Learning Science Through Research
Published by the Keck Geology Consortium
Short Contributions
Keck Geology Consortium
Volume 34
May 2022
doi: 10.18277/AKRSG.2022.34.12

MEASURING CHANGES IN CHANNEL MORPHOLOGY AND VOLUME OF MOBILIZED SEDIMENT FOLLOWING THE REMOVAL OF A LOWHEAD DAM IN ROCKBRIDGE COUNTY, VA

KATIE LARKIN, Washington & Lee University
Project Advisor: Eva Lyon

INTRODUCTION

Dam removals have increased in frequency in the 21st century (USGS Dam Removal Information Portal, 2020), and the environmental and geomorphological impacts of dams have been a popular topic of scientific study. Dams contribute to the fragmentation of rivers, in which a free-flowing channel is restricted to a number of slow-velocity or slackwater reaches (Graf, 1999). Slowed water velocity allows fine grains to settle, causing a localized buildup of fine sediment and depleting downstream areas of this material. By interrupting the natural movement of eroded solids and waters in rivers and changing the flux between reservoirs, fluvial systems begin to interact differently with the land through which they run (Marren, 2014). Dams are able to propagate signals up and downstream upon their emplacement; they cause an increase in local base level and cause a significant obstruction in the channel (e.g., Leopold & Bull, 1979; Merritts et. al, 2013; Dow et. al., 2020). Similarly, the removal of dams has the potential to interrupt the equilibrium state of a river, causing bank instability and incision into the riverbed, among other geomorphological reactions (Simon, 1994). Short-term studies on dam removals have been well-studied over the last few decades, but long-term channel impacts are far less understood (e.g., Merritts et. al., 2013).

The Maury River, a 42.8-mile-long tributary of the James River, is characterized by a coarse bed load and armor, consisting mostly of rounded Cambrian Keefer, Rose Hill, and Tuscarora sandstone cobbles and angular Ordovician Edinburg limestones. The Jordan's Point Dam (Fig. 1), a low head structure dating back to 1805, is one of numerous mill dams and lock-and-dam structures constructed on the Maury River in response to increased industrial activity. After a 70-year obsolescence, the structurally unsound dam was removed in May 2019; WLU student Chantal Iosso (2020) established baseline conditions following the removal of the dam and predicted future conditions. Notably, she found that the dam did not store significant quantities of fines during its emplacement. My investigation aims to characterize channel change over the last two years, using Iosso's data for comparison, in order to define the extent of post-removal channel restructure and adjustment. I will also provide quantitative data estimating change in channel area and the approximate volume of sediment mobilized since the dam removal.

Figure 1. The Jordan's Point Dam, seen looking upstream, in March 2019. The structures downstream of the dam are concrete pylons, which were part of an old railroad bridge (Young, 2019); they have since been moved and now reside on river left downstream of the dam.

METHODS

Field methods

Cross sections were measured in Summer 2021. Locations were selected based on cross sections measured in Iosso and Harbor (2020) (Fig. 2). The sections immediately above and below the dam experienced the most channel change and restructuring since 2019, and were thus subject to repeat measurement. Cross sections were measured using a TopCon GTS-301 Total Station to capture changes in elevation or channel morphology, both of which can indicate changes in river behavior. Channel width is thought to have undergone negligible change from 2019 to 2021 due to the relatively short time frame of the study; channel adjustments of this magnitude generally occur on a longer timeframe (e.g., Simon, 1994; Wolman and Leopold, 1957; Merritts et al., 2013).

Channel bed grain size analyses followed the Wolman pebble count procedure using a gravelometer. Three samples were measured at every meter along the transect. We calculated the mean grain size, or d_{50}, with this formula:

(smallest grain size (mm) x # obs.) + … (largest grain size (mm) x # obs.)/ (total obs.)

We calculated d_{90} by multiplying total observations by 0.9, then noting the value of the corresponding observation. During these calculations, any specimen with a grain size larger than 180 was assigned a size of 180+ millimeters and a phi value of 256, pertaining to the next largest size on a gravelometer. Given the exceptionally coarse nature of the alluvium, such an adjustment was performed numerous times. The focus of the grain size sampling was to understand longer-term changes in bed armor size and river competency.

Analytical methods

The resulting cross section plots constructed in Microsoft Excel were used to calculate channel measurements in three dimensions, including wetted perimeter, change in channel area, and volume of alluvium removed. Wetted perimeter was calculated using Pythagorean's Theorem. Waterline positions noted during fieldwork were used to denote the boundaries of these measurements. Channel area was calculated based on changes in bed elevation made visible by the cross section projections. Trapezoidal under-curve area was calculated for each year; 2019 and 2021 under curve areas were subtracted from each other to determine total change in channel area.

Figure 2. Aerial view of 2019 and 2021 cross section locations. Inset map shows location of dam in the Maury River watershed.

The total volume of material removed between each cross section was calculated using a piecewise integration, which took distance and change in channel area at each cross section into account. The resulting value estimates the entire volume of sediment removed by extrapolating the results from each cross section onto the entire 376-meter-long study area.

Critical shear stresses for the d_{50} and d_{90} were calculated in order to gauge changes to the mobile fraction of alluvium; the following critical shear stress equation, developed by Shields (1936) and modified by Fischenich (2001) was used:

$$\tau_{cr} = 0.06 \times g(\rho_s - \rho_w)d \times \tan\varphi$$

Where τ_{cr} is the critical shear stress, g is the acceleration due to gravity, ρ_w is the density of water, ρ_s is the density of the substrate, d is the particle size of interest, and φ is angle of repose of the substrate. Substrate density was assigned a value of 2659 kg/m^3 according to the bulk density of Tuscarora sandstone, a major unit making up the bed load in the Maury River (Manger, 1963).

RESULTS

Degradation, or localized removal of channel sediment, is the dominant channel response in all cross sections. Where alluvium has been removed, the "pockets" of removed alluvium tend to be lenticular in shape. Pockets in the upper reaches tend to be shorter and deeper, occurring more as concentrated zones rather than vast degradational areas found in the lower reaches (Fig. 3). In comparing the 2019 and 2021 cross sections, the thalweg seems to have migrated from the center of the river to river left and changed in profile from a sharp 'v-shape' to a gentler-sloped and wider zone of high-velocity flow, particularly in the upper reaches. Despite the consistent trend of degradation, channel shape is variable between the upstream and downstream areas.

In the upper reaches (Cross Sections 6, 7, and 8), degradation signals were strong and channel restructure was relatively consistent in shape and distribution. Repositioning of the thalweg to the center of the channel and significant erosion of material has resulted in a trapezoidal channel shape, particularly at Cross Sections 6 and 7 (Fig. 3); the thalweg is located on river left at Cross Section 8.

In the reaches just above the dam (4 and 5), the trend of degradation continues to a varying extent. Cross Section 5 remained practically unchanged between 2019 and 2021 and experienced only minor degradation. Cross Section 4 was subject to a high degree of degradation, and the elevation of the channel bottom has been reduced by a noticeable amount.

Degradation continues at and below the dam, though to a lesser magnitude than observed upstream. Channel roughness increased between 2019 and 2021 at Cross Section 3 (site of the dam), and numerous small v-shaped breaks in the dam structure have developed. The channel at Cross Section 1 below the dam is wider, flatter, and generally symmetrical in shape. Degradation in this area is minor, but distributed throughout the entire channel instead of in pockets.

Channel area (Fig. 4) increased between 2019 and 2021 at every cross section. Minimal change in area was observed at the dam (Cross Section 3) and

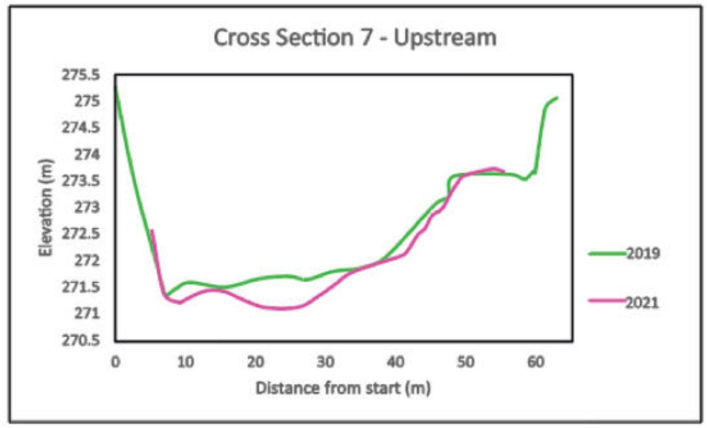

Figure 3. Example cross section from the upper reach, about 300 meters upstream of the removed dam.

the maximum observed change in area occurred just upstream at Cross Section 4. Percent change in channel area was disproportionately large at Cross Section 6. Taking the changes in channel area into account, an estimated 3,934.7 m^3 of alluvium has been mobilized between 2019 and 2021 over the course of the 376-meter study site.

Both average grain size and grain size distribution increased between 2019 and 2021. 2019 d_{50} values for Cross Sections 4, 7, and 8 were the same, but a higher d_{90} value was recorded for Cross Section 4. 2021 measurements recorded the highest d_{50} value for Cross Section 1, and the highest d_{90} values for Cross Section 4. The d_{90} at Cross Section 4 is double that of Cross Sections 7 and 8, exceeding the 1.67x difference observed in 2019. Between 2019 and 2021, the percent increases in d_{50} from downstream to upstream (4 to 8) are 187%, 111%, and 101%. The percent increases in d_{90} are 105%, 70.6%, and 70.6%. Greatest changes in average and 90th-percentile grain sizes are present at cross section 4, just upstream of the former dam site. Shear stresses have declined between 2019 and 2021 at each cross section. Critical shear stress increases at each cross section reflect the aforementioned changes in grain sizes between 2019 and 2021.

DISCUSSION

Channel cross sections recorded a change in channel area from 4-25 m^2, with proximity to the dam and channel substrate acting as the largest controls. Lowest levels of degradation were recorded at Cross Section 5, the only location where limestone bedrock makes up a significant part of the channel. Mobilization

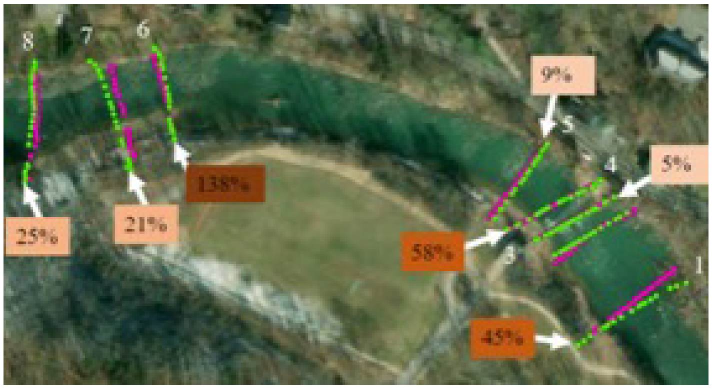

Figure 4. Calculated change in channel area between 2019 and 2021.

of this limestone bedrock is heavily dependent on numerous conditions; entrainment, or 'quarrying' of bedded carbonates is controlled by the location and orientation of fractures as well as hydraulic conditions (Miller, 1991). The evolution of bedrock channel systems in response to disturbances is also understood to operate on a longer timeframe than alluvial systems. Thus, the retention of channel structure at this location makes sense given the channel substrate.

The highest degree of degradation occurred just upstream of the dam at Cross Section 4, where the erosive effect of dam breaching would be strongest. Distribution of degradation downstream of the dam was measurable (7 m^2) but shallow and relatively evenly distributed within the channel, as opposed to the pocketed removal visible in the upper reaches. Iosso (2020) recorded higher channel bed elevations in a sediment ramp immediately upstream of the dam, but this was the only significant buildup of sediment in the channel recorded in 2019. Iosso hypothesized that grain sizes as large as cobbles (64-256 mm) were able to be transported over the dam during high flow. Pearson and Pizzuto (2015) made similar observations, noting that transport of sediment over a low-storage impoundment was aided by a sediment ramp. Degradation at Cross Section 4 has likely recorded the mobilization and leveling of this ramp, as opposed to the incision of a legacy sediment package.

Changes in channel bed armor makeup reflect the changes in flow conditions made evident by the cross sections. Percent change in grain size decreases in magnitude moving upstream, given the inverse relationship between geomorphic signal intensity and distance from the disturbance (Simon & Hupp, 1987). Additionally, bed armor grain sizes in the upper reaches tend to be smaller than those at and downstream of the dam site; a wider range of values was also observed in the lower reaches. The growing range of grain sizes and diversity of channel structure is reflective of a restoration of unobstructed flow, in which flow conditions and sediment behavior differ greatly depending on location (Kibler et al., 2011). This is in contrast to the prior dammed status of the river, wherein the river was restricted to a dammed 'pool' and was subject to slackwater conditions.

HEC-RAS modeling by Iosso (2020) found that a significant increase in sediment transport capacity was likely for the 500 meters of river upstream of the dam; given the extent of degradation and coarsening of the riverbed, this prediction appears to have been correct. At the time of sampling, Iosso found that d_{90} cobbles were mobilized by events as small as 2-year floods; however, her recorded d_{90} values of 74-150 mm are comparatively smaller than the 128-256 mm range observed in 2021. Floods are known to serve as major geomorphic events that have the potential to mobilize a large range of cobbles. Between 2019 and 2021, peak discharge was recorded as a 1.5 year flood (USGS NWIS, 2022). Elevated transportation capacity has likely played a major role in the shaping of the channel. The relatively minor peak discharge between 2019 and 2021 was able to transport material, meaning that high-discharge events will continue to erode the mobile fraction of the subarmor. Currently, interplay between sediment load and transport capacity continue to define the extent of equilibration; as the bed armor coarsens, mobile sediment supply is increasingly limited. As expected from the increase in grain size, critical shear stress of d_{90} sediment in 2021 (112.4 - 224.9 N/m^2) is notably higher than 2019 (65.9 - 109.8 N/m^2), and no observations support a significant change in flow conditions following Iosso's work.

CONCLUSIONS

Between 2019 and 2021, conditions in the Maury River have been conducive to mass mobilization of sediment and channel restructure. The degradation of almost 4000 m^3 of sediment from the 376 meter reach is consistent with observations from other dam removals (e.g., Merritts et. al, 2013; Kibler et. al, 2011; etc), though this degradation has likely occurred to a lesser extent due to the coarseness of the alluvium. Bed armor grain size analyses support an immediate winnowing of fine sediment stored in the channel was induced by the dam removal and subsequent base level fall. Mobilization of remaining larger cobbles is ongoing, but peak sediment flux has likely already occurred (e.g., Merritts et al., 2014).

ACKNOWLEDGEMENTS

This material is based upon work supported by the Keck Geology Consortium and the National Science Foundation under Grant No. 2050697. This research was also supported by the Edgar W. Spencer ('53) Geology Field Research Fund. I also thank Keck Advisors, Drs. Eva Lyon and Margaret Anne Hinkle, fellow students Ani Croy, Haley Culbertson, Christopher Goldmann, Mia Groff, Maddie Holicky, Martina Pulido, Kallan Wilde, and Noah Willis. Finally, thanks to Chantal Iosso and Dr. David Harbor, whose work helped form the foundation of this study.

REFERENCES

Dow, S., Snyder, N.P., Ouimet, W.B., Martini, A.M., Yellen, B., Woodruff, J.D., Newton, R.M., Merritts, D.J., and Walter, R.C., 2020, Estimating the timescale of fluvial response to anthropogenic disturbance using two generations of dams on the South River, Massachusetts, USA: Earth Surface Processes and Landforms, v. 45, p. 2380–2393, doi:10.1002/esp.4886.

Graf, W.L., 1999, Dam nation: A geographic census of American dams and their large-scale hydrologic impacts: Water Resources Research, v. 35, p. 1305–1311, doi:10.1029/1999WR900016.

Fischenich, C., 2001, Stability Thresholds for Stream Restoration Materials: Engineer Research And Development Center Vicksburg Ms Environmental Lab, https://apps.dtic.mil/sti/citations/ADA392430 (accessed April 2022).

Kibler, K., Tullos, D., and Kondolf, M., 2011, Evolving Expectations of Dam Removal Outcomes: Downstream Geomorphic Effects Following Removal of a Small, Gravel-Filled Dam1: Evolving Expectations of Dam Removal Outcomes: Downstream Geomorphic Effects Following Removal of a Small, Gravel-Filled Dam: JAWRA Journal of the American Water Resources Association, v. 47, p. 408–423, doi:10.1111/j.1752-1688.2011.00523.x.

Leopold, L.B., and Bull, W.B., 1979, Base Level, Aggradation, and Grade: American Philosophical Society, 35 p.

Leopold, L.B., and Wolman, M.G., 1957, River channel patterns: Braided, meandering, and straight: U.S. Government Printing Office Professional Paper USGS Numbered Series 282-B, 50 p., http://pubs.er.usgs.gov/publication/pp282B (accessed April 2022).

Manger, G. E., Porosity and bulk density of sedimentary rocks, 1963, doi:10.3133/b1144E.

Marren, P.M., Grove, J.R., Webb, J.A., and Stewardson, M.J., 2014, The Potential for Dams to Impact Lowland Meandering River Floodplain Geomorphology: The Scientific World Journal, v. 2014, p. 1–24, doi:10.1155/2014/309673.

Merritts, D. et al., 2013, The rise and fall of Mid-Atlantic streams: Millpond sedimentation, milldam breaching, channel incision, and stream bank erosion, in The Challenges of Dam Removal and River Restoration, Geological Society of America, doi:10.1130/2013.4121(14).

Miller, J.R., 1991, The Influence of Bedrock Geology on Knickpoint Development and Channel-Bed Degradation along Downcutting Streams in South-Central Indiana: The Journal of Geology, v. 99, p. 591–605, doi:10.1086/629519.

Pearson, A.J., and Pizzuto, J., 2015, Bedload transport over run-of-river dams, Delaware, U.S.A.: Geomorphology, v. 248, p. 382–395, doi:10.1016/j.geomorph.2015.07.025.

Shields, A. (1936) Application of similarity principles and turbulence research to bed-load movement. California Institute of Technology , Pasadena, CA. (Unpublished)

Simon, A., and Hupp, C.R., 1987, Channel Evolution In Modified Alluvial Streams: Transportation Research Record, p. 9, http://pubs.er.usgs.gov/publication/70014832 (accessed April 2022).

Simon, A., 1994, Gradation processes and channel evolution in modified West Tennessee streams; process, response, and form: Professional Paper, doi:10.3133/pp1470.

Wildman, L.A.S., and MacBroom, J.G., 2005, The evolution of gravel bed channels after dam removal: Case study of the Anaconda and Union City Dam removals: Geomorphology, v. 71, p. 245–262, doi:10.1016/j.geomorph.2004.08.018.