The influence of landslides on channel flood response: A case study from the Colorado Front Range

Bennett, G.L.[1,2], Ryan, S.[1], Scholtes, J.[3], Rathburn, S.L[2], Kean, J.W[4], Rengers, F.K[4]

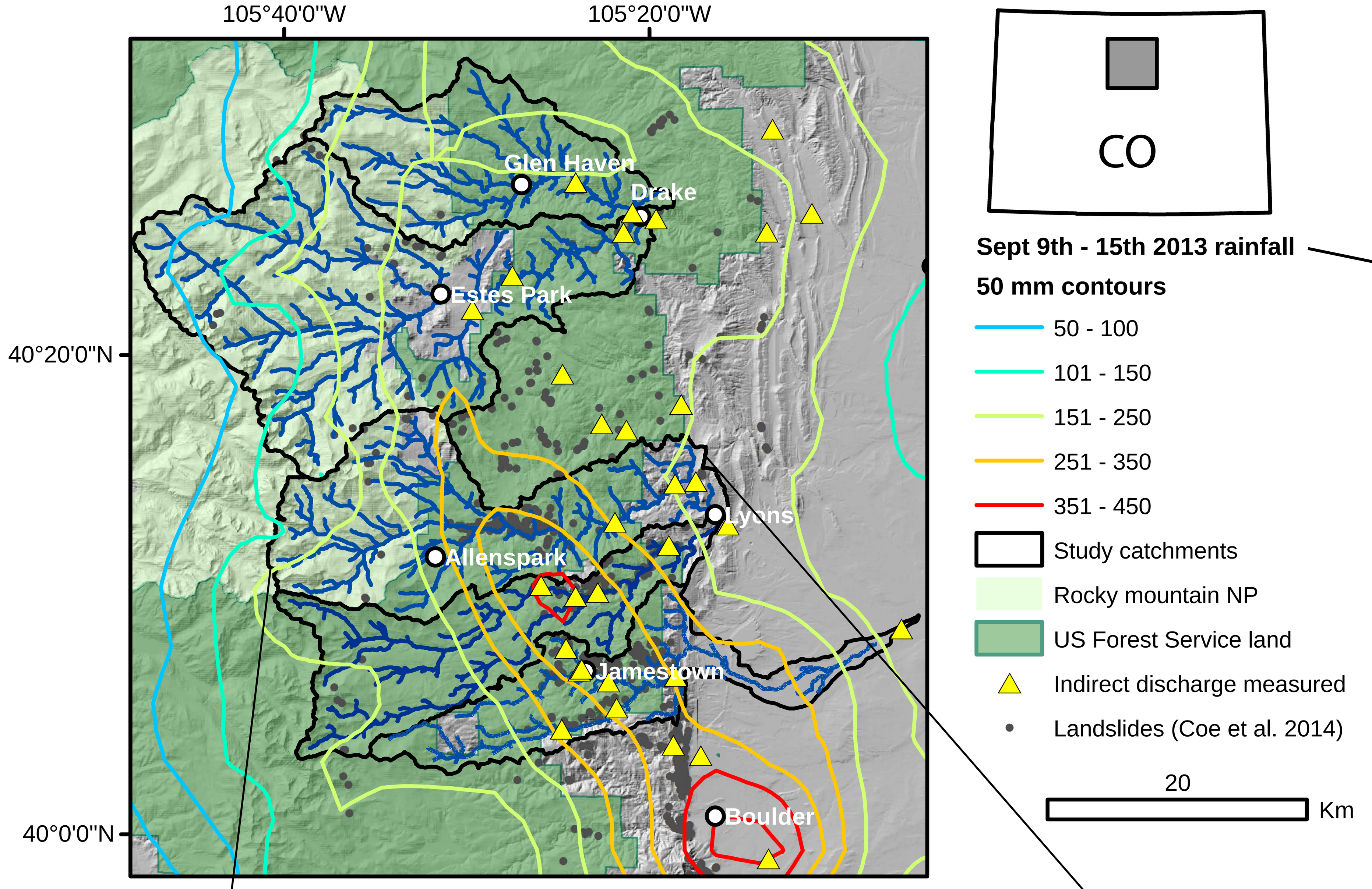
[1] US Forest Service, Rocky Mountain Research Station, Fort Collins, CO, [2] Department of Geosciences, Colorado State University, Fort Collins, CO, [3] Bureau of Reclamation, Lakewood, CO, [4] USGS, Golden, CO

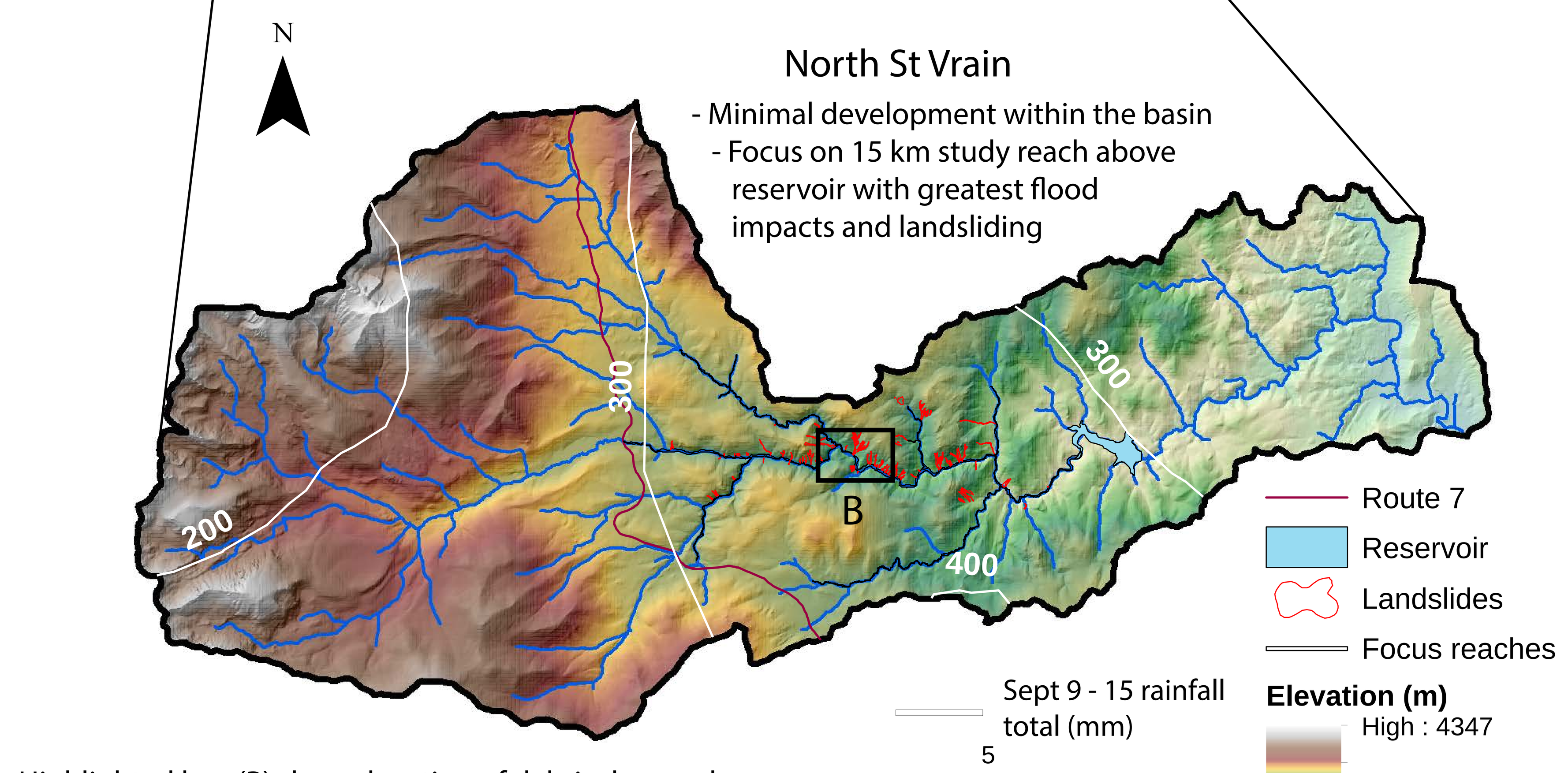
EP33D-1022

1) Abstract

Studies have identified the role of thresholds and gradients in stream power in inducing geomorphic change during floods (Magilligan et al., 2015; Gartner et al., 2015). At much longer time scales, empirical and modeling studies suggest the role of landslides in modifying channel response to external forcing (Bennett et al., 2016). However, the influence of landslides on channel response to an individual flood event remains largely unexplored. Here we investigate the influence of landslides on channel response to a 1000-yr rainfall event in Colorado, USA. From 9 – 15th September 2013 up to 450 mm of rain fell across a 100 km-wide swath of the Colorado Front Range, triggering >1000 landslides and inducing major flooding in several catchments. The flood caused extensive channel erosion, deposition and planform change, resulting in significant damage to property and infrastructure and even loss of life. We use a combination of pre and post flood LiDAR and field mapping to quantify geomorphic change in several catchments spanning the flooded region. We make a reach-by-reach analysis of channel geomorphic change metrics (e.g. volume of erosion) in relation to landslide sediment input and total stream power as calculated from radar-based rainfall measurements. Preliminary results suggest that landslide-sediment input may complicate the predictive relationship between channel erosion and stream power through generation of landslide dams and dam burst events and sediment bulking of the flow. These results have implications for predicting channel response to floods and for flood planning and mitigation.

2) Study site

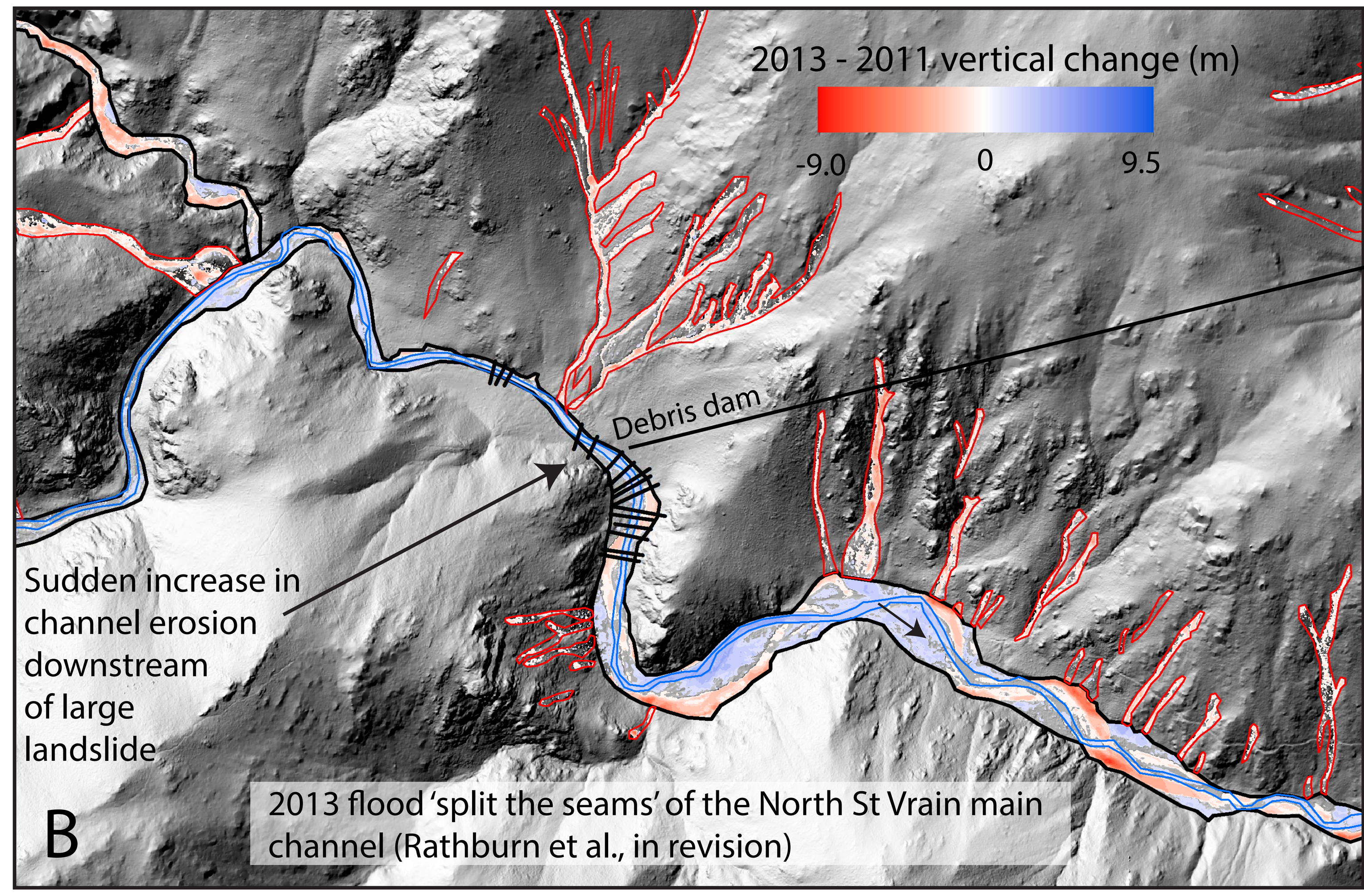




Highlighted box (B) shows location of debris dam and dam burst event detailed in Methods and Results

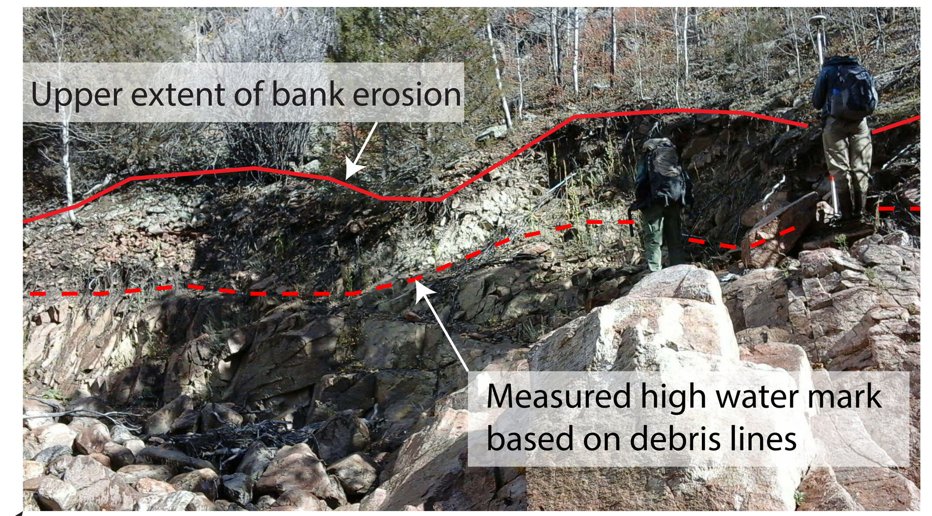
3) Methods and Results

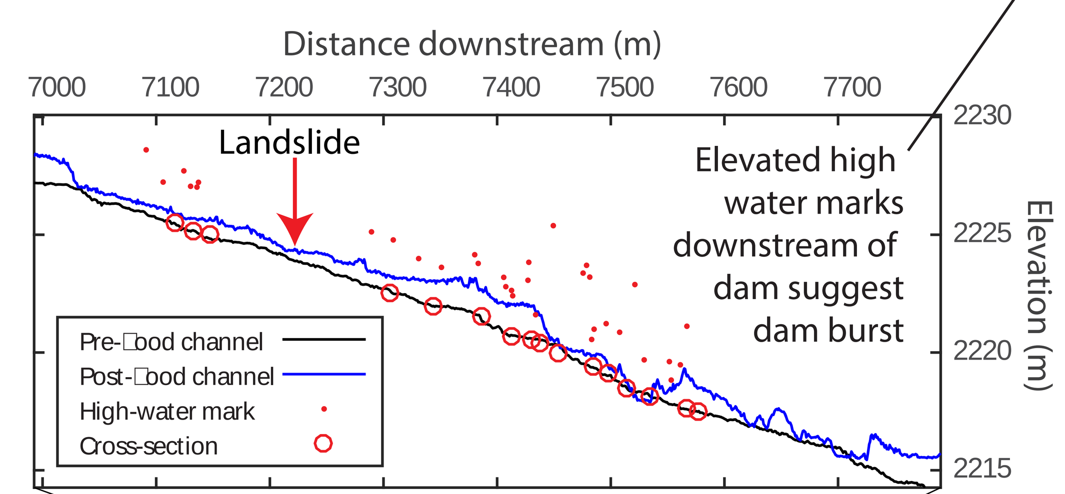
1. Differencing of pre (2011) and post (2013) flood LiDAR DEMs and interpretation of patterns of erosion



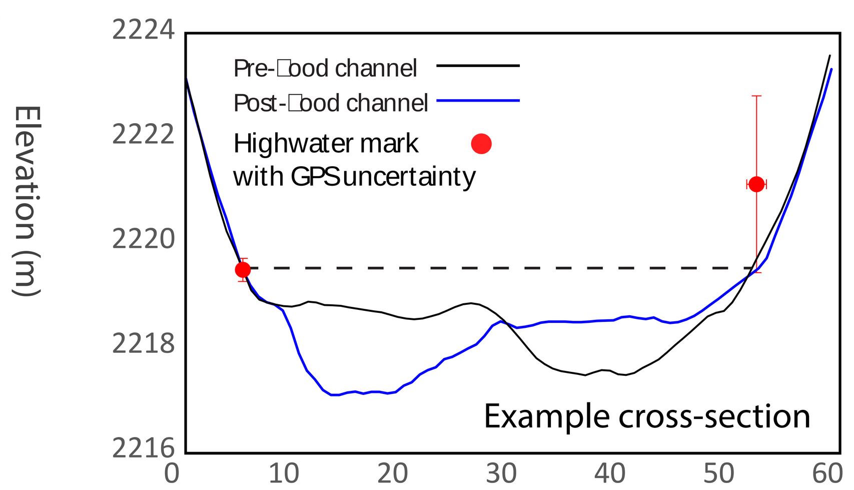
2. Discovery of remants of a debris dam just upstream of the observed increase in channel erosion.

3. Measurement of highwater marks up and downstream of debris dam with GPS to reconstruct flood peak discharge (Q_{peak})





4. Estimation of Q_{peak} from highwater marks and pre and post flood LiDAR, assuming critical flow



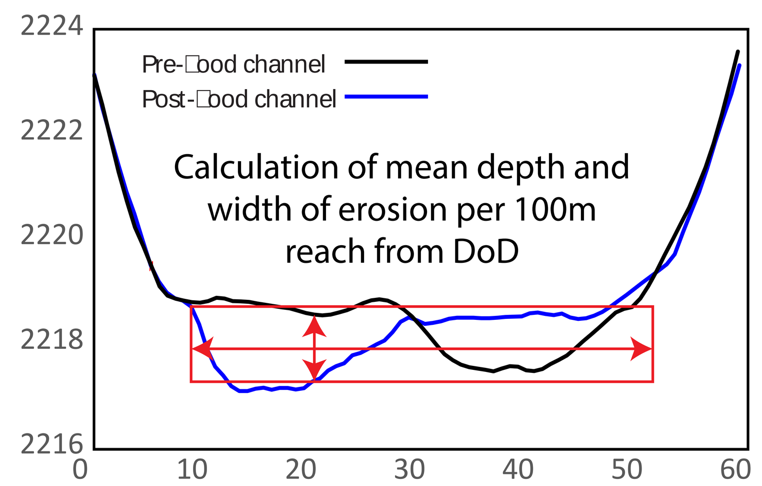
5. Modeling of peak discharge based on rainfall (Q_{runoff}) from the NCEP rainfall radar data (Gochis et al., 2015) and using flow routing with a 10m DEM within To-poToolbox 2 (Schwanghart and Scherler, 2014).

Assumptions: Peak runoff occurred on 11th September (Moody, 2016) once saturation had been reached. Runoff into channels was instantaneous.

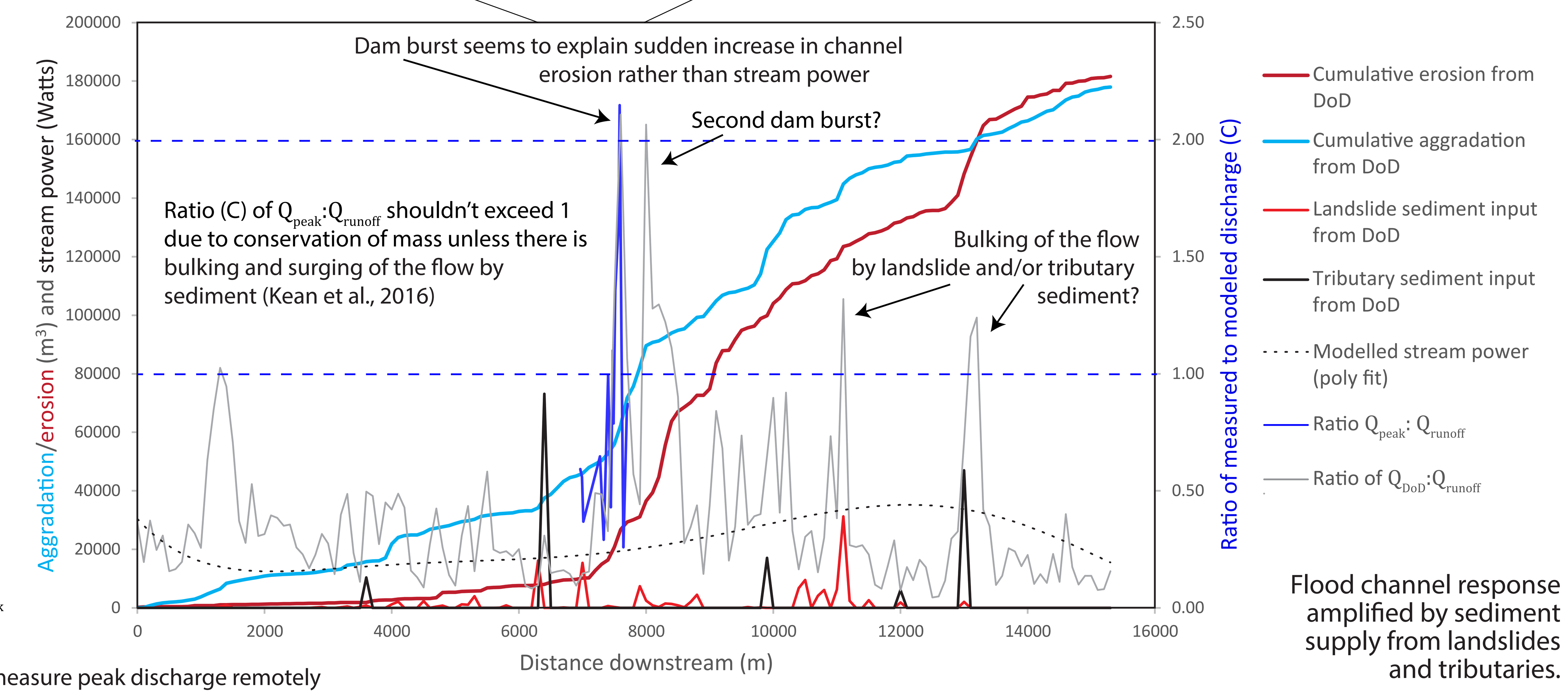
Q_{runoff} validated based on indirect peak discharge measurements of Moody (2016) at outlet of the North St Vrain (~380 m³/s)

6. Modeling of stream power based on Q_{runoff} and a 10m DEM

7. Calculation of peak discharge (Q_{DoD}) from LiDAR Dem of Difference (DOD)



- Use DoD width and depth to calculate cross-sectional area and hydraulic radius.
- Assumption of critical flow to calculate Q_{DoD} for each 100m reach.
- Good agreement with Q_{peak} in studied reach.
- Potential new method to measure peak discharge remotely



Flood channel response amplified by sediment supply from landslides and tributaries.

4) Conclusions and future work

The Colorado Front Range flood of September 2013 triggered multiple landslides and extensive flooding. Landslides not only accounted for ~50% of the sediment eroded by the event (Rathburn et al., in revision) but also had a profound effect on the channel geomorphic response. We find evidence for a debris dam in the North St Vrain that built up downstream of a large landslide and burst during the flood, creating a 'runaway train' of channel erosion that is not predicted by modeled stream power alone. Elsewhere, we find evidence for elevated channel erosion related to flow bulking by landslides and tributaries.

In future research we plan to model the dam accumulation and bursting to investigate the role of landslides in channel geomorphic response in more detail. We also plan to extend analysis to other flooded catchments.

5) Acknowledgements and references

Thanks to Russ Schumacher for providing rainfall radar data.

Bennett, G.L., Miller, S.R., Roering, J.J., Schmidt, D.A., 2016. Landslides, threshold slopes and the survival of relict terrain in the wake of the Mendocino Triple Junction. Geology, doi: 10.1130/G37530.1
Gartner, J.D., Dade, W.B., Renshaw, C et al., 2015. Gradients in stream power influence lateral and downstream sediment flux in floods. Geology, doi: 10.1130/G36969.1
Gochis, D., Schumacher, R., et al., 2014. The great Colorado flood of September 2013, AMS Bull, doi 10.1175/BAMS-D-13-00241.1
Kean, J.W., McGuire, L.A., Rengers, F.K, et al., 2016. Amplification of postwildfire peak flow by debris. GRL, doi 10.1002/2016GL069661
Magilligan, F.J., Buraas, E.M., Renshaw, C.E.,2015. The efficacy of stream power and flow duration on geomorphic responses to catastrophic flooding. Geomorphology, doi:10.1016/j.geomorph.2014.08.016
Moody, J. A., 2016. Estimates of peak discharge for 21 sites in the Front Range in Colorado in response to extreme rainfall in September 2013. USGS Report 2016-5003.
Rathburn, S., Bennett, G.L., Wohl, E., et al., The fate of sediment, wood and organic carbon eroded during an extreme flood, Colorado Front Range, USA. In revision with Geology.

Tracking the Fate of Sediment After an Extreme Flood

Eidmann, Johanna S.[1]; Rathburn, Sara L.[1]; Huson, Ken[2]

[1]Colorado State University [2]City of Longmont, CO

Introduction

~ Site Location and Background ~

From September 9-15, 2013, a tropical storm swept across the Colorado Front Range, producing a >200-year flood[1]. North St. Vrain, which flows into Ralph Price Reservoir west of Lyons, CO, was one of the most affected rivers. Within a 15-km reach of the North St. Vrain upstream of the reservoir, the storm produced:

- between 200 and 450 mm of precipitation[2]
- over 108 landslides[3]
- up to 10 m of aggradation (a volume of 246,000 m^3 of sediment) at an 800 m reach upstream of the reservoir, transforming it into an approach channel[3]
- an addition of 300,000 m^3 of sediment, producing an estimated 2% loss in reservoir storage capacity[3]

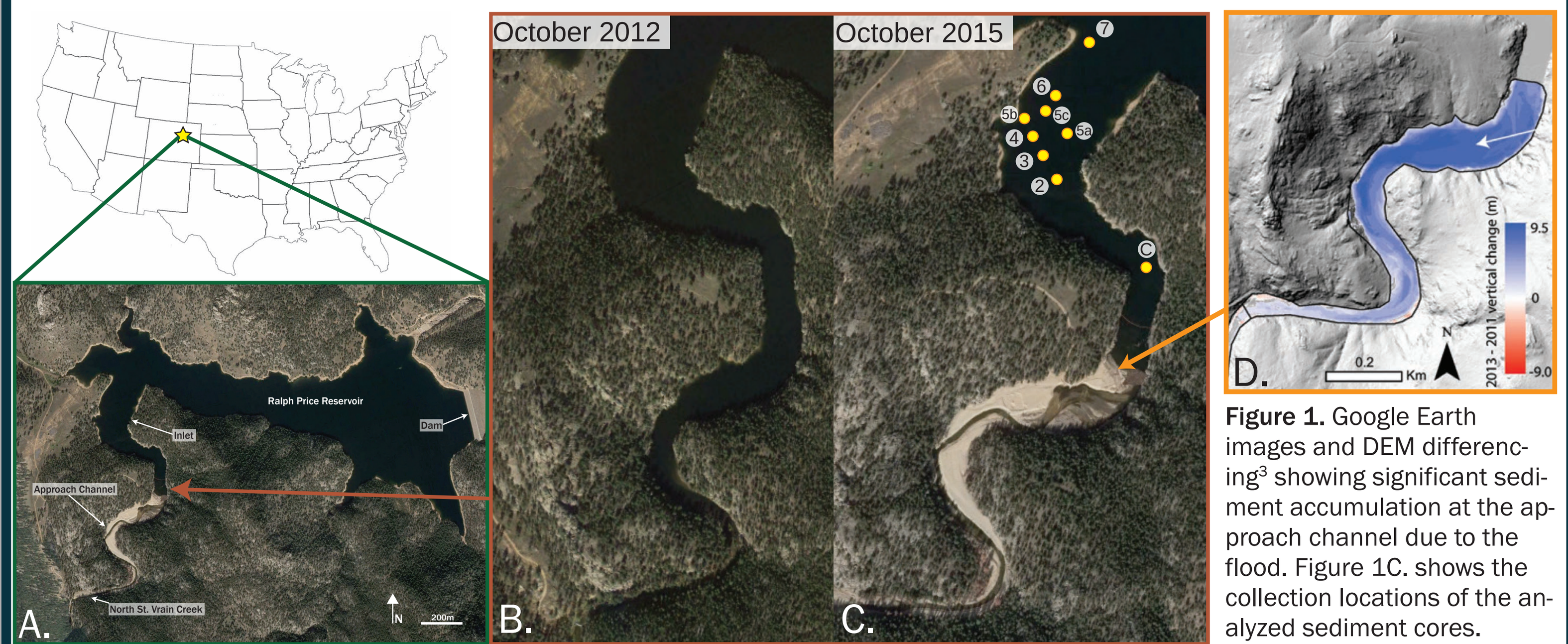


Figure 1. Google Earth images and DEM differencing[3] showing significant sediment accumulation at the approach channel due to the flood. Figure 1C. shows the collection locations of the analyzed sediment cores.

~ Research Questions and Objectives ~

- What is the volume of sediment that continues to be remobilized into the reservoir? How is this distributed spatially and temporally?
- How did post-flood (2014) rates of sedimentation and erosion compare to rates after a drop in reservoir baselevel (2016-2017)?
- What is the rate of delta progradation at the inlet between 2013 and 2017? Is this rate changing or remaining constant?

~ Field Research and Reservoir Activity Timeline ~

2013 September: four-day tropical storm, producing significant aggradation

October: FEMA lidar flown over reservoir

2014 April: conduct bathymetric survey of the inlet (Year 1)

2016 April: conduct bathymetric survey of the inlet (Year 3)

November: reservoir begins to be drained for downstream construction. Water level decreases by approximately 10 meters

2017 April: collect 8 cores along and across the reservoir inlet

May: conduct bathymetric survey of the reservoir; limited access to the inlet due to the low water level

July: water level of the reservoir increased to its original level

August: conduct bathymetric survey of the inlet (Year 4)

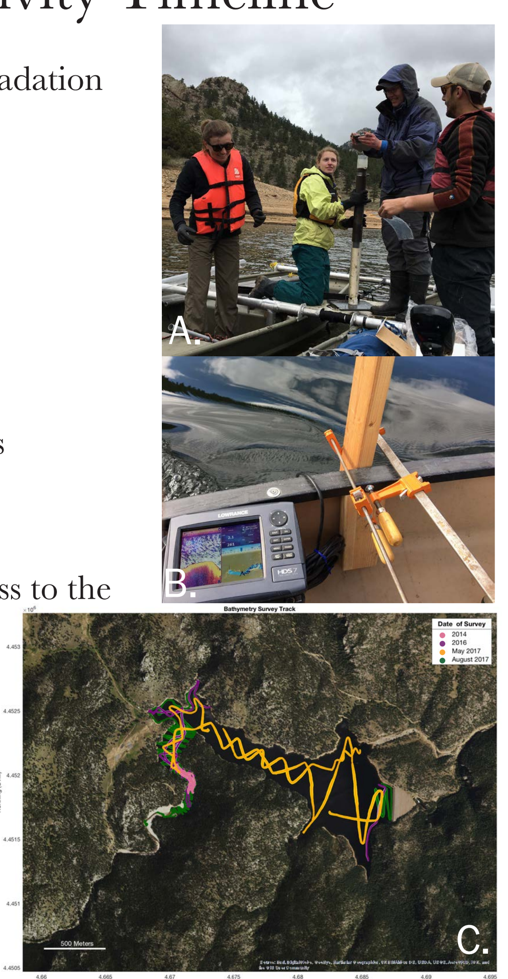
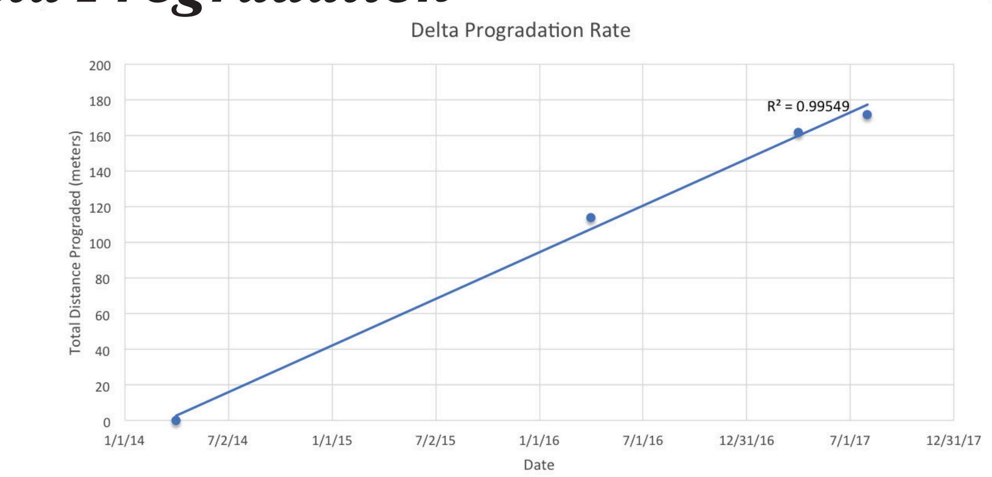


Figure 2. Pictures showing fieldwork including core collection (A) and traces of the bathymetric survey (B). Figure 2c. shows the spatial extent of various bathymetric surveys at Ralph Price Reservoir.

Results and Analysis

Delta Progradation



- Repeat bathymetry reveals that the delta front has prograded over 170 meters since the September 2013 flood.
- The rate of delta progradation (50 m/yr) has remained constant between April 2014 and April 2016 (post-flood), and between April 2016-May 2017 (period associated with a 10m drop in base level)
- The sub-annual rate of progradation between May 2017 and August 2017 (encompassing Spring snowmelt) suggests a decrease in progradation rate. An additional bathymetric survey in April 2018 is needed to confirm this hypothesis.

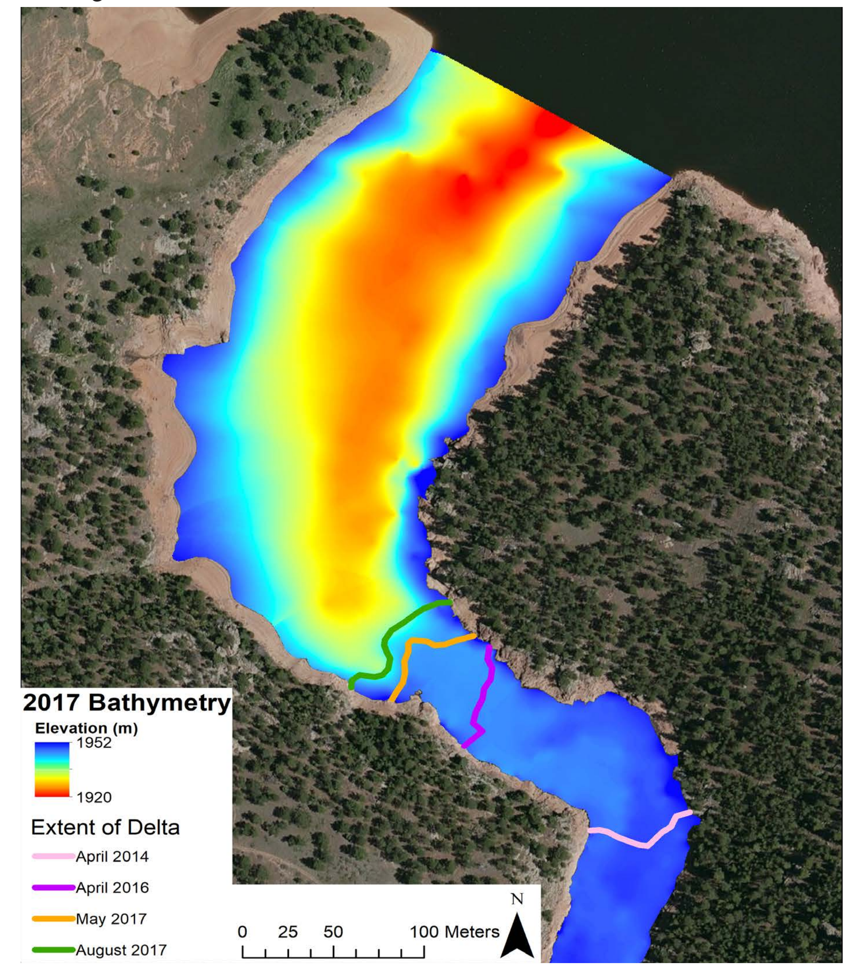


Figure 3. The August 2017 bathymetry of the reservoir inlet. Colored lines indicate the postion of the delta front with time.

Bathymetric Change Detection

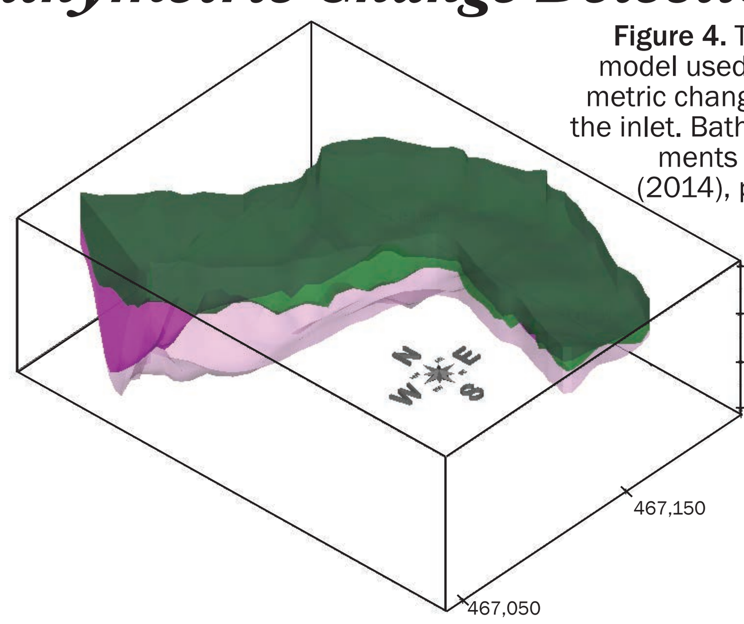


Figure 4. The 3-dimensional model used to calculate volumetric changes in sediment in the inlet. Bathymetric measurements are shown in pink (2014), purple (2016) and green (2017).

Time Interval	Volume Eroded (m^3)	Volume Deposited (m^3)	Net Volume Moved (m^3)	Total Volume (m^3)
April 2014 to April 2016	1,151	68,231	67,080	69,383
April 2016 to August 2017	15,657	5,551	-10,106	21,209
April 2014 to August 2017	64	57,039	56,974	57,103

- Between 2014 and 2017, over 57,000 m^3 of sediment has been deposited in Ralph Price Reservoir inlet
- The drop in baselevel (2016-2017) is likely associated with erosion of sediment from the inlet and deposition into the reservoir.

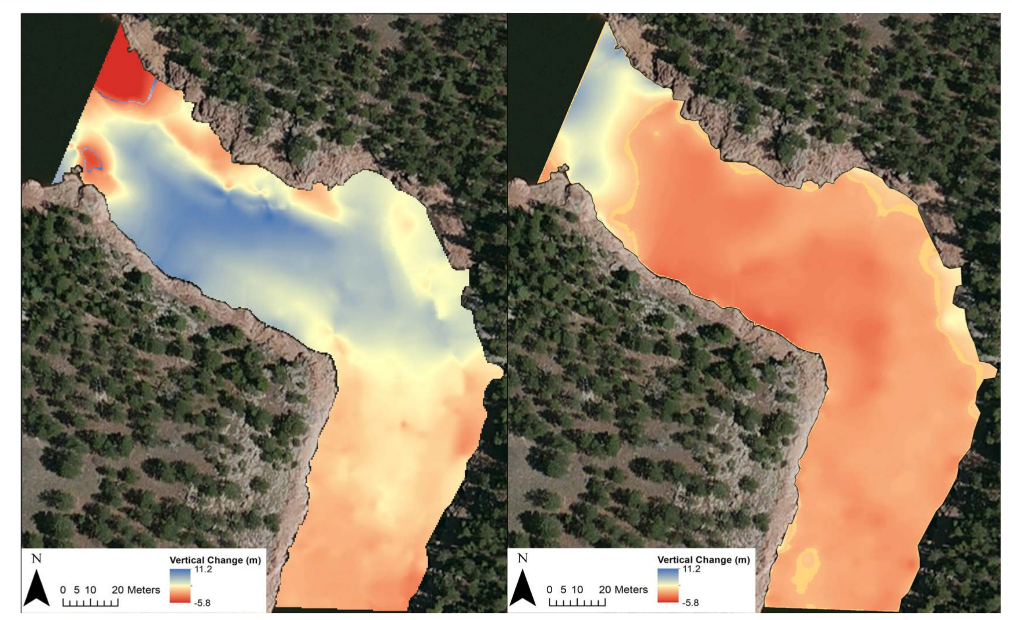
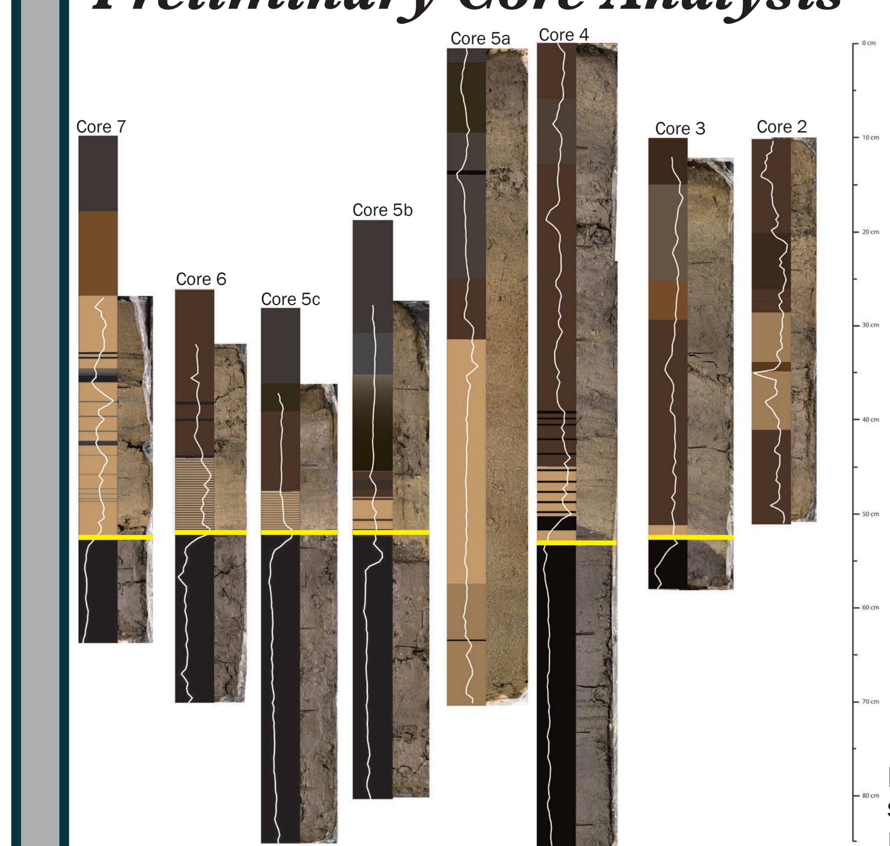


Figure 5. Maps of the inlet indicating spatial vertical changes in bathymetry between April 2014 and August 2017.

Preliminary Core Analysis



- Cores collected from the inlet show visually distinct stratigraphic layers associated with pre- and post-flood sediments. An associated spike in magentic susceptibility at the contact between pre- and post-flood confirms this sudden transition.
- Cores collected from the inlet show post-flood sediment accumulation between 20 cm to 70 cm.
- Geostatistical analysis of volumetric sediment accumulation, when applying flood-related sediment thickness in cores across the inlet, predicts an accumulation of 26,000 m^3 of sediment. Using sediment cores therefore underpredicts estimates of volumetric inputs into the reservoir relative to bathymetric change detection.

Figure 6. An illustration of the cores collected across the inlet. White lines indicate changes in magnetic susceptibility. Visual analysis of the cores show changes in stratigraphy with depth, as well as the pre-flood to post-flood sediment interface (shown in yellow).

Future Analysis

Figure 7. A modified Google image indicating the locations of fieldwork data that will be analyzed in future research.

Field Data Collected (completed):

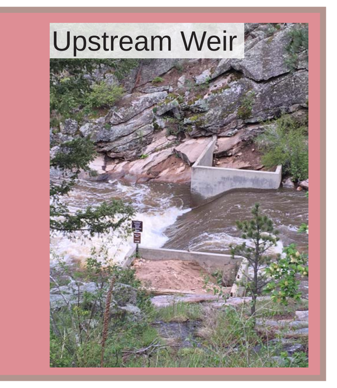
- Delta Bathymetry (Apr. 2014, Apr. 2016, May 2017, Aug. 2017)
- Sediment Cores (Apr. 2017)

Field Data Collected:

- Channel Dimensions (Aug. 2016, Aug. 2017)
- High-resolution Digital Elevation Model (Apr. 2017, Oct. 2017)
- Channel grain size distribution (Oct. 2014, Aug. 2017)
- Tracking gravel and cobble movement using RFID tags (between Apr. 2017 and Oct. 2017, and ongoing)

Field Data Collected:

- Weir discharge measurements (Apr. 2017 - ongoing)



~ Research Questions ~

- What are the drivers to channel morphological changes?
- Is the magnitude of overall channel response after the flood decreasing with time?
- Can we use changes in channel geometry at the approach channel to calculate annual sediment deposition of the delta?

~ Research Objectives~

- Incorporate measured discharge values into morphodynamic models to test our predictive capabilities of channel change
- Predict the continued progradation of the delta with time

Acknowledgements

City of Longmont, Jamie Freel
Colorado Water Institute
Colorado Scientific Socity
Association of Engineering Geologists
American Water Resources Association
Geosyntec Consultants (Eryn Torres)
Dr. Michael Ronayne, Dr. Brandon McElroy
Dr. Christy Briles, Juli Scamardo,
Michael Gordon, Adam Nielson

References

1. Yochum, S., 2015, September 2013 Colorado Front Range flood: Peak flows, flood frequencies, and impacts: Proceedings, 3rd Joint Federal Interagency Conference on Sedimentation and Hydrologic Modeling, p. 537–548, https://acwi.gov/sos/pubs/3rdJFIC/Contents/3F-Yochum.pdf.
2. Coe, J.A., Kean, J.W., Godt, J.W., Baum, R.L., Jones, E.S., Gochis, D.J., and Anderson, G.S., 2014, New insights into debris-flow hazards from an extraordinary event in the Colorado Front Range: GSA Today, v. 24, p. 4–10, doi: 10 .1130 /GSATG214A .1.
3. S.L Rathburn, G.L. Bennett, E.E. Wohl, C. Briles, B. McElroy, N. Sutfin; The fate of sediment, wood, and organic carbon eroded during an extreme flood, Colorado Front Range, USA. Geology ; 45 (6): 499–502. doi: https://doi.org/10.1130/G38935.1

THE GEOLOGICAL SOCIETY OF AMERICA®

The fate of sediment, wood, and organic carbon eroded during an extreme flood, Colorado Front Range, USA

S.L Rathburn[1], G.L. Bennett[1,2], E.E. Wohl[1], C. Briles[3], B. McElroy[4], and N. Sutfin[1]
[1]Department of Geosciences, Campus Delivery 1482, Colorado State University, Fort Collins, Colorado 80523-1482, USA
[2]U.S. Forest Service, Rocky Mountain Research Station, 240 Prospect Road, Fort Collins, Colorado 80526, USA
[3]Department of Geography and Environmental Sciences, Campus Box 172, University of Colorado Denver, Denver, Colorado 80217-3364, USA
[4]Department of Geology and Geophysics, Department 3006, University of Wyoming, Laramie, Wyoming 82071, USA

ABSTRACT

Identifying and quantifying the dominant processes of erosion and tracking the fate of sediment, wood, and carbon eroded during floods is important for understanding channel response to floods, downstream sediment and carbon loading, and the influence of extreme events on landscapes and the terrestrial carbon cycle. We quantify sediment, wood, and organic carbon (OC) from source to local sink following an extreme flood in the tectonically quiescent, semiarid Colorado (USA) Front Range. Erosion of >500,000 m^3 or as much as ~115 yr of weathering products occurred through landsliding and channel erosion during September 2013 flooding. More than half of the eroded sediment was deposited at the inlet and delta of a water supply reservoir, resulting in the equivalent of 100 yr of reservoir sedimentation and 2% loss in water storage capacity. The flood discharged 28 Mg C/km^2, producing an event OC flux equivalent to humid, tectonically active areas. Post-flood remobilization resulted in a further ~100 yr of reservoir sedimentation plus export of an additional 1.3 Mg C/km^2 of wood, demonstrating the ongoing impact of the flood on reservoir capacity and carbon cycling. Pronounced channel widening during the flood created accommodation space for 40% of flood sediment and storage of wood and eroded carbon. We conclude that confined channels, normally dismissed as transport reaches, can store and export substantial amounts of flood constituents.

INTRODUCTION

Extreme floods in mountainous regions typically coincide with mass movements through intense precipitation. This combination profoundly alters hillslopes, riparian areas, and channel geometry, and introduces large volumes of sediment, wood, and nutrients such as organic carbon (OC) into rivers. Identifying and quantifying the magnitudes and processes of erosion of sediment, wood, and OC from hillslopes and channels and tracking the fates of flood constituents through budgeting are important for understanding channel response to floods, as well as for informing management and restoration.

Budgets for fluvial materials can also be used to create context for short-term, small-scale measurements of mass fluxes, particularly during episodic extreme events, and to understand the relative importance of diverse local sources and sinks at varying time and space scales. Mass budgets thus form a vital part of studies of the critical zone, yet they rarely combine the triad of sediment, wood, and carbon. Existing studies of sediment and/or wood-derived fluxes come from tropical and/or tectonically active regions (e.g., Hilton et al., 2008; Wohl and Ogden, 2013). Mountainous mid-latitude regions have been highlighted as hotspots of OC accumulation (Schimel and Braswell, 2005), yet we lack details of OC dynamics for these regions (e.g., Smith et al., 2001), particularly with respect to the significance of extreme events to OC fluxes and partitioning of OC fluxes into sediment and wood.

We present an integrated sediment, wood, and OC budget derived from a semiarid, tectonically quiescent catchment in the southern Rocky Mountains (western USA) that underwent an extreme rainstorm and associated hillslope failures and flooding in September 2013. The Ralph Price Reservoir at the lower end of North St. Vrain Creek (NSV) in the Colorado Front Range allows us to develop a source-to-sink budget of sediment, wood, and OC fluxes during the 2013 storm. Unlike other canyons in the Front Range where extensive post-flood sediment and wood removal occurred, no unquantified post-flood clearance was carried out along NSV Creek, thus it provides an ideal setting to document the immediate and ongoing effects of the flood. We quantify fluxes of sediment, wood, and carbon within the catchment during the 2013 event and quantify post-flood remobilization to understand the fate of flood-derived constituents and the processes of continued downstream transport and loading to the reservoir. Fluxes during and after the extreme disturbance are then compared to decadal and long-term average rates from the study area to assess the significance of the event geomorphically and for the terrestrial carbon cycle.

STUDY SITE AND METHODS

NSV Creek is underlain by Precambrian granite and biotite schist (Braddock and Cole, 1990) and drains the east side of the Continental Divide in northern Colorado (Fig. 1). The mountainous portion of NSV Creek has cascade, step-pool, or riffle-run morphology formed in cobble to boulder-size sediment. Valley geometry varies longitudinally, although the study reach is laterally confined, with the valley bottom generally less than eight times the bankfull channel width. A 15 km reach of NSV Creek is bounded upstream by a low-gradient beaver meadow where 2013 flood effects were minimal (overbank deposition of sand and gravel; Wohl et al., 2017) and downstream by Ralph Price Reservoir where the trapping efficiency for sediment (>0.63 mm), wood, and OC is effectively 100%. As it enters the reservoir, NSV Creek is ~15 m wide and drains 245 km^2. The upper basin is within Rocky Mountain National Park and a city preserve and has undergone minimal logging, land development, or flow regulation.

From 9–15 September 2013, a large tropical storm produced >350 mm of precipitation (Gochis et al., 2015), generating a >200 yr flood (Yochum, 2015) that swept through towns along the base of the Front Range, causing multiple deaths and extensive damage to infrastructure. Peak flood discharge measured through the spillway of Ralph Price Reservoir was estimated as 280 m^3/s (K. Huson, 2013, personal commun.; mean annual peak flow of 20 m^3/s; Wohl et al., 2004). This discharge was sustained for at least a day following peak rainfall intensity. Abundant landslides stripped hillslopes in the NSV (Coe et al., 2014; Rengers et al., 2016). Erosion by landsliding of hundreds to thousands of years of hillslope weathering projects was determined in basins to the south (Anderson et al., 2015), but our study is the first (of which we are aware) to quantify the fate of the eroded sediment, along

Data Repository item 2017158 | doi:10.1130/G38935.1

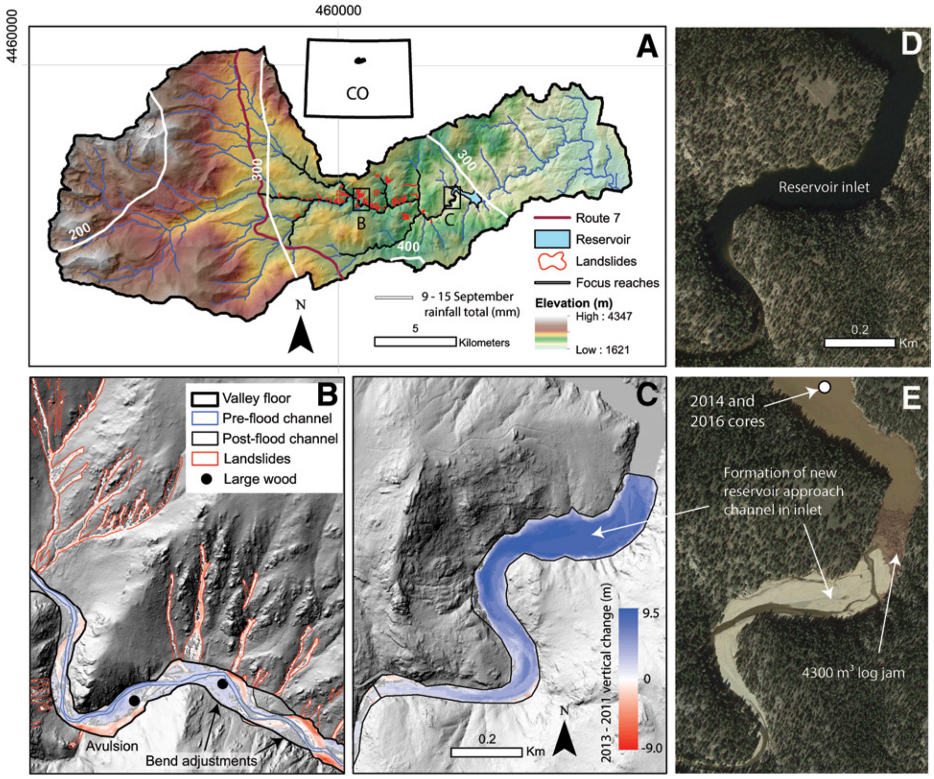


Figure 1. Flood impacts in the North St. Vrain Creek catchment, northern Colorado, USA. A: Catchment location, topography, and study sites with respect to total flood rainfall and landslides. B: Digital elevation model of difference (DoD) between pre-flood and post-flood lidar for the study reach highlighted in A. C: DoD showing extensive flood deposition in the reservoir inlet, forming a new approach channel. Vertical change in range of red to blue, and horizontal scale in C, applies to B and C. D: Reservoir inlet shown in C. Images in D and E are from Google Earth™. E: Locations of a large log jam formed during the flood, new approach channel, and reservoir delta cores.

with wood and carbon, and to document the ongoing implications for reservoir storage and carbon cycling.

A combination of field work and analysis of remotely sensed data was used to quantify sediment, wood, and OC budgets along a 15 km reach (100 km^2) of NSV Creek upstream from the reservoir in which rainfall and flood effects were concentrated (Fig. 1A). We quantified flood-derived sediment, wood, and OC inputs (I) and outputs (O) and compared these to stored volumes (ΔS), using the simple budget equation $I - O = \Delta S$, where O is sediment, wood, and carbon delivered to Ralph Price Reservoir. No flushing of sediment, wood, and associated OC has occurred since dam closure in May 1969, allowing us to compare flood and post-flood sedimentation rates with decadal rates prior to the flood.

Sediment Input, Output, and Storage

Inputs of sediment were quantified through a digital elevation model (DEM) of difference (DoD) produced from 2011 (pre-flood) and 2013 (post-flood) lidar-derived DEMs with Geomorphic Change Detection (GCD) software (Wheaton et al., 2010). We identified a minimum level of detection as 2 standard deviations of elevation change in areas with no expected change, setting a threshold of ±0.34 m for the DoD. We mapped the aerial extent of landslides initiated during the 2013 storm as well as processes of channel erosion and deposition and performed a budget segregation with GCD to associate volumes of erosion and deposition with these different processes. Volumetric uncertainty associated with the 0.34 m threshold is propagated into the sediment budget and typically ranges from 7% to 40% for a particular geomorphic unit.

We quantified output sediment volume at the reservoir inlet from the DoD, along with repeat ground-based topographic surveys. We quantified sediment deposited in the reservoir delta by differencing sonar bathymetry collected in March 2014 and preimpoundment topography. We determined the flood contribution of sedimentation in the delta from a reservoir core (Fig. 1E) collected after the flood that showed clear flood and pre-flood stratigraphy, as well as through extensive probing of delta sediment to determine representative aggradation over the broader delta area. The core was collected from the distal portion of the delta toe where large lateral variability in sediment composition is unlikely.

Remobilization of sediment along the approach channel during snowmelt 2014 was quantified using field surveys. Horizontal and vertical error averaged 1–6 cm and 6–9 cm, respectively. We collected another reservoir core in 2016 (Fig. 1E) to quantify additional contributions to the delta following 2 yr of above-average snowmelt runoff in 2014 and 2016.

Wood Input, Output, and Storage

We quantified wood input from the area of floodplain erosion estimated from the DoD. We applied an average volume of wood per area, V = 234 m^3/ha, calculated from undisturbed sections of the riparian corridor using $V = AH\rho$, where A is mean trunk basal area, H is mean tree height, and ρ is mean stem density. Hillslope input of wood is considered negligible because the hillslopes affected by landsliding were not heavily vegetated pre-flood (Rengers et al., 2016). Wood output at the reservoir inlet was based on an estimate of wood removed by contractors following the flood (Fig. DR1 in the GSA Data Repository[1]).

OC Input, Output, and Storage

Organic carbon addressed herein is that within sediment eroded from hillslopes and riparian areas distinguished as soil, litter, and large wood, and organic material analyzed in core sediment collected from the reservoir delta. Input of carbon is based on area of disturbance estimated by lidar differencing and on values of carbon in soil, litter, and above-ground biomass of 85, 30, and 100 Mg C/ha, respectively (DeLuca and Aplet, 2008). These values are representative of montane, fire-maintained, ponderosa pine forests with a stand age of ~100 yr (DeLuca and Aplet, 2008), accurately describing our study area.

RESULTS

2013 Flood Sediment, Wood, and Carbon Budget

More than 500,000 m^3 of sediment were eroded in the flood with nearly equal inputs from hillslope and channel erosion (Fig. 2; Table DR1). Landsliding dominated hillslope erosion, with 108 landslides (10–23,000 m^3) eroding a volume of 218,000 m^3, or 43% of the total flood eroded volume. Tributary channels contributed a further 152,400 m^3 (30%) of sediment. Erosion along the trunk channel accounted for the remaining 135,500 m^3 (27%) of flood eroded sediment, with lateral erosion through processes of bend adjustment (widening without avulsion)

[1]GSA Data Repository item 2017158, tabulated sediment, wood, and carbon volumes; pre- and post-flood sediment yields and carbon loading; total organic carbon compared to extreme events worldwide (with Figures DR1–DR7 of reservoir core and ^{210}Pb ages); electrical resistivity and ground-penetrating radar results; and grain size analyses, is available online at http://www.geosociety.org/datarepository/2017/ or on request from editing@geosociety.org.

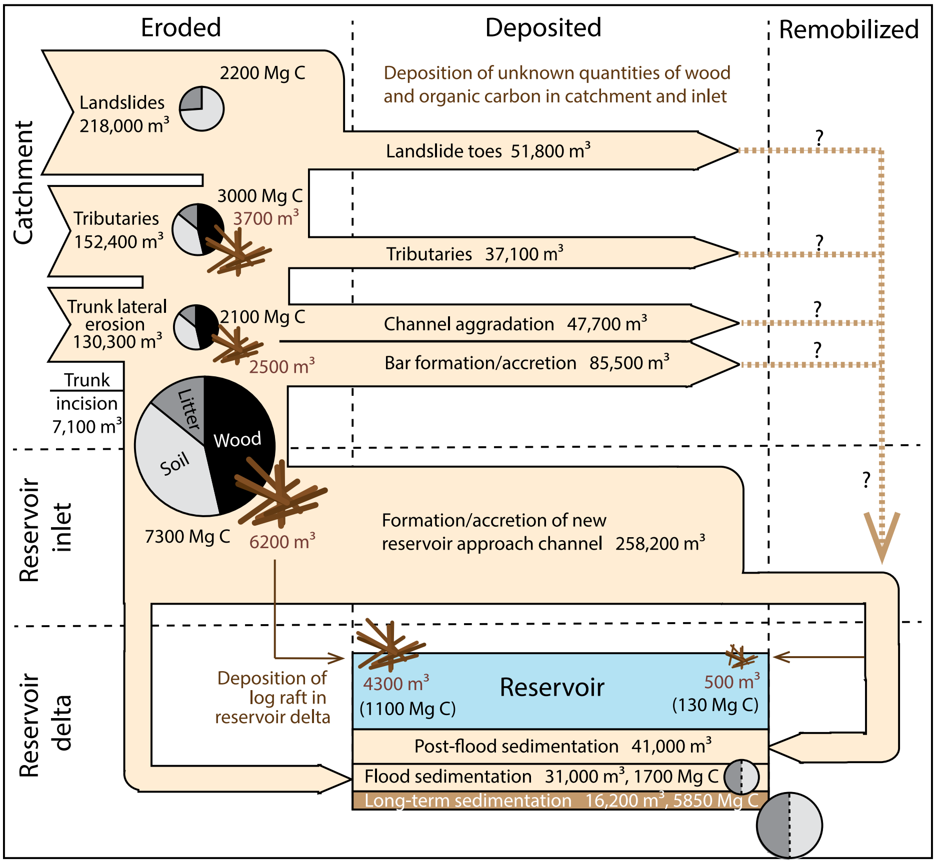


Figure 2. Flood and post-flood sediment, carbon, and wood flux diagram for the North St. Vrain Creek catchment, Colorado, USA. Pie diagrams represent organic carbon as soil, litter, and wood, and illustrated wood jams represent volumes of large wood. Colors of boxes, arrows, and text are consistent for sediment (tan) and wood (brown), with pie diagram colors for soil (gray), litter (dark gray), and wood (black) as carbon. The sediment flux component is based on Fryirs and Brierley (2001).

and bank erosion accounting for 97% of the total (Figs. 1B and 3).

Approximately 60% (289,200 m^3) of eroded sediment was discharged into the reservoir; ~50% (258,200 m^3) was deposited in the inlet, forming a new approach channel (Figs. 1C and 1E), and an additional 10% (31,000 m^3) of sediment was deposited within the reservoir delta based on a comparison of post-flood reservoir bathymetry with pre-dam topography and sediment core. Summing inlet and delta sediment deposition indicates a loss of total water storage capacity of ~2%.

The remaining ~40% of flood-eroded sediment (222,000 m^3) was deposited in the catchment upstream from the reservoir (Fig. 1B), predominantly within the accommodation space created by lateral erosion across the valley bottom or at the scoured toes of hillslopes in highly confined reaches. Flood erosion of the NSV channel occupied the entire width of the valley along ~90% of the study reach (Fig. DR2). We observe a strong correlation between sediment aggradation and channel widening (Fig. 3). The greatest widening and sediment aggradation were associated with the processes of bend adjustment and avulsions, which were in turn associated with large wood accumulation in the channel that possibly caused log jams (Fig. 3; Figs. DR2 and DR3B).

The difference between sediment input (507,800 m^3) and output (289,200 m^3) plus storage (222,000 m^3) produces a discrepancy of only 3400 m^3 in our budget, allowing us to account for the fate of 99% of total eroded sediment (Fig. 2; Table DR1). It is likely that the missing 1% is due to large amounts of unquantified suspended sediment in the reservoir, evident in post-flood images (Fig. 1E). Therefore, the budget is a minimum estimate of loading to the reservoir.

Lateral erosion of the floodplain input 6200 m^3 of wood. This is nearly balanced by 4300 m^3 of wood that was removed after the flood from a large floating jam in the reservoir (Figs. 1E and 2; Fig. DR1). We estimate that ~2000 m^3 of wood remains stored in sediment in the new reservoir approach channel and within log jams in the upper catchment (Table DR1).

Approximately 7300 Mg C were eroded during the flood, with 2200 Mg C as soil OC from channels and hillslopes, and 5100 Mg C stripped from the channel corridor as wood, litter, and soil carbon (Table DR1). Organic carbon deposited in the reservoir was estimated as 2800 Mg C, with 1100 Mg C of this deposited as wood in a large log jam at mouth of the reservoir (Fig. 1E) and the remainder as fine organic matter in the reservoir delta. We treat the OC component in the budget as an order of magnitude approximation.

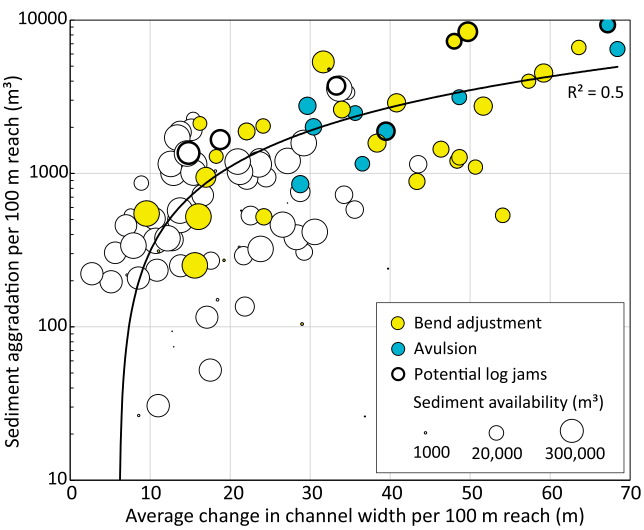


Figure 3. Associations between flood sediment aggradation, channel widening, processes of bend adjustment and avulsion, and potential log jams along North St. Vrain Creek, Colorado, USA. Channel-width change was measured as the difference between pre-flood and post-flood channel corridor (see Fig. 1B) at 20 m increments averaged by 100 m reach compared to sediment aggradation. Marker size is proportional to sediment availability calculated as the cumulative net change downstream.

Long-Term Significance of the Flood Geologically and for the Carbon Cycle

The flood resulted in a lowering of 3.4 mm averaged over the 100 km^2 area of lidar analysis (Table DR2); this is ~57–115× greater than cosmogenic nuclide erosion rates for the region of 0.03–0.06 mm/yr (Dethier et al., 2014). We estimate that a minimum of 420 mm of flood sedimentation occurred within Ralph Price Reservoir, nearly 100× greater than the 5.4 mm/yr background sedimentation rate over the 44 yr life of the dam. The flood carbon yield of 28 Mg C/km^2 was ~50× greater than pre-flood carbon yield of 0.5 Mg C/km^2 (Table DR3).

Post-flood Remobilization

Snowmelt runoff in 2014 resulted in 3 m of channel incision of unconsolidated flood deposits in the reservoir approach channel (Figs. DR5 and DR6), remobilizing 41,000 m^3 of sediment into the reservoir delta (Fig. 2; Table DR1). A further 1.30 Mg C/km^2 was remobilized into the reservoir as large wood, equivalent to a further 21 yr of carbon loading based on pre-flood carbon yield.

DISCUSSION

We document the fate of sediment, wood, and carbon in a highly flood-affected catchment in the Colorado Front Range. The 2013 flood caused 57–115 yr of erosion and 100 yr of reservoir sedimentation. Notably, the 5.4 mm/yr pre-flood sedimentation rate is comparable to modern post-fire erosion rates from burned areas of similar elevation in Colorado (Moody and Martin, 2001). High decadal rates of sedimentation likely reflect the crystalline geology and location of the study reach downstream from a knickzone formed by rapid incision of rivers through the softer sediment of the Front Range piedmont (Anderson et al., 2015).

NSV flooding produced 28 Mg C/km^2 through erosion of soil carbon, litter, and wood. This value is comparable, on an order of magnitude, to estimates of storm-derived carbon in wetter and/or tectonically active areas (Table DR3). High-OC storm inputs into NSV Creek are likely related to a longer storm recurrence interval and extensive lateral channel erosion that denuded valley bottom OC in soils, litter, and riparian vegetation. Post-flood wood removed from the reservoir was identified primarily as riparian in origin. Furthermore, recovery of hillslope weathering products, riparian vegetation, and overbank sediment deposition, the basis for reestablishing pre-flood carbon stocks, will take much longer along NSV Creek than for tropical counterparts, and may be ~10^2–10^3 yr.

Although flood yields of sediment and carbon (particularly as wood) were very high for the NSV catchment both historically and in comparison to extreme events elsewhere, much eroded material remains stored in the catchment in the accommodation space created through pronounced channel widening. The stored sediment represents another potential 1% loss of total water storage capacity within the reservoir. Our results indicate that many flood-affected Front Range rivers store, and therefore will export, sediment, wood, and carbon for years to come, posing ongoing challenges to downstream communities and reservoirs and with implications for carbon cycling on lower order streams that make up a majority of stream length. Continued high discharges may result in disproportionate transport of coarse particulate organic matter (Turowski et al., 2016). In a disturbance context, confined channels have long been treated as transport reaches (Montgomery, 1999). A flood-induced change in channel confinement, however, brings new focus to flood-affected confined channels regionally and to rivers worldwide that function as important post-flood source areas.

CONCLUSIONS

We developed an integrated sediment, wood, and organic carbon (OC) budget from source to anthropogenic sink following an extreme flood in the Colorado Front Range through a combination of lidar differencing, reservoir surveying, and coring. Extensive landsliding and channel erosion during September 2013 flooding transformed the reservoir inlet into an approach channel, deposited ~100 yr of sediment into the reservoir, accounting for ~2% loss in capacity, and produced an OC flux equivalent to those documented in more humid, tectonically active areas. Approximately 40% of flood sediments remain stored in the upper catchment, predominantly within accommodation space created by flood-induced channel widening. Post-flood snow melt remobilized and redeposited a flood-equivalent volume of sediment from the approach channel to the reservoir. Our results indicate that many flood-affected Front Range rivers will export sediment, wood, and carbon for years to come, posing ongoing challenges for water-supply management, with implications for terrestrial carbon cycling. Although confined rivers function as dominantly transport reaches, pronounced channel widening during extreme events may accommodate sediment storage and switch these channels to post-flood source areas.

ACKNOWLEDGMENTS

Funding was provided through National Science Foundation award EAR-1410472 and the Gladys Cole Memorial Fund (Quaternary Geology and Geomorphology Division, Geological Society of America). We thank the numerous people who helped in the field, laboratory, and with data analysis. Jon Major and two anonymous reviewers helped clarify the text.

REFERENCES CITED

Anderson, S.W., Anderson, S.P., and Anderson, R.S., 2015, Exhumation by debris flows in the 2013 Colorado Front Range Storm: Geology, v. 43, p. 391–394, doi:10.1130/G36507.1.

Braddock, W.A., and Cole, J.S., 1990, Geologic map of Rocky Mountain National Park and vicinity, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-1973, scale 1:50,000.

Coe, J.A., Kean, J.W., Godt, J.W., Baum, R.L., Jones, E.S., Gochis, D.J., and Anderson, G.S., 2014, New insights into debris-flow hazards from an extraordinary event in the Colorado Front Range: GSA Today, v. 24, p. 4–10, doi:10.1130/GSATG214A.1.

DeLuca, T., and Aplet, G., 2008, Charcoal and carbon storage in forest soils of the Rocky Mountain west: Frontiers in Ecology and the Environment, v. 6, p. 18–24, doi:10.1890/070070.

Dethier, D., Ouimet, W., Bierman, P., Rood, D., and Balco, G., 2014, Basins and bedrock: Spatial variation in ^{10}Be erosion rates and increasing relief in the southern Rocky Mountains, USA: Geology, v. 42, p. 167–170, doi:10.1130/G34922.1.

Fryirs, K., and Brierley, G., 2001, Variability in sediment delivery and storage along river courses in Bega catchment, NSW, Australia: Implications for geomorphic river recovery: Geomorphology, v. 38, p. 237–265, doi:10.1016/S0169-555X(00)00093-3.

Gochis, D., Schumacher, R., Friedrich, K., Doesken, N., Kelsch, M., Sun, J., Ikeda, K., Lindsey, D., Wood, A., and Dolan, B., 2015, The great Colorado flood of September 2013: American Meteorological Society Bulletin, v. 96, p. 1461–1487, doi:10.1175/BAMS-D-13-00241.1.

Hilton, R.G., Galy, A., and Hovius, N., 2008, Riverine particulate organic carbon from an active mountain belt: Importance of landslides: Global Biogeochemical Cycles, v. 22, GB1017, doi:10.1029/2006GB002905.

Montgomery, D., 1999, Process domains and the river continuum: American Water Resources Association Journal, v. 35, p. 397–410, doi:10.1111/j.1752-1688.1999.tb03598.x.

Moody, J., and Martin, D., 2001, Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range: Earth Surface Processes and Landforms, v. 26, p. 1049–1070, doi:10.1002/esp.253.

Rengers, F.K., McGuire, L.A., Coe, J.A., Kean, J.W., Baum, R.L., Staley, D.M., and Godt, J.W., 2016, The influence of vegetation on debris-flow initiation during extreme rainfall in the northern Colorado Front Range: Geology, v. 44, p. 823–826, doi:10.1130/G38096.1.

Schimel, D., and Braswell, B.H., 2005, The role of mid-latitude mountains in the carbon cycle: Global perspective and a western US case study, *in* Huber, U.M., et al., eds., Global change and mountain regions: Amsterdam, Springer, p. 449–456, doi:10.1007/1-4020-3508-X_45.

Smith, S.V., Renwick, W.H., Buddemeier, R.W., and Crossland, C.J., 2001, Budgets of soil erosion and deposition for sediments and sedimentary organic carbon across the conterminous United States: Global Biogeochemical Cycles, v. 15, p. 697–707, doi:10.1029/2000GB001341.

Turowski, J., Hilton, R., and Sparkes, R., 2016, Decadal carbon discharge by a mountain stream is dominated by coarse organic matter: Geology, v. 44, p. 27–30, doi:10.1130/G37192.1.

Wheaton, J.M., Brasington, J., Darby, S.E., and Sear, D.A., 2010, Accounting for uncertainty in DEMs from repeat topographic surveys: Improved sediment budgets: Earth Surface Processes and Landforms, v. 35, p. 136–156, doi:10.1002/esp.1886.

Wohl, E., and Ogden, F., 2013, Organic carbon export in the form of wood during an extreme tropical storm, upper Rio Chagres, Panama: Earth Surface Processes and Landforms, v. 38, p. 1047–1416, doi:10.1002/esp.3389.

Wohl, E., Kuzma, J., and Brown, N., 2004, Reach-scale channel geometry of a mountain river: Earth Surface Processes and Landforms, v. 29, p. 969–981, doi:10.1002/esp.1078.

Wohl, E., et al., 2017, Mapping longitudinal stream connectivity in the North St. Vrain Creek watershed of Colorado: Geomorphology, v. 277, p. 171–181, doi:10.1016/j.geomorph.2016.05.004.

Yochum, S., 2015, September 2013 Colorado Front Range flood: Peak flows, flood frequencies, and impacts: Proceedings, 3rd Joint Federal Interagency Conference on Sedimentation and Hydrologic Modeling, p. 537–548, https://acwi.gov/sos/pubs/3rdJFIC/Contents/3F-Yochum.pdf.

Manuscript received 22 September 2016
Revised manuscript received 26 January 2017
Manuscript accepted 29 January 2017

Printed in USA