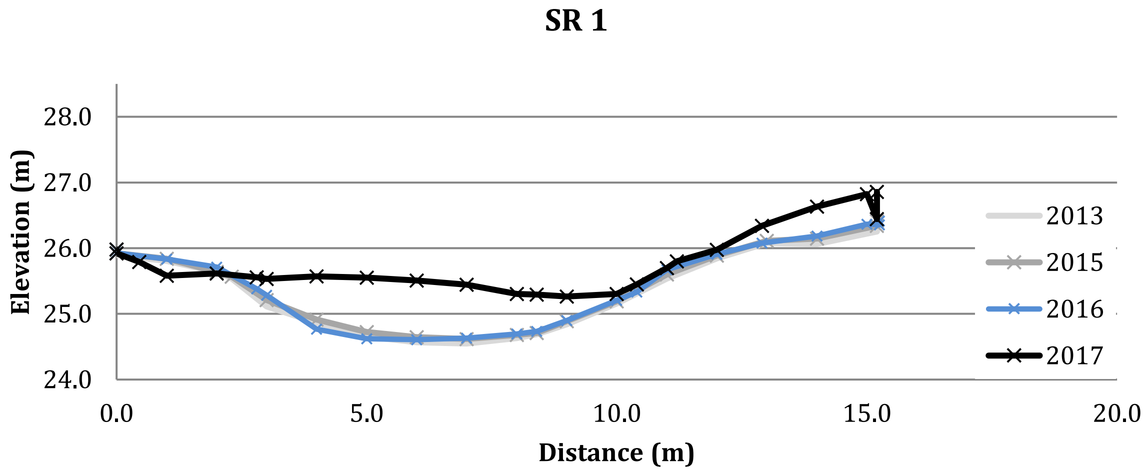

BW 2
33.5
33.0
32.5
32.0
31.5
Elevation (m)
0.0
5.0
10.0
15.0
Distance (m)
2015
2016
2017


BW 3
33.0
32.5
32.0
31.5
31.0
Elevation (m)
0.0
5.0
10.0
15.0
Distance (m)
2015
2016
2017

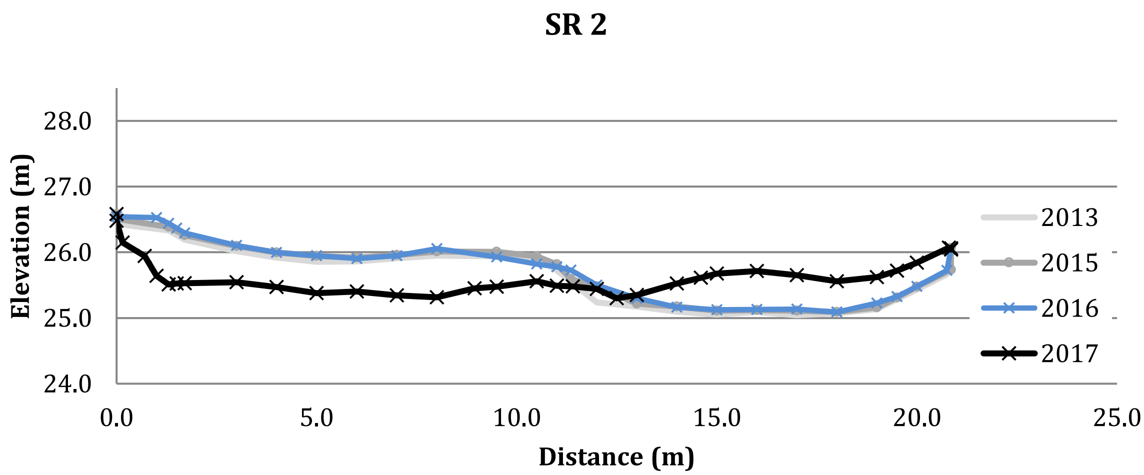

BW 4
33.5
33.0
32.5
32.0
31.5
31.0
30.5
Elevation (m)
0.0
5.0
10.0
Distance (m)
2015
2016
2017


BW 5
33.5
33.0
32.5
32.0
31.5
31.0
30.5
Elevation (m)
0.0
5.0
10.0
Distance (m)
2015
2016
2017

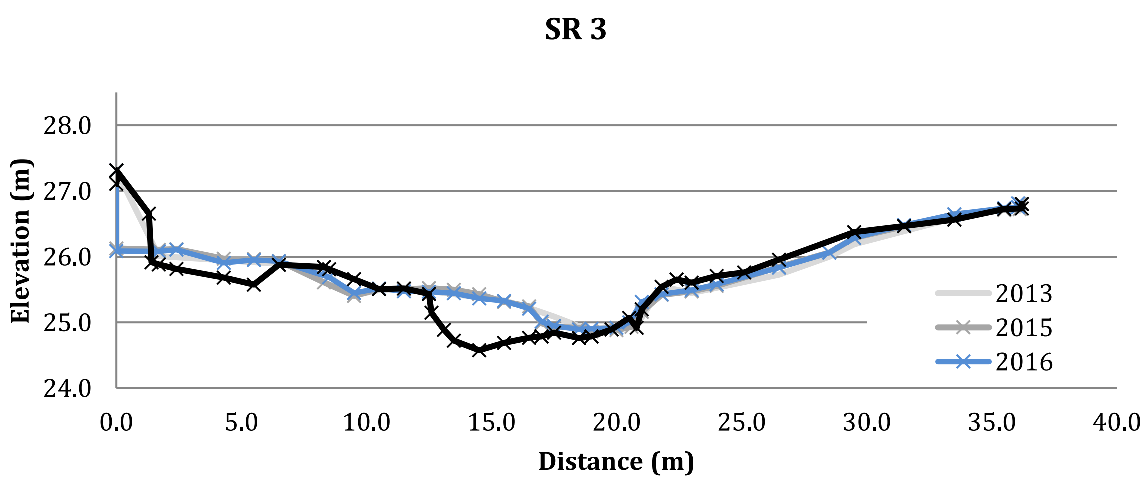

BW 6
33.5
33.0
32.5
32.0
31.5
31.0
Elevation (m)
0.0
5.0
10.0
15.0
Distance (m)
2015
2016
2017



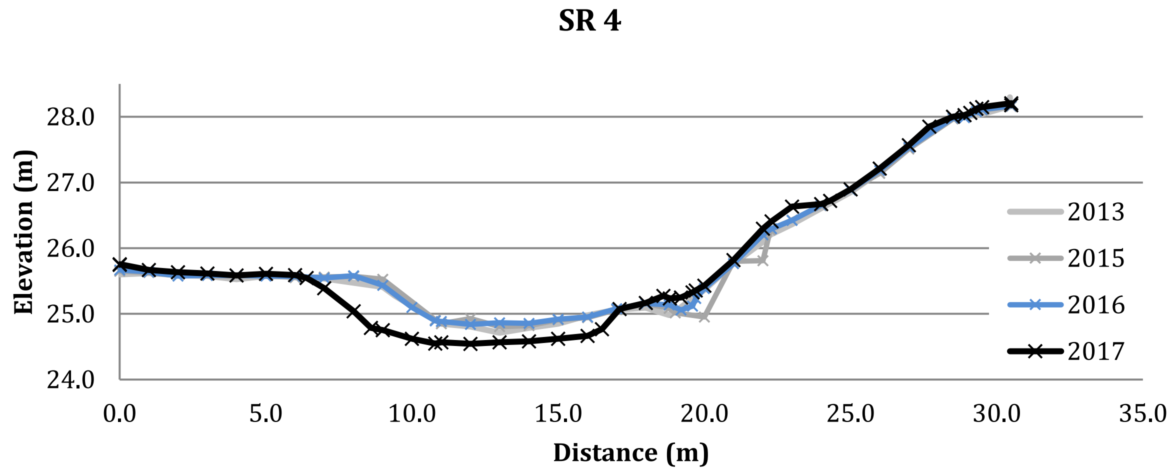
SR 1
28.0
27.0
26.0
25.0
24.0
Elevation (m)
0.0
5.0
10.0
15.0
20.0
Distance (m)
2013
2015
2016
2017

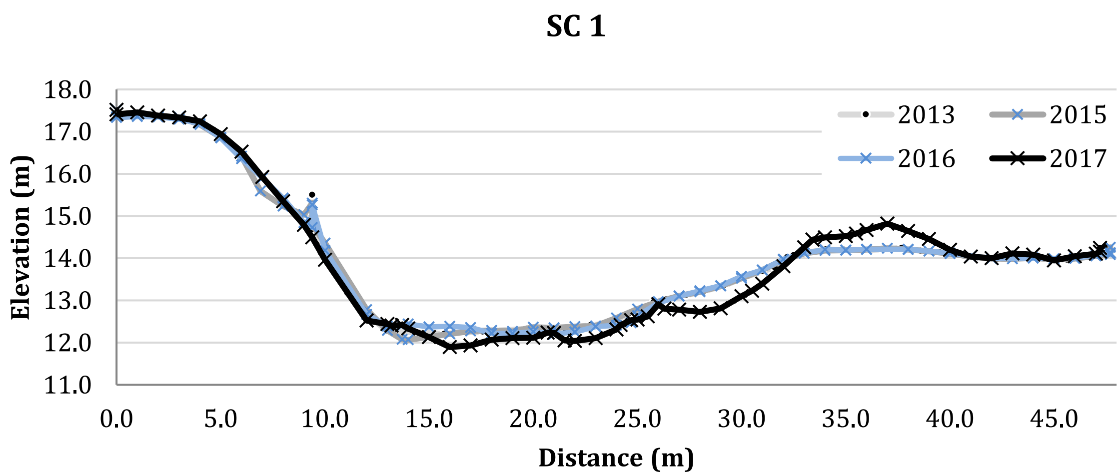


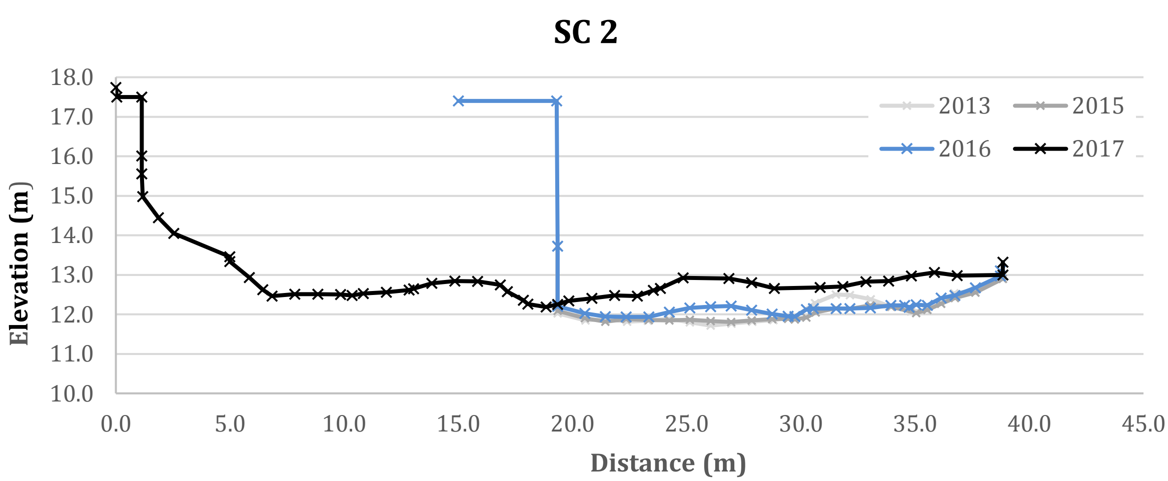
SR 2
28.0
27.0
26.0
25.0
24.0
Elevation (m)
0.0
5.0
10.0
15.0
20.0
25.0
Distance (m)
2013
2015
2016
2017

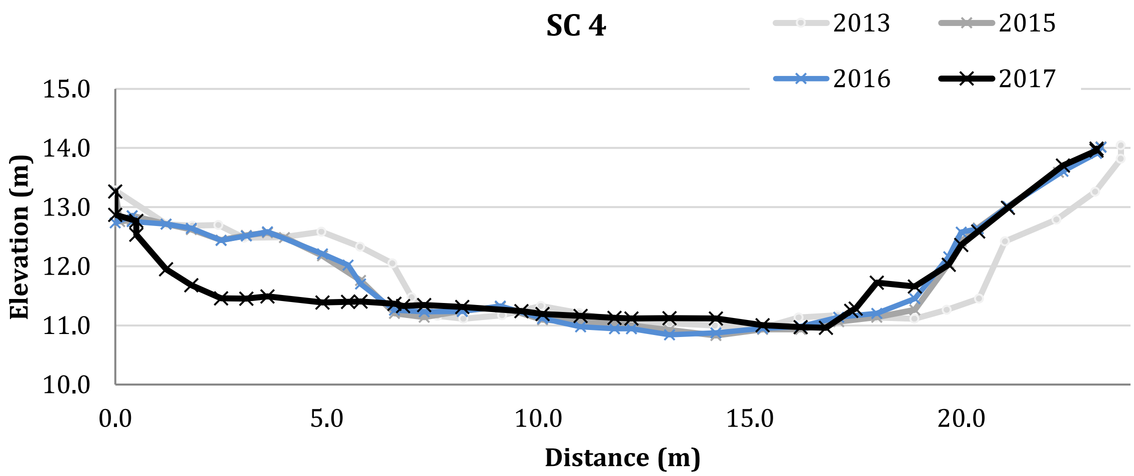


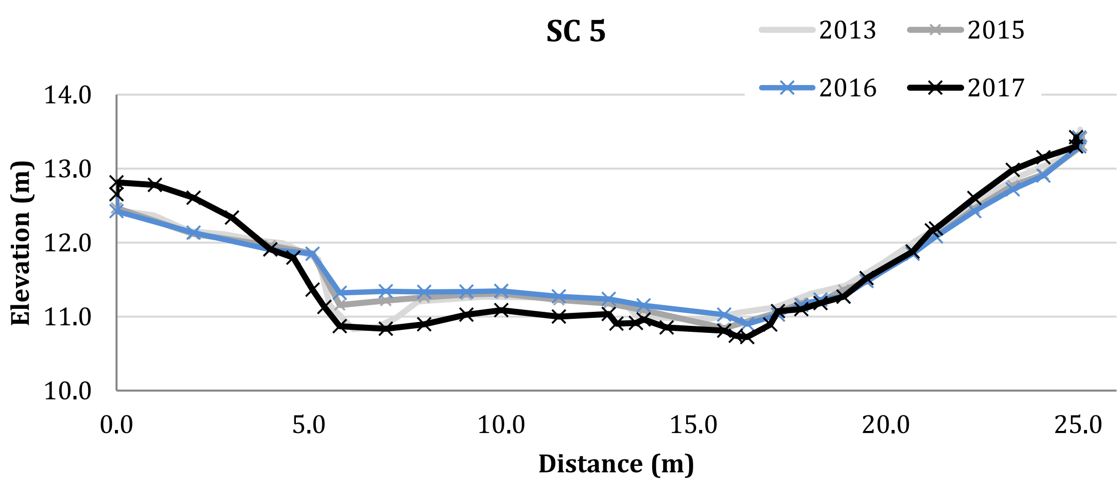
SR 3
28.0
27.0
26.0
25.0
24.0
Elevation (m)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
Distance (m)
2013
2015
2016

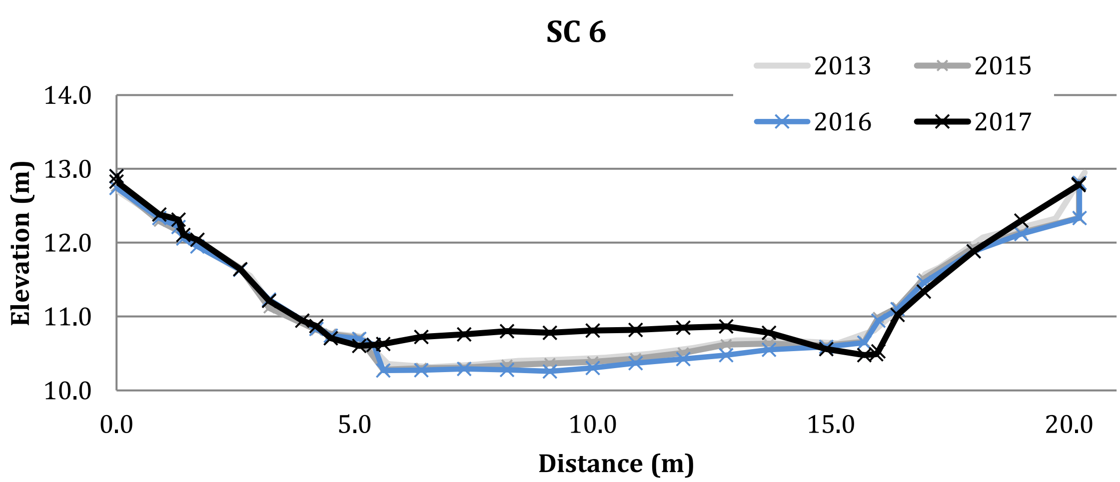

SR 4
Elevation (m)
28.0
27.0
26.0
25.0
24.0
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
Distance (m)
2013
2015
2016
2017

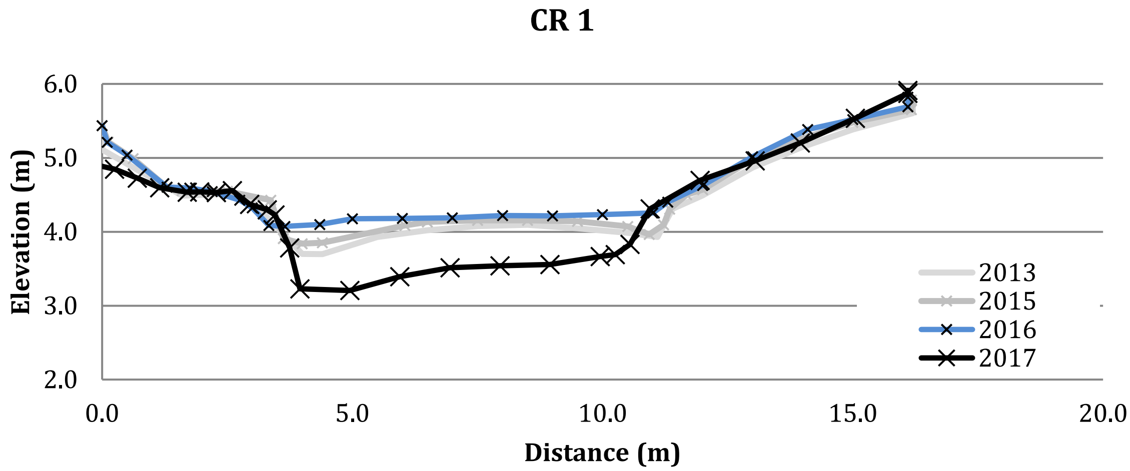

SC 1
Elevation (m)
18.0
17.0
16.0
15.0
14.0
13.0
12.0
11.0
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
Distance (m)
2013
2015
2016
2017

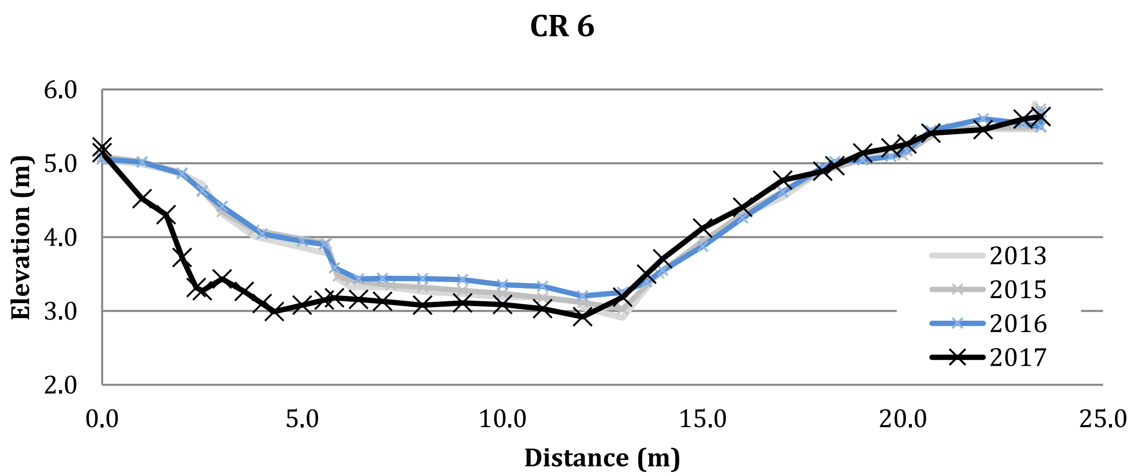

SC 2
Elevation (m)
18.0
17.0
16.0
15.0
14.0
13.0
12.0
11.0
10.0
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
Distance (m)
2013
2015
2016
2017


SC 4
2013
2015
2016
2017
Elevation (m)
15.0
14.0
13.0
12.0
11.0
10.0
0.0
5.0
10.0
15.0
20.0
Distance (m)


SC 5
2013
2015
2016
2017
Elevation (m)
14.0
13.0
12.0
11.0
10.0
0.0
5.0
10.0
15.0
20.0
25.0
Distance (m)

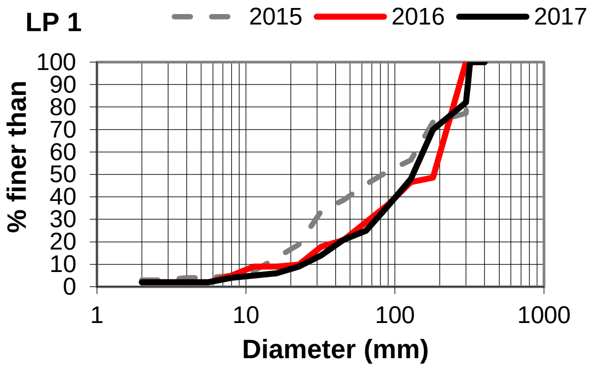

SC 6
2013
2015
2016
2017
Elevation (m)
14.0
13.0
12.0
11.0
10.0
0.0
5.0
10.0
15.0
20.0
Distance (m)

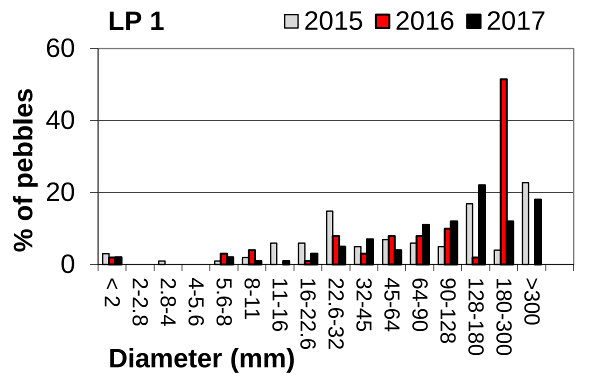

CR 1
6.0
5.0
4.0
3.0
2.0
Elevation (m)
0.0
5.0
10.0
15.0
20.0
Distance (m)
2013
2015
2016
2017

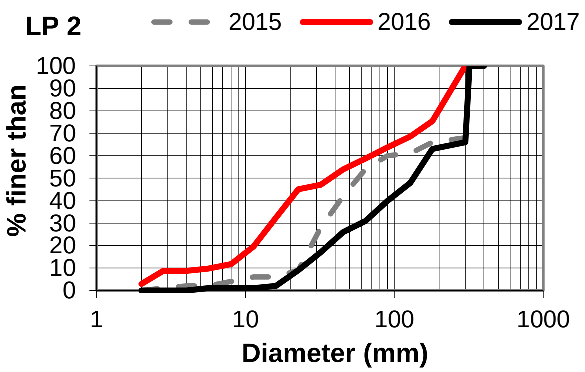

CR 6
6.0
5.0
4.0
3.0
2.0
Elevation (m)
0.0
5.0
10.0
15.0
20.0
25.0
Distance (m)
2013
2015
2016
2017

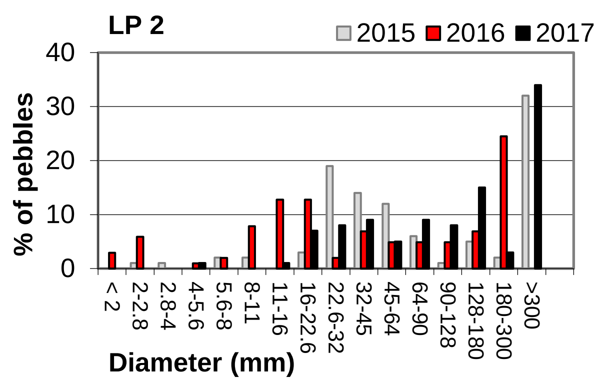
7 Appendix B: Pebble Count Plots

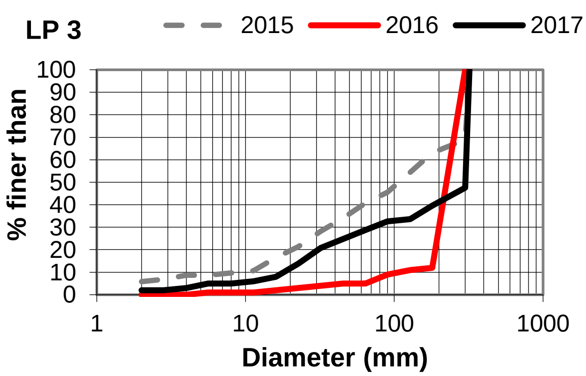
Channel pebble counts for each cross section within each reach. Reaches are denoted by their reach abbreviation (LP, DDU, DDL, BW, SR, SC, and CR) and transect number descending from upstream to downstream (1 to 4 or 6).

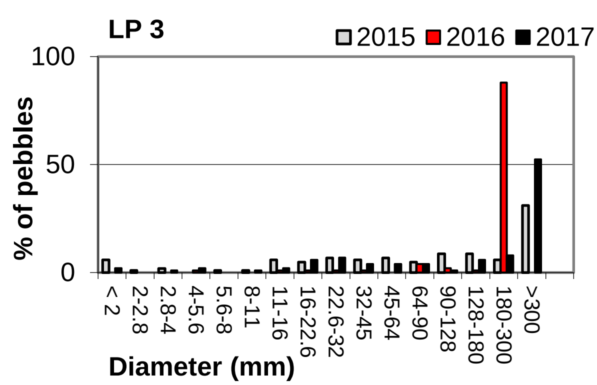


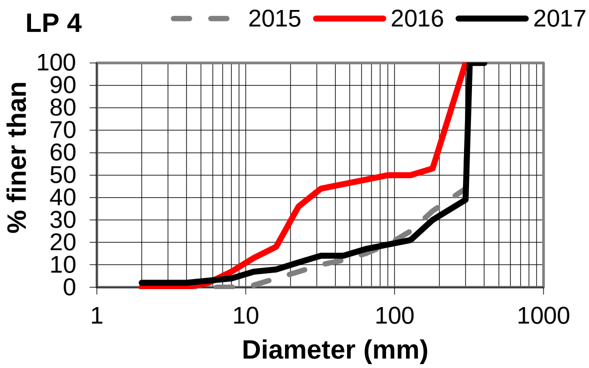


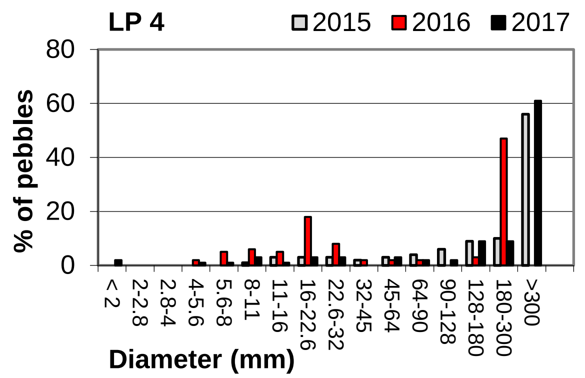


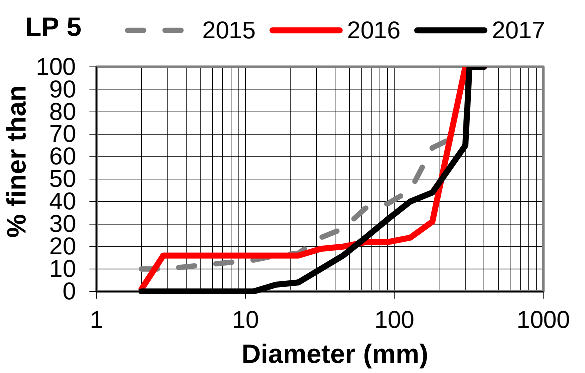


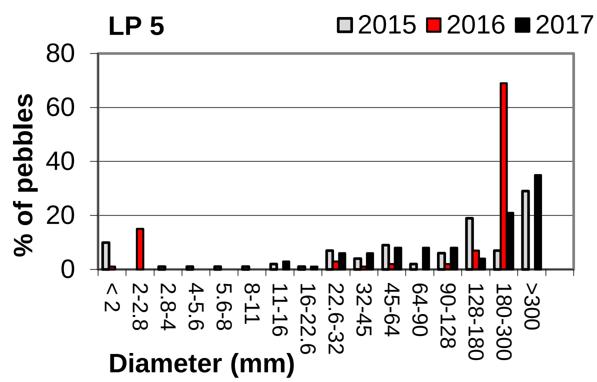


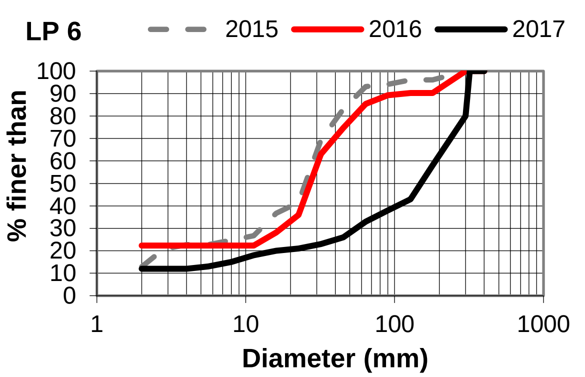


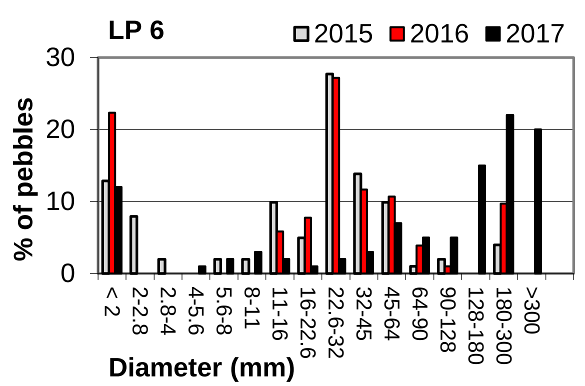

LP 4
2015
2016
2017
% finer than
Diameter (mm)
1
10
100
1000

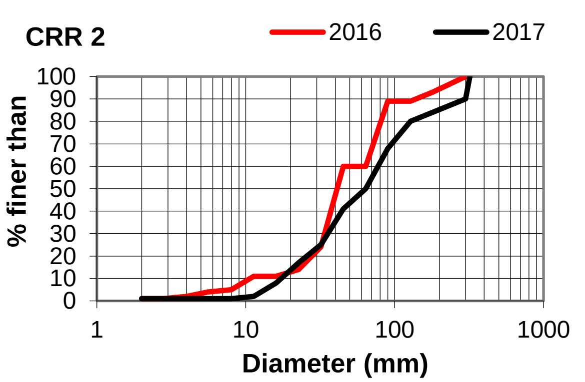

LP 4
2015
2016
2017
% of pebbles
Diameter (mm)
< 2
2-2.8
2.8-4
4-5.6
5.6-8
8-11
11-16
16-22.6
22.6-32
32-45
45-64
64-90
90-128
128-180
180-300
>300

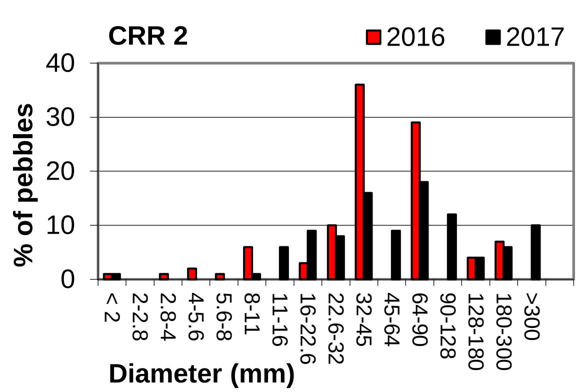

LP 5
2015
2016
2017
% finer than
Diameter (mm)
1
10
100
1000

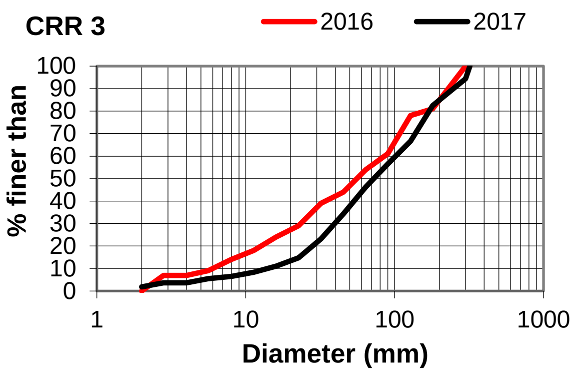

LP 5
2015
2016
2017
% of pebbles
Diameter (mm)
< 2
2-2.8
2.8-4
4-5.6
5.6-8
8-11
11-16
16-22.6
22.6-32
32-45
45-64
64-90
90-128
128-180
180-300
>300

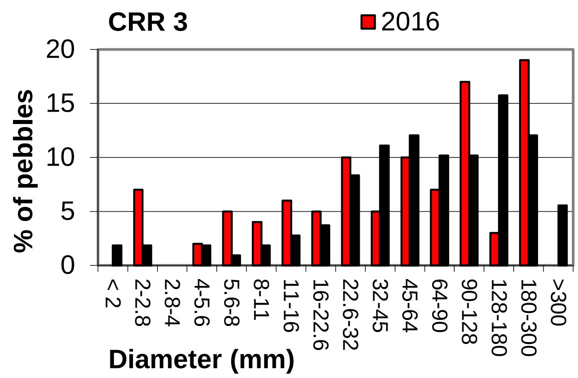

LP 6
2015
2016
2017
% finer than
Diameter (mm)
1
10
100
1000

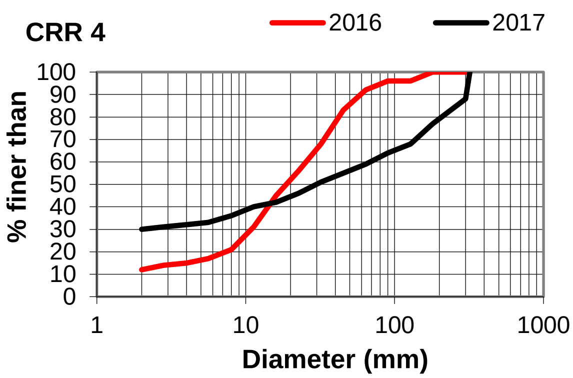

LP 6
2015
2016
2017
% of pebbles
Diameter (mm)
< 2
2-2.8
2.8-4
4-5.6
5.6-8
8-11
11-16
16-22.6
22.6-32
32-45
45-64
64-90
90-128
128-180
180-300
>300

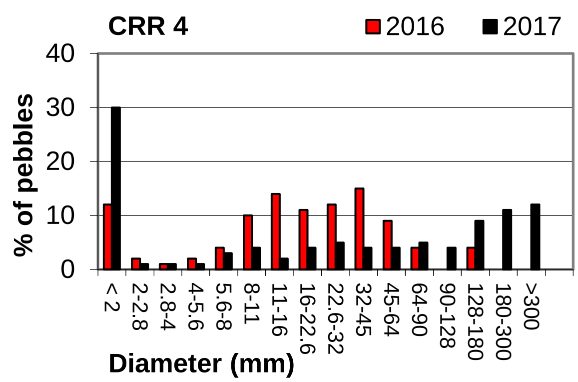

CRR 2
2016
2017
% finer than
Diameter (mm)
1
10
100
1000

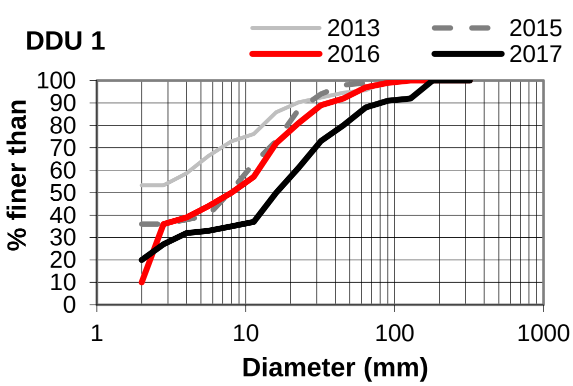

CRR 2
2016
2017
% of pebbles
Diameter (mm)
< 2
2-2.8
2.8-4
4-5.6
5.6-8
8-11
11-16
16-22.6
22.6-32
32-45
45-64
64-90
90-128
128-180
180-300
>300

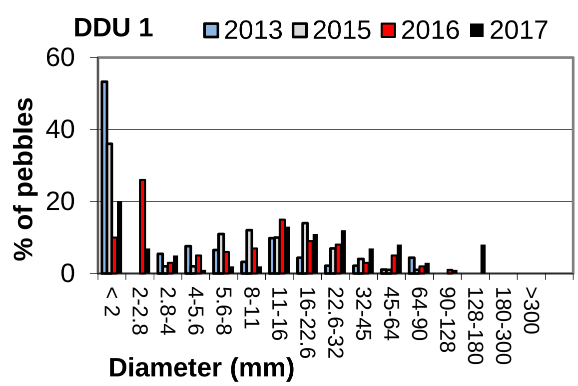

CRR 3
2016
2017
% finer than
Diameter (mm)

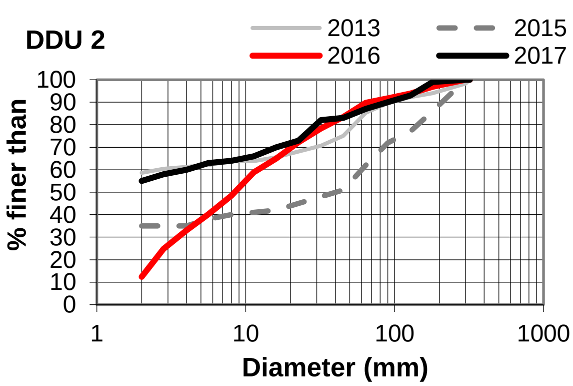

CRR 3
2016
% of pebbles
Diameter (mm)

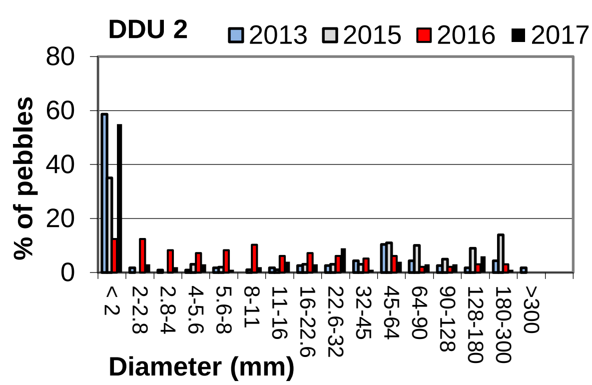

CRR 4
2016
2017
% finer than
Diameter (mm)

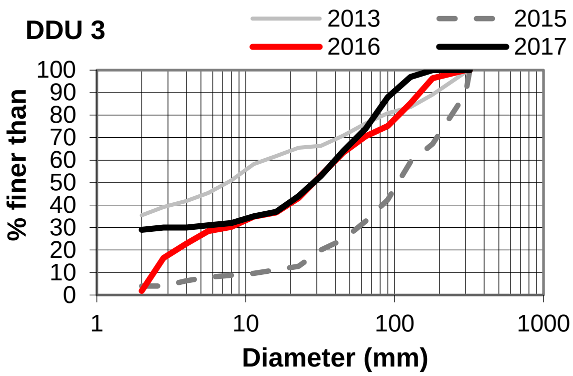

CRR 4
2016
2017
% of pebbles
Diameter (mm)

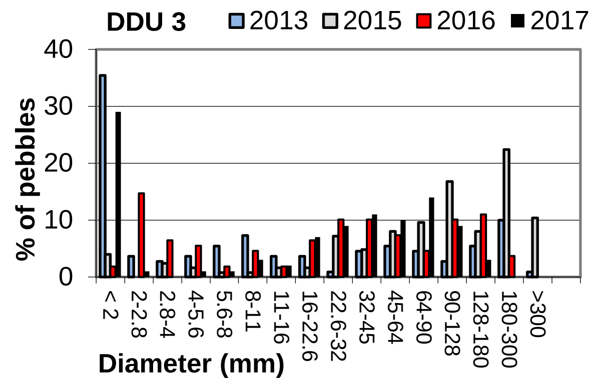

DDU 1
2013
2015
2016
2017
% finer than
Diameter (mm)

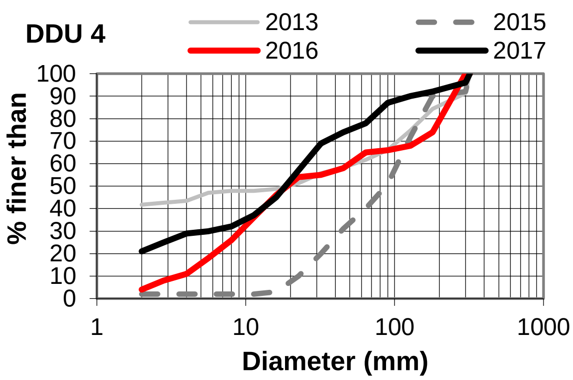

DDU 1
2013
2015
2016
2017
% of pebbles
Diameter (mm)

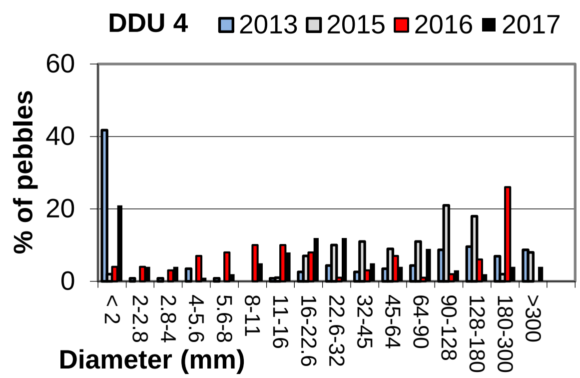

DDU 2
2013
2015
2016
2017
% finer than
Diameter (mm)

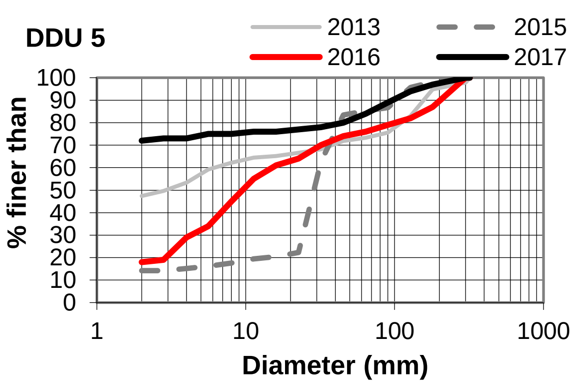

DDU 2
2013
2015
2016
2017
% of pebbles
Diameter (mm)

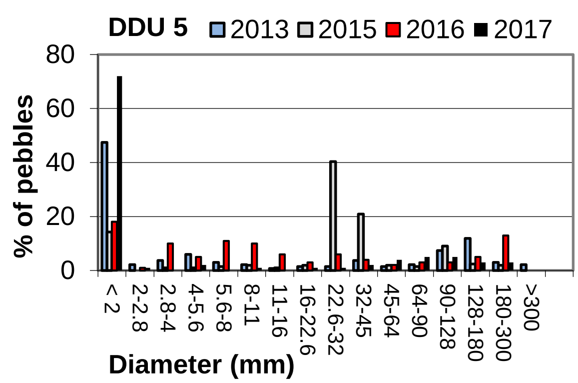

DDU 3
2013
2015
2016
2017
% finer than
Diameter (mm)

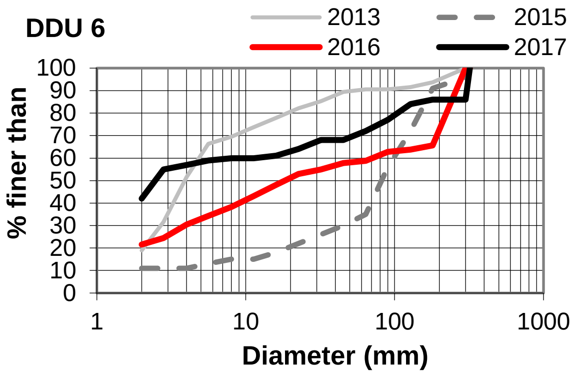

DDU 3
2013 2015 2016 2017
% of pebbles
< 2
2-2.8
2.8-4
4-5.6
5.6-8
8-11
11-16
16-22.6
22.6-32
32-45
45-64
64-90
90-128
128-180
180-300
>300
Diameter (mm)

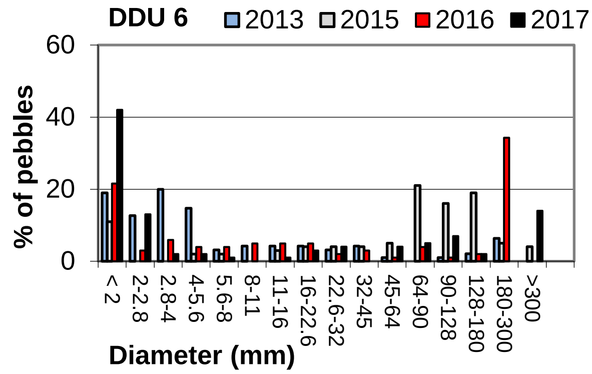

DDU 4
2013
2015
2016
2017
% finer than
Diameter (mm)

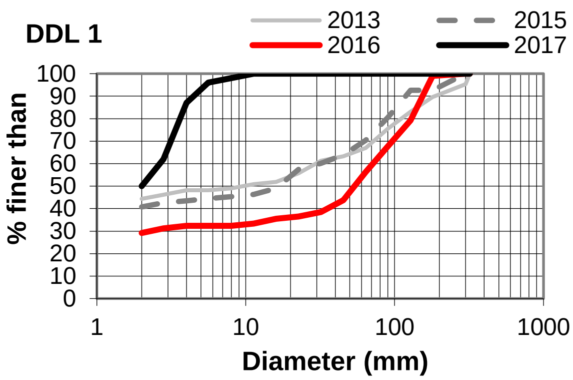

DDU 4
2013 2015 2016 2017
% of pebbles
< 2
2-2.8
2.8-4
4-5.6
5.6-8
8-11
11-16
16-22.6
22.6-32
32-45
45-64
64-90
90-128
128-180
180-300
>300
Diameter (mm)

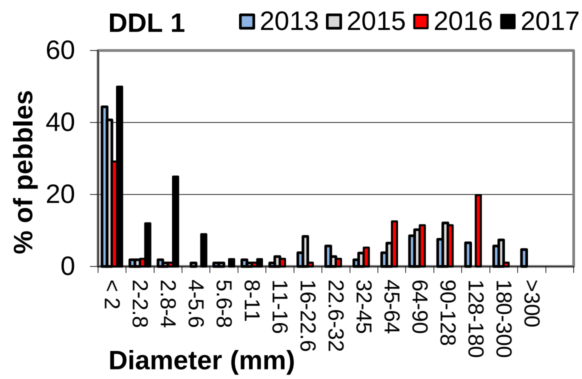

DDU 5
2013
2015
2016
2017
% finer than
Diameter (mm)

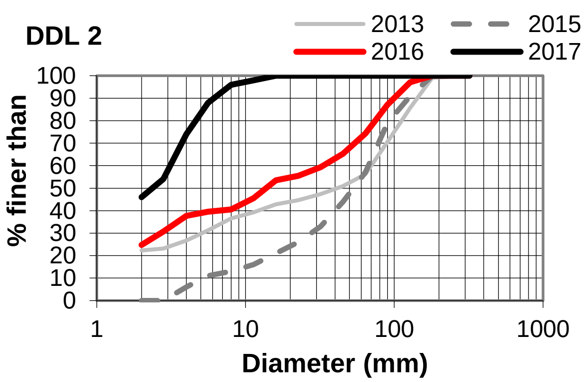

DDU 5
2013 2015 2016 2017
% of pebbles
< 2
2-2.8
2.8-4
4-5.6
5.6-8
8-11
11-16
16-22.6
22.6-32
32-45
45-64
64-90
90-128
128-180
180-300
>300
Diameter (mm)

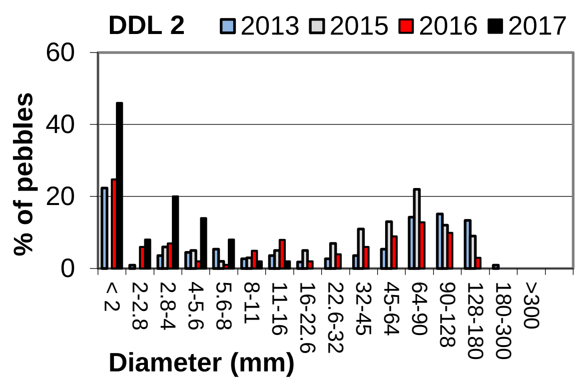

DDU 6
2013
2015
2016
2017
% finer than
Diameter (mm)

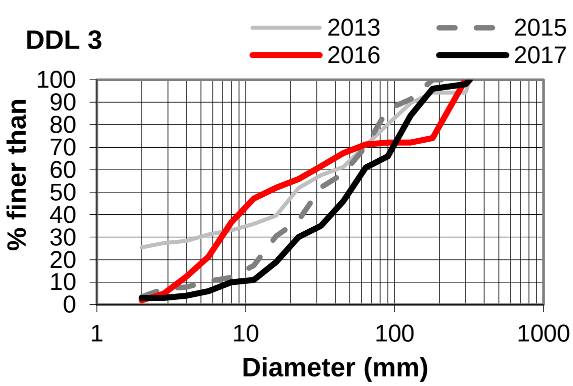

DDU 6
2013 2015 2016 2017
% of pebbles
Diameter (mm)

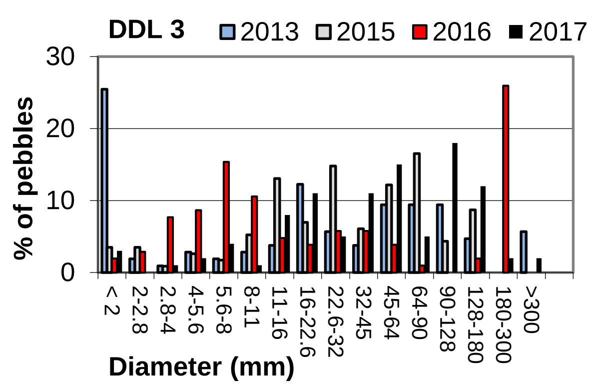

DDL 1
2013
2015
2016
2017
% finer than
Diameter (mm)

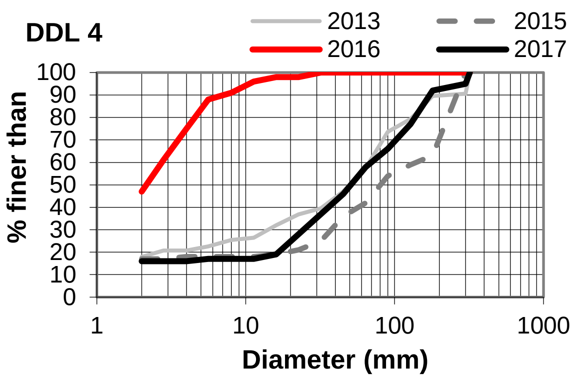

DDL 1
2013 2015 2016 2017
% of pebbles
Diameter (mm)

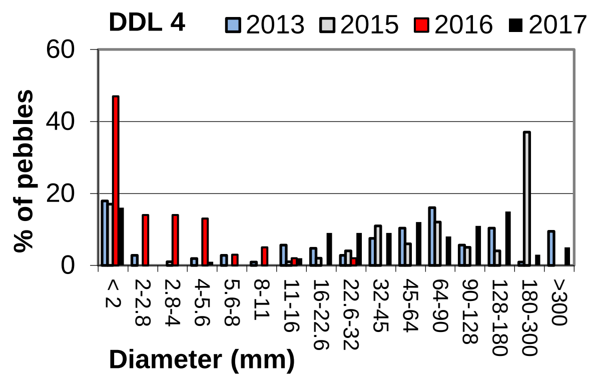

DDL 2
2013
2015
2016
2017
% finer than
Diameter (mm)

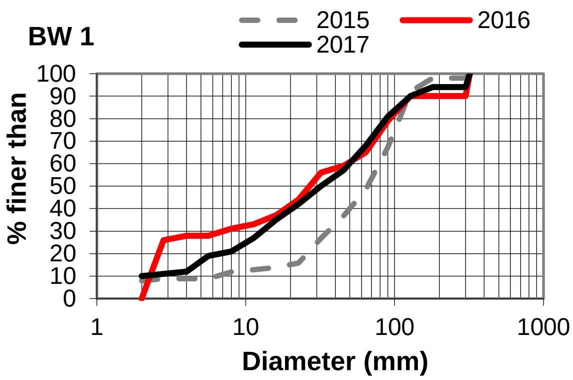

DDL 2
2013 2015 2016 2017
% of pebbles
Diameter (mm)

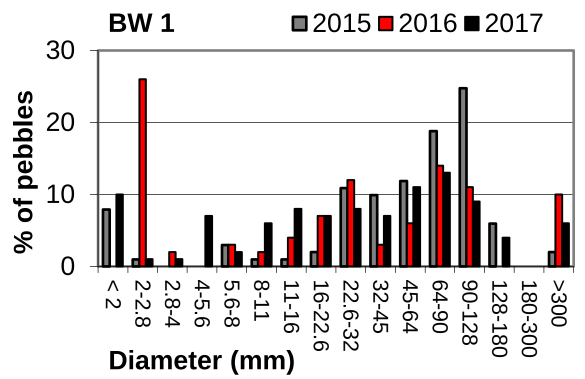

DDL 3
2013
2015
2016
2017
% finer than
Diameter (mm)

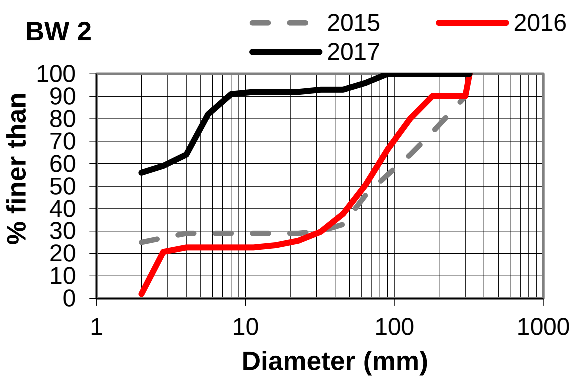

DDL 3
2013 2015 2016 2017
% of pebbles
Diameter (mm)

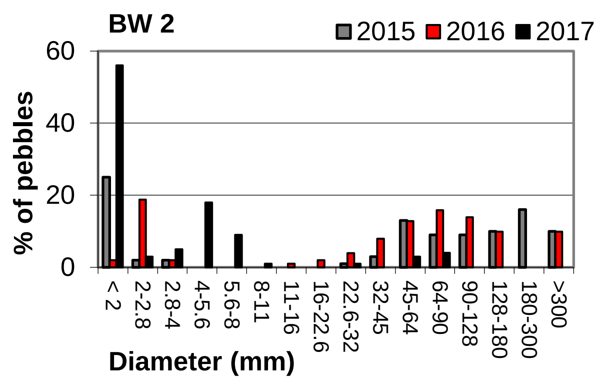

DDL 4
2013
2015
2016
2017
% finer than
Diameter (mm)

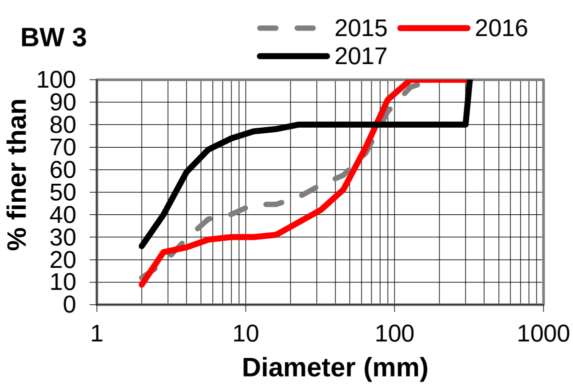

DDL 4
2013 2015 2016 2017
% of pebbles
< 2
2-2.8
2.8-4
4-5.6
5.6-8
8-11
11-16
16-22.6
22.6-32
32-45
45-64
64-90
90-128
128-180
180-300
>300
Diameter (mm)

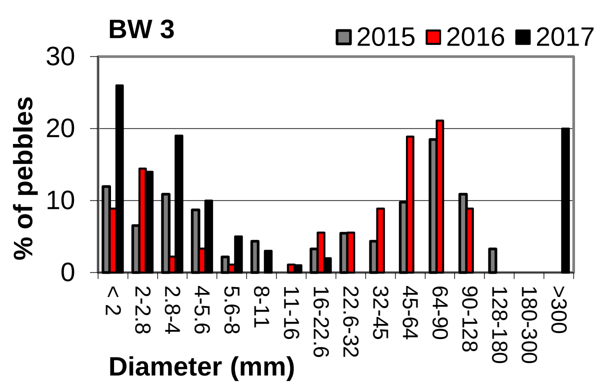

BW 1
2015
2016
2017
% finer than
Diameter (mm)

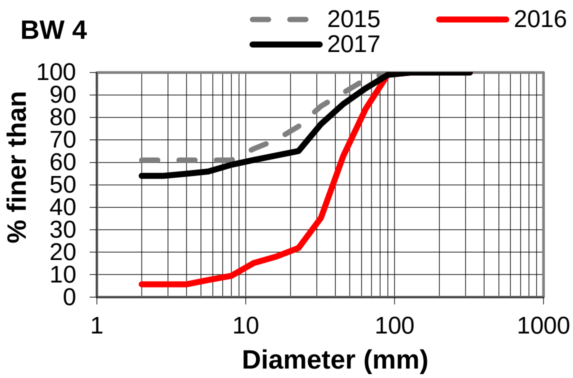

BW 1
2015 2016 2017
% of pebbles
Diameter (mm)

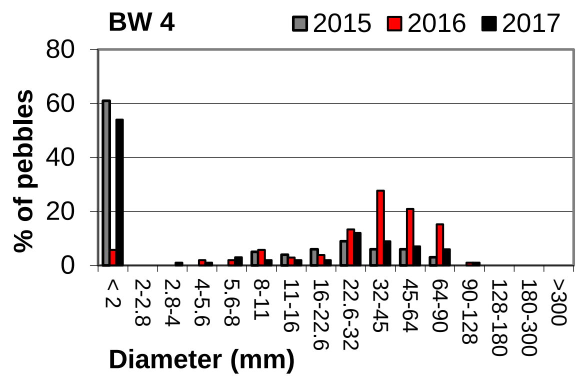

BW 2
2015
2016
2017
% finer than
Diameter (mm)

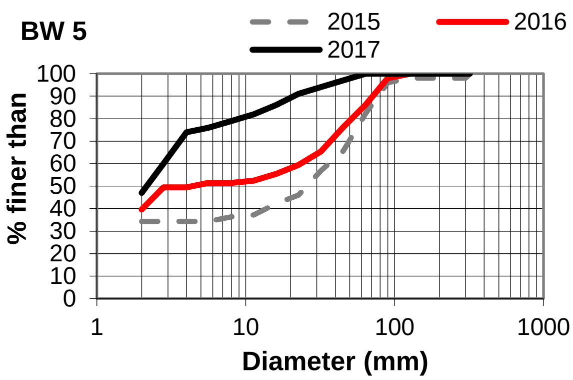

BW 2
2015 2016 2017
% of pebbles
Diameter (mm)

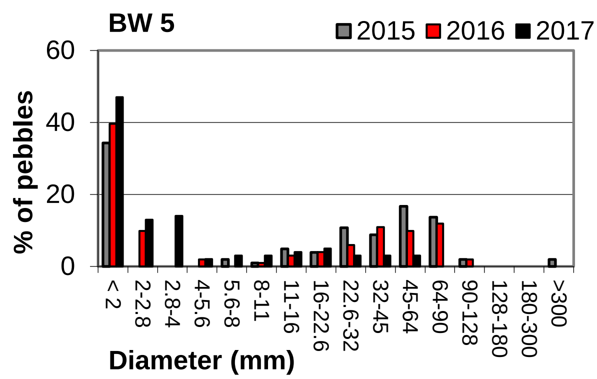

BW 3
2015
2016
2017
% finer than
Diameter (mm)

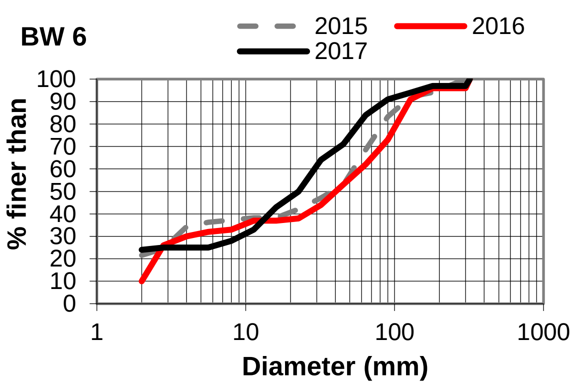

BW 3
2015 2016 2017
% of pebbles
Diameter (mm)

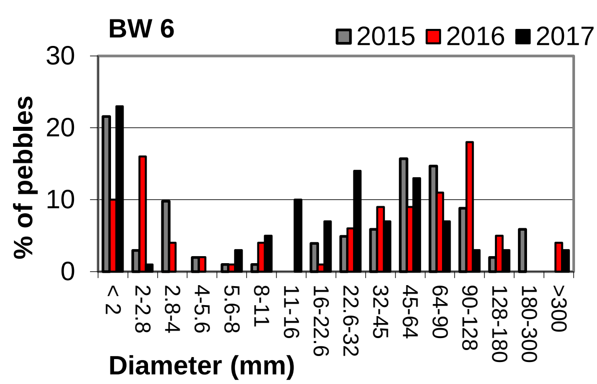

BW 4
2015
2016
2017
% finer than
Diameter (mm)

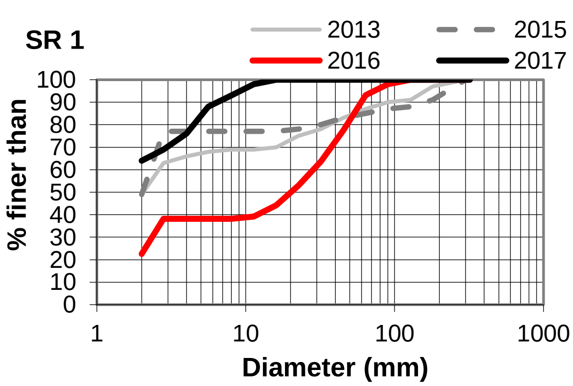

BW 4
2015
2016
2017
% of pebbles
Diameter (mm)

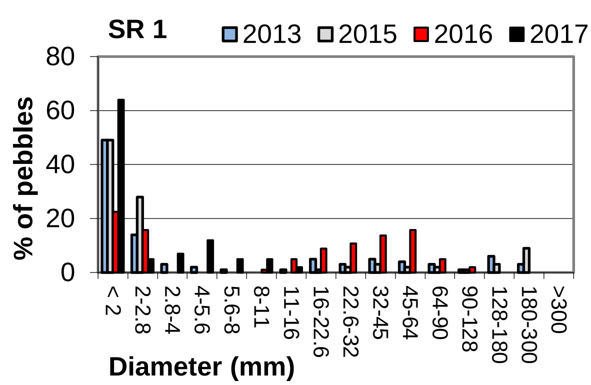

BW 5
2015
2016
2017
% finer than
Diameter (mm)

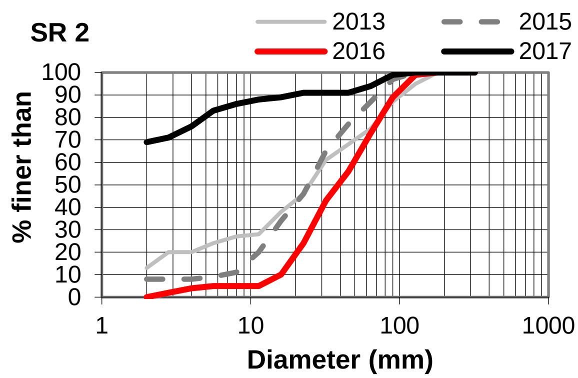

BW 5
2015
2016
2017
% of pebbles
Diameter (mm)

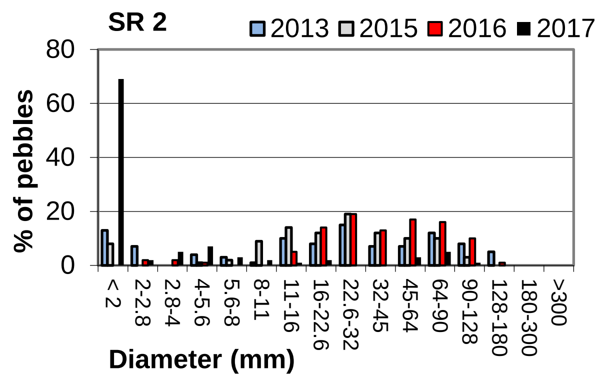

BW 6
2015
2016
2017
% finer than
Diameter (mm)

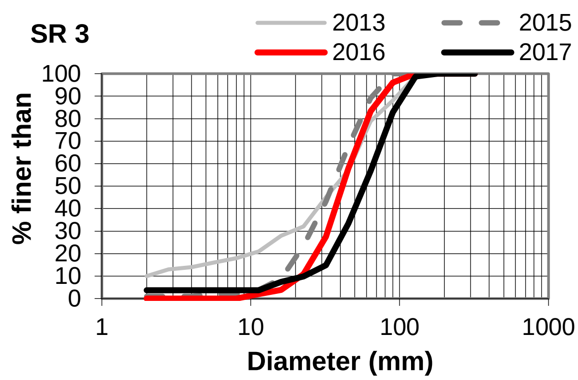

BW 6
2015
2016
2017
% of pebbles
Diameter (mm)

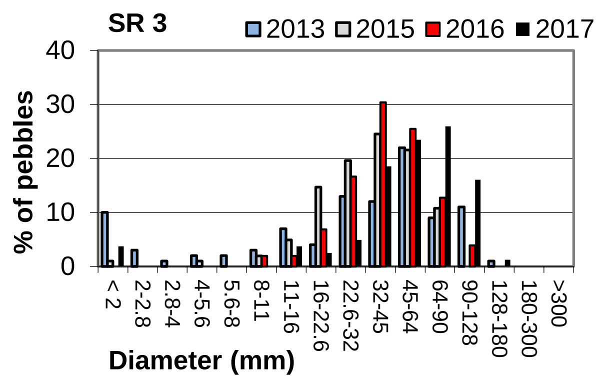

SR 1
2013
2015
2016
2017
% finer than
Diameter (mm)

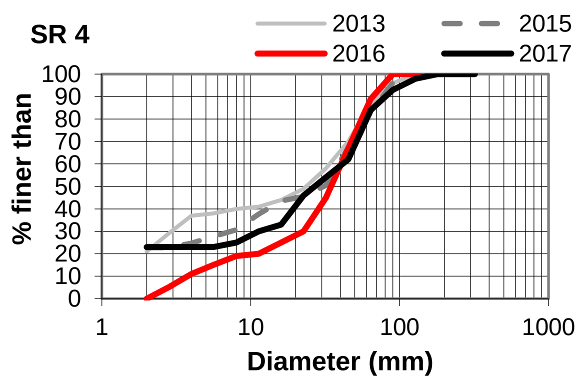

SR 1
2013
2015
2016
2017
% of pebbles
Diameter (mm)

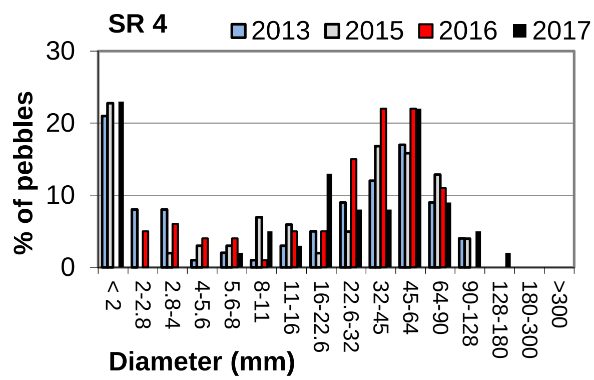

SR 2
2013
2015
2016
2017
% finer than
Diameter (mm)

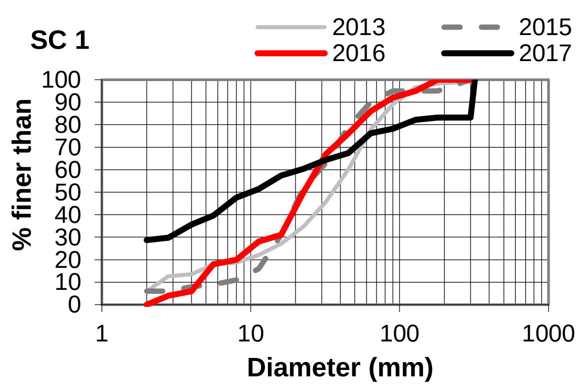

SR 2
2013 2015 2016 2017
% of pebbles
< 2
2-2.8
2.8-4
4-5.6
5.6-8
8-11
11-16
16-22.6
22.6-32
32-45
45-64
64-90
90-128
128-180
180-300
>300
Diameter (mm)

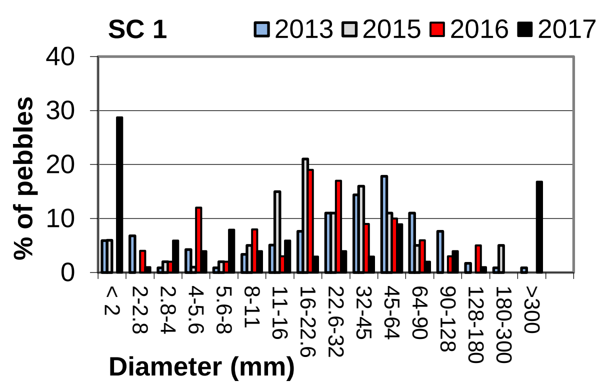

SR 3
2013
2015
2016
2017
% finer than
Diameter (mm)

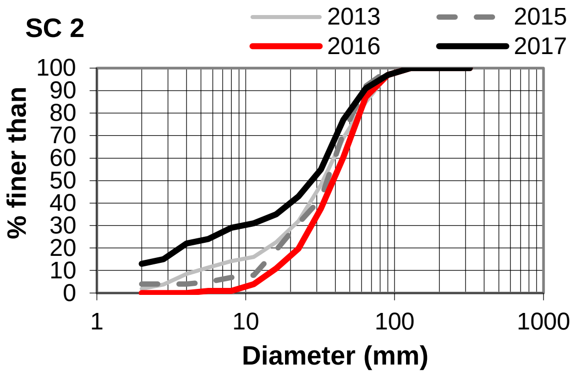
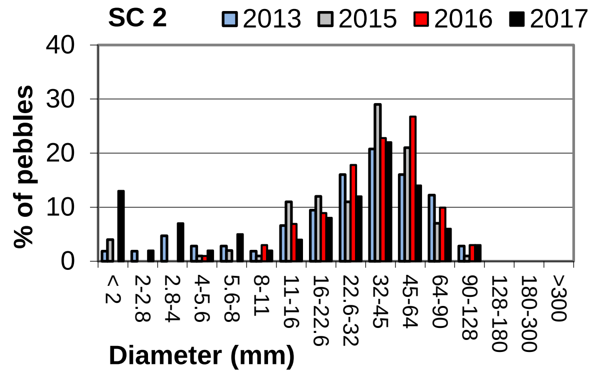
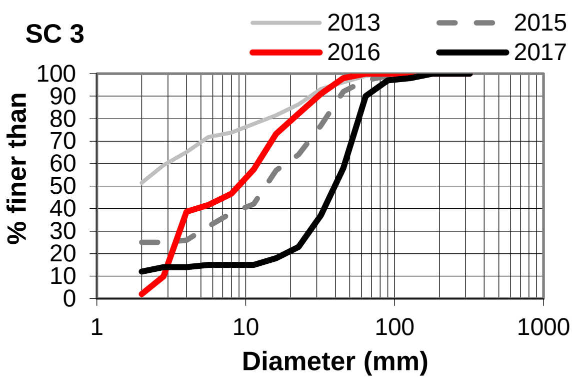
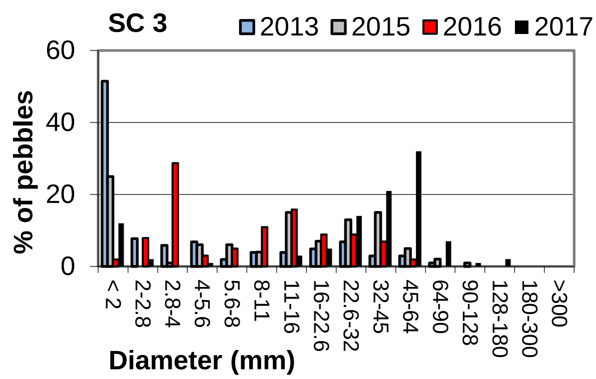
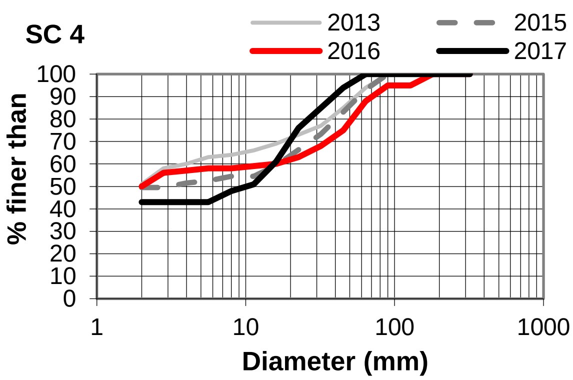
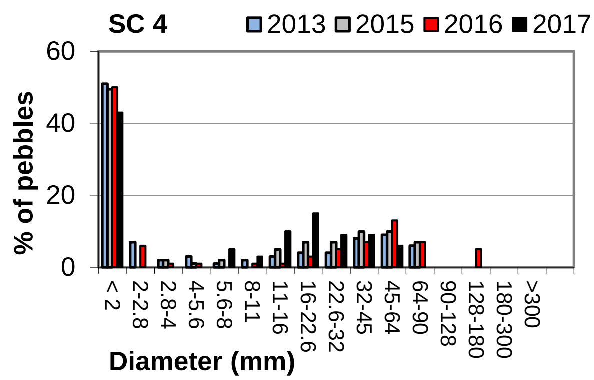
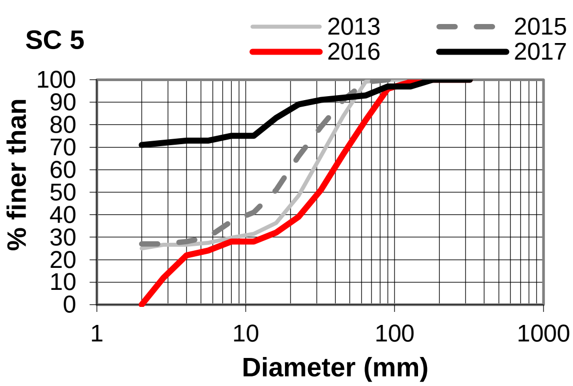
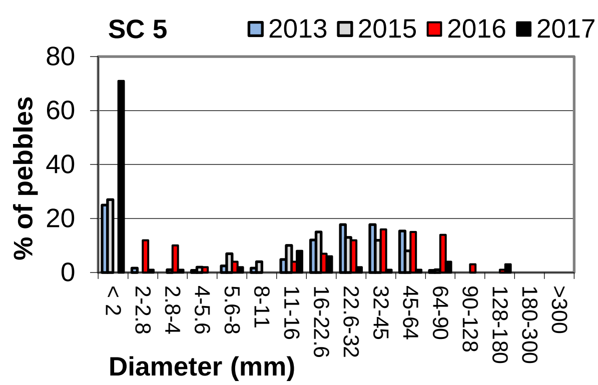

SR 3
2013 2015 2016 2017
% of pebbles
< 2
2-2.8
2.8-4
4-5.6
5.6-8
8-11
11-16
16-22.6
22.6-32
32-45
45-64
64-90
90-128
128-180
180-300
>300
Diameter (mm)

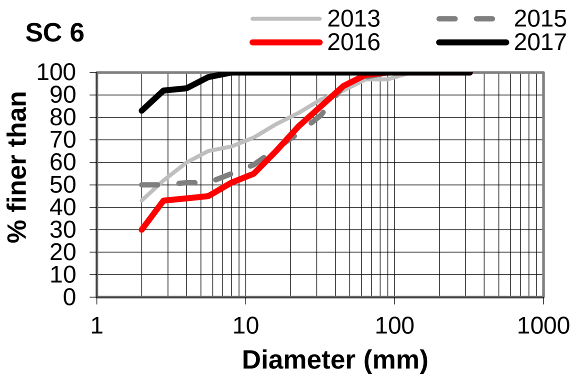

SR 4
2013
2015
2016
2017
% finer than
Diameter (mm)

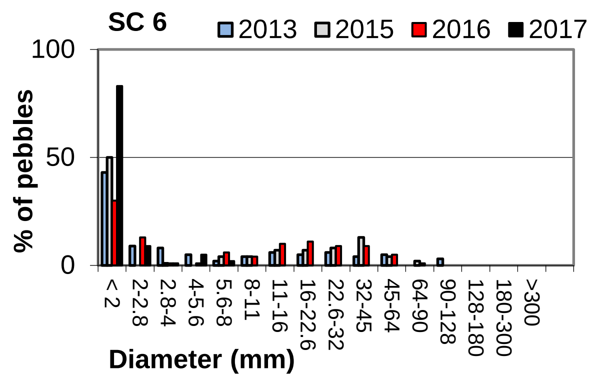

SR 4
2013 2015 2016 2017
% of pebbles
< 2
2-2.8
2.8-4
4-5.6
5.6-8
8-11
11-16
16-22.6
22.6-32
32-45
45-64
64-90
90-128
128-180
180-300
>300
Diameter (mm)

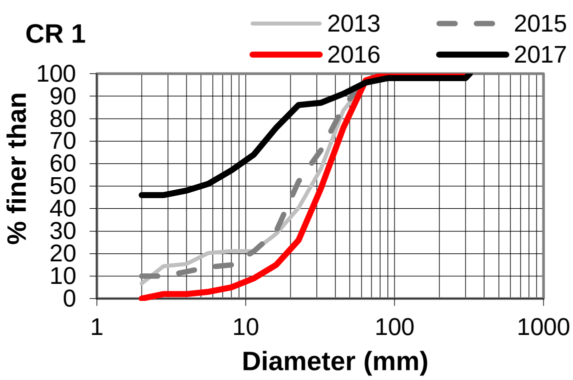

SC 1
2013
2015
2016
2017
% finer than
Diameter (mm)

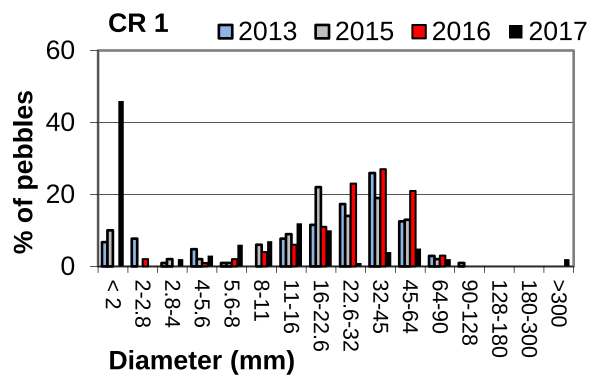

SC 1
2013 2015 2016 2017
% of pebbles
< 2
2-2.8
2.8-4
4-5.6
5.6-8
8-11
11-16
16-22.6
22.6-32
32-45
45-64
64-90
90-128
128-180
180-300
>300
Diameter (mm)

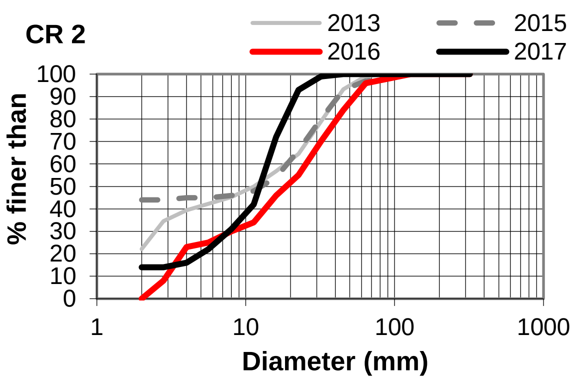

SC 2
2013
2015
2016
2017
% finer than
Diameter (mm)

SC 2
2013
2015
2016
2017
% of pebbles
Diameter (mm)

SC 3
2013
2015
2016
2017
% finer than
Diameter (mm)

SC 3
2013
2015
2016
2017
% of pebbles
Diameter (mm)

SC 4
2013
2015
2016
2017
% finer than
Diameter (mm)

SC 4
2013
2015
2016
2017
% of pebbles
Diameter (mm)

SC 5
2013
2015
2016
2017
% finer than
Diameter (mm)

SC 5
2013
2015
2016
2017
% of pebbles
Diameter (mm)

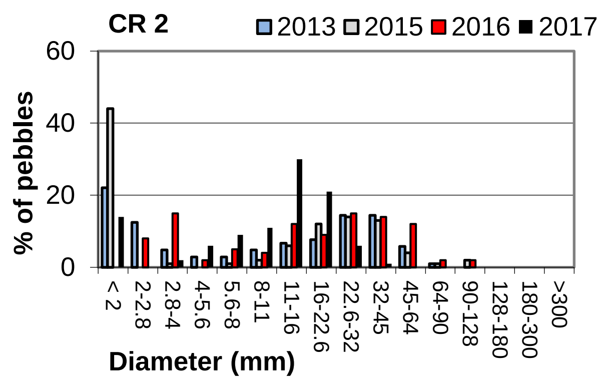

SC 6
2013
2015
2016
2017
% finer than
100
90
80
70
60
50
40
30
20
10
0
1
10
100
1000
Diameter (mm)

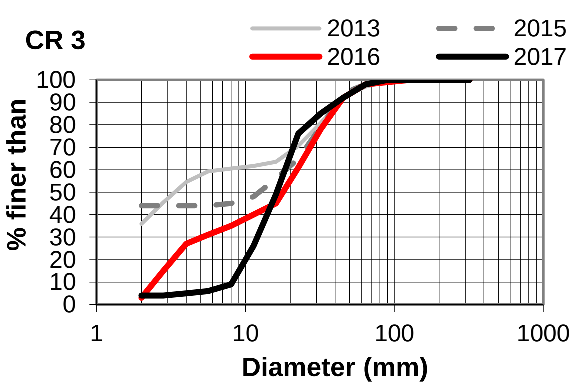

SC 6
2013 2015 2016 2017
% of pebbles
100
50
0
< 2
2-2.8
2.8-4
4-5.6
5.6-8
8-11
11-16
16-22.6
22.6-32
32-45
45-64
64-90
90-128
128-180
180-300
>300
Diameter (mm)

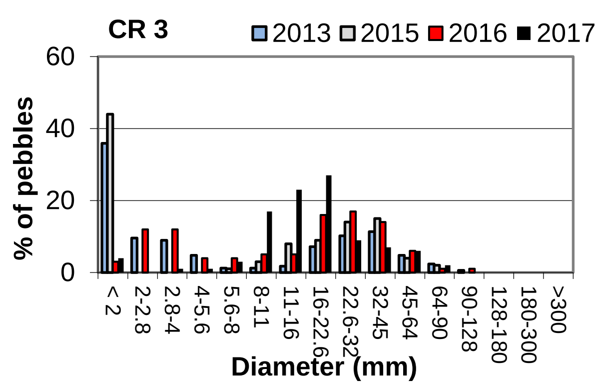

CR 1
2013
2015
2016
2017
% finer than
100
90
80
70
60
50
40
30
20
10
0
1
10
100
1000
Diameter (mm)

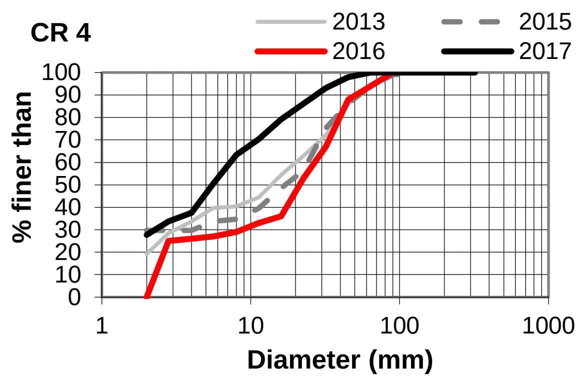

CR 1
2013 2015 2016 2017
% of pebbles
60
40
20
0
< 2
2-2.8
2.8-4
4-5.6
5.6-8
8-11
11-16
16-22.6
22.6-32
32-45
45-64
64-90
90-128
128-180
180-300
>300
Diameter (mm)

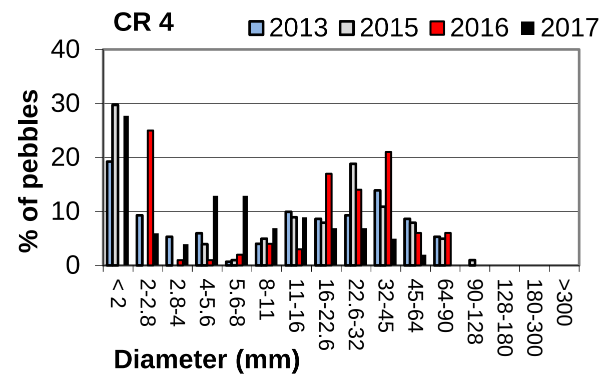

CR 2
2013
2015
2016
2017
% finer than
100
90
80
70
60
50
40
30
20
10
0
1
10
100
1000
Diameter (mm)

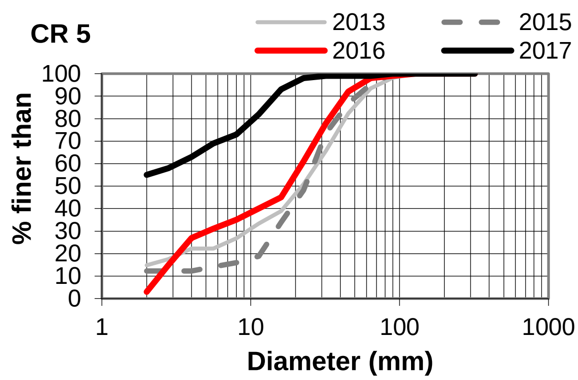

CR 2
2013 2015 2016 2017
% of pebbles
60
40
20
0
< 2
2-2.8
2.8-4
4-5.6
5.6-8
8-11
11-16
16-22.6
22.6-32
32-45
45-64
64-90
90-128
128-180
180-300
>300
Diameter (mm)

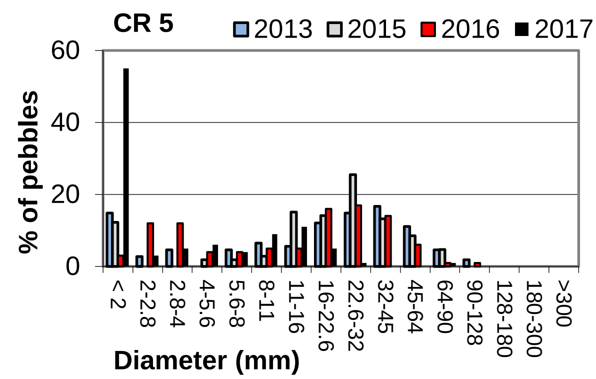

CR 3
2013
2015
2016
2017
% finer than
100
90
80
70
60
50
40
30
20
10
0
1
10
100
1000
Diameter (mm)

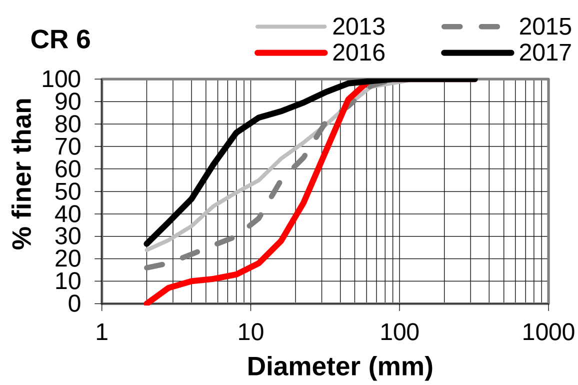

CR 3
2013 2015 2016 2017
% of pebbles
60
40
20
0
< 2
2-2.8
2.8-4
4-5.6
5.6-8
8-11
11-16
16-22.6
22.6-32
32-45
45-64
64-90
90-128
128-180
180-300
>300
Diameter (mm)

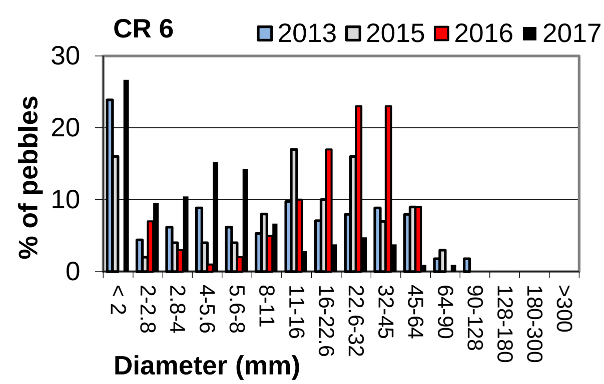

CR 4
2013
2015
2016
2017
% finer than
Diameter (mm)


CR 4
2013 2015 2016 2017
% of pebbles
< 2
2-2.8
2.8-4
4-5.6
5.6-8
8-11
11-16
16-22.6
22.6-32
32-45
45-64
64-90
90-128
128-180
180-300
>300
Diameter (mm)


CR 5
2013
2015
2016
2017
% finer than
Diameter (mm)


CR 5
2013 2015 2016 2017
% of pebbles
< 2
2-2.8
2.8-4
4-5.6
5.6-8
8-11
11-16
16-22.6
22.6-32
32-45
45-64
64-90
90-128
128-180
180-300
>300
Diameter (mm)


CR 6
2013
2015
2016
2017
% finer than
Diameter (mm)


CR 6
2013 2015 2016 2017
% of pebbles
< 2
2-2.8
2.8-4
4-5.6
5.6-8
8-11
11-16
16-22.6
22.6-32
32-45
45-64
64-90
90-128
128-180
180-300
>300
Diameter (mm)