Linking Sedimentation and Erosion Patterns with Reservoir Morphology and Dam Operations during Streambed Drawdowns in a Flood-control Reservoir in the Oregon Cascades

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Abstract

Since water-year (WY) 2011, pool levels at Fall Creek Lake, Oregon, are temporarily lowered to an elevation near historical streambed each fall, creating free-flowing channel conditions that facilitate downstream passage of juvenile spring Chinook salmon. These drawdown operations have also mobilized substantial quantities of predominantly fine (<2 mm) reservoir sediment as well as some coarser gravels. To assess the potential impact of reservoir sediment erosion and transport on downstream reach morphology and habitats, linkages between reservoir sedimentation in Fall Creek Lake and drawdown-related reservoir erosion are inferred from geomorphic mapping and volumetric change analyses developed from high resolution aerial photographs and digital elevation models of the empty reservoir. Recent and historical drawdown operations have helped maintain a thalweg in much of Fall Creek Lake, constraining most coarse-grained sediment transport and re-deposition, whereas fine-grained deposition has mainly occurred on the former floodplain and lowermost reservoir reaches. Fine-grained sediment deposits are thickest and bury pre-dam morphology immediately upstream of the dam where they are accessible to fluvial erosion during streambed drawdown operations. Farther from the dam, where pre-dam morphology has not been buried, erosion is limited to sediment accumulation in the reservoir thalweg and minor tributary and 'drawdown' channels. In former floodplain regions of the reservoir not adjacent to the thalweg, thicker sediment deposits are inaccessible to fluvial erosion at full streambed drawdown. Altogether, these findings highlight controls on patterns and processes of reservoir erosion during drawdowns. This understanding of long-term sedimentation and streambed-drawdown erosion at Fall Creek Lake allows better evaluation and anticipation of the timing, magnitude, and sediment characteristics delivered to downstream reaches.

Introduction

At Fall Creek Dam in northwestern Oregon (Figure 1), flow managers with the U.S. Army Corps of Engineers (USACE) lower lake levels to streambed each fall to facilitate the downstream passage of juvenile spring Chinook salmon through the 55-m tall dam, creating temporary free-flowing channel conditions in Fall Creek Lake. Since water-year (WY) 2011, these streambed drawdown events have mobilized substantial quantities of predominantly fine (<2 mm) sediment, as well as some coarser gravels, which have the potential to impact morphology and habitats of downstream gravel-bed reaches. Understanding short and long-term geomorphic impacts to downstream reaches requires an evaluation of the processes and patterns of reservoir erosion and likely responses to future changes in inflows or dam operations. Process-based geomorphic mapping of landforms and reservoir substrate from high-resolution datasets acquired in WY 2016 provide a basis for linking sedimentation and erosion processes to dam operations, while analyses of historical and recent datasets are used to characterize the magnitude of changes inferred from geomorphic mapping. The findings presented here are part of a larger study that investigates the upstream-downstream coupled geomorphic responses to drawdown operations. In this paper, we focus on (1) understanding the patterns and processes of sedimentation and erosion in Fall Creek Lake and (2) identifying key factors that control erosion and sediment export from the reservoir during streambed drawdown operations.

Background and Study Area

Fall Creek Dam captures flow and sediment from a 477 km^2 area of western Oregon. Volcanic and volcaniclastic rocks of Eocene to Miocene age dominate the Western Cascades geology underlying the Fall Creek basin (Smith and Roe, 2015). The basin is characterized by a Mediterranean climate with warm dry summers and cool wet winters, with most winter precipitation falling as rain and a mean annual precipitation of 170 cm/year. Fall Creek Dam was completed in 1966 as part of the Willamette Valley Project, a system of 13 dams on tributaries of the Willamette River, which were constructed for the primary purpose of flood risk management (USACE 2019b). The dam is a rock fill structure with concrete spillway and three sets of nested fish horns at different elevations that pass water and fish downstream, although the horns are inadequate for downstream fish passage (USACE, written commun.). Unique to this infrastructure among Willamette Valley Project dams are two regulating outlets at the base of the dam. The 55-m-high, 1,554-m-long dam is operated primarily for flood risk management, as well as water quality, irrigation, recreation, and habitat, and has a storage capacity of 115,000 acre-feet (USACE, 2019a) and sediment trapping efficiency of about 74 % (Schenk and Bragg, 2014).

During the flood season from November to March, pool levels are restricted to 252 m (NAVD 88; 44 m above full drawdown) with minimum pool at 222 m (14 m above full drawdown) (Figure 1). Conservation season from April to November is not restricted to a maximum pool elevation (USACE, 2019a). The 2008 Biological Opinion for USACE's Willamette Valley Project (referred to as the 'BiOp') identified actions for Fall Creek Dam to improve downstream passage and survival of juvenile spring Chinook salmon that included lowering lake levels below elevation 219 m (11 m above full drawdown; NMFS, 2008; Figure 1). In WY2012, annual experimental streambed drawdowns to 208 m (Figure 1) at Fall Creek Dam lowered pool levels to free-flowing conditions. This magnitude of drawdown is now part of the standard operations. Historical lake level records and anecdotal reports (USGS gage 14150900, Fall Creek Lake near Lowell, Oregon; USACE, 2017) indicate streambed drawdowns also occurred in multiple years prior to WY 2012 (WYs 1969–75, 1977, 1982), and pool levels have been drawn below minimum conservation pool, but not as far as streambed in many other years.

Approaches

Geomorphic Mapping to Characterize Fall Creek Lake Processes

A processed-based framework through geomorphic mapping is used to interpret the evolution of reservoir sedimentation and erosion. Digital maps documenting surface landforms in Fall Creek Lake were developed from Digital Elevation Models (DEMS) and aerial photographs (acquired WY 2012 and 2016). Landform mapping units were developed to better understand potential sediment mobilization and delivery to reaches downstream of the dam. Here, we focus on five key mapping units (Table 1); the completed mapping hierarchy includes 17 geomorphically distinct landform mapping units and is more fully described in Keith and Stratton (in progress).

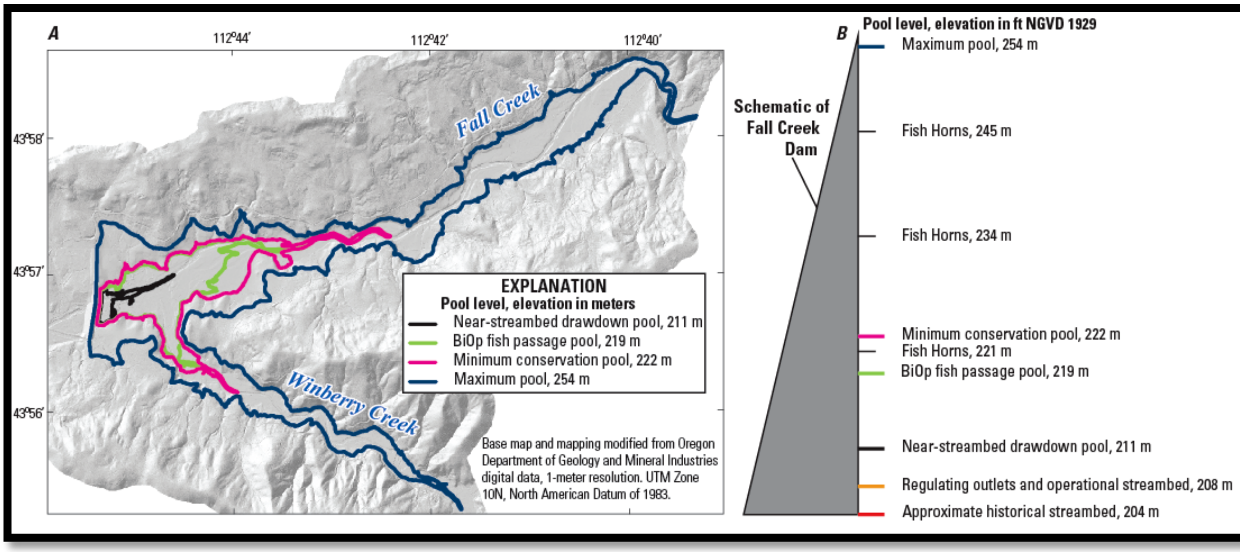

Figure 1. (A) Fall Creek Lake, Oregon, study area including key pool elevation contours and (B) schematic of Fall Creek Dam scaled to dam height (horizontal exaggeration) with key elevations related to operational pool levels and infrastructure.

Table 1. Key landform mapping units related to sedimentation regime.

[See Keith and Stratton (in progress) for additional landform mapping units and more detailed descriptions of mapping domains, landforms, and substrate.]

Landform mapping unit	Description	Sediment Regime Between Minimum and Maximum Pool Level	Sediment Regime: During Streambed Drawdown Conditions
Drawdown distributary zone	Broad areas of the reservoir floor that are morphologically similar to drawdown surfaces but form a series of splays and small deltaic lobes cross-cut by erosional features.	Lacustrine deposition	Deposition of newly eroded sediments and scour of channels
Drawdown surface	Typically planar surfaces created from incision and abandonment or dissection from reservoir floor by channel erosion around the feature.	Lacustrine deposition	Fluvial erosion of reservoir floor
Drawdown channel	Channels that typically originate on the reservoir floor or reservoir hillslope. Water draining from the low gradient floor may concentrate, increasing local capacity to mobilize and transport fine sediment. Over time, can evolve through knickpoint migration or increases in local slope.	Lacustrine deposition	Fluvial erosion of reservoir floor
Littoral reservoir floor	Localized, relatively flat areas along the reservoir margins adjacent to the mapping boundary at maximum conservation pool elevation.	Neutral with minor lacustrine deposition	Neutral
Pelagic reservoir floor	Low-gradient reservoir floor between reservoir hillslope and main reservoir channels. At maximum conservation pool (254 m), would be deeply inundated by water.	Main area of lacustrine deposition	Neutral with near-channel areas likely to experience fluvial erosion
Reservoir hillslope	Steep, formerly forested valley walls, that often extend from the reservoir floor to the reservoir margins at elevation 254 m.	Wave erosion with re-distribution of sediment downslope	Typically neutral; erosional during rain events or with mass failures

Quantification of Drawdown-Related Erosion

Lidar (light detecting and ranging) data acquired in early WY 2012 during full streambed drawdown and structure-from-motion (SfM) topography acquired on November 10, 2016 (Keith and Mangano, in progress), were used to estimate volumetric changes in sediment erosion and deposition in the lower Fall Creek reservoir, as well as assess spatial patterns of change for that period. Comparisons between datasets were made with Geomorphic Change Detection (GCD) Software (Riverscapes Consortium, 2018) within ArcGIS to quantify net volumetric change. The analyses focused on the reservoir floor and main channel in the lower approximately 2.5 km of the reservoir.

Results and Discussion

Pre-dam Morphology of Fall Creek Lake

Fall Creek Lake occupies a relatively narrow valley defined by the Fall and Winberry Creeks (Figure 2). Pre-dam morphology at Fall Creek Lake reviewed for this study is limited to interpretation of 1936 pre-dam aerial photographs and 2012 lidar displaying buried reservoir topography. Steep, bare reservoir hillslopes were heavily forested prior to dam construction, and much of the reservoir floor appears to have been used for agricultural purposes prior to dam construction, with fields typically extending to a single, discontinuous row of trees along the Fall and Winberry Creek channels. Both creeks appear to have been relatively straight, single-thread channels through the middle of the valley floor with intermittent bedrock outcrops. Where present, gravel bars were as large as 2,700 m^2 and were primarily bare of vegetation. Side channels and alcoves were limited to co-location with gravel bars.

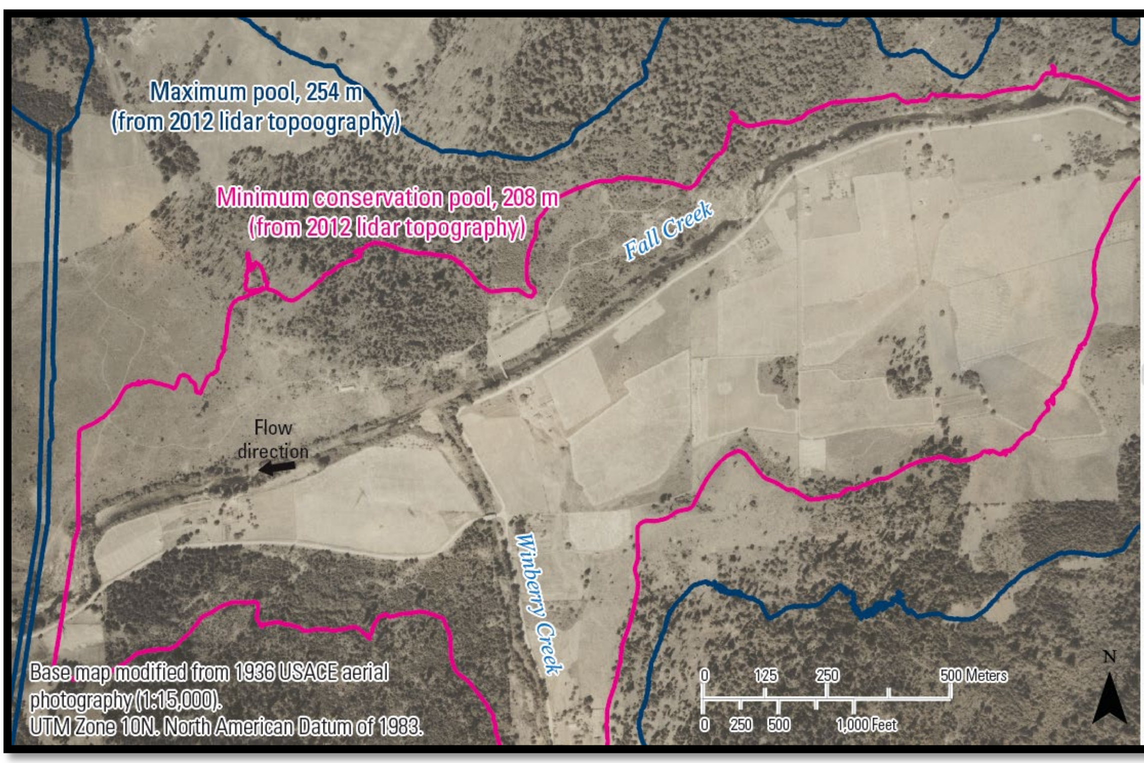

Figure 2. Pre-dam aerial photograph (1936) of the Fall Creek valley in the vicinity of the present-day lower Fall Creek Lake Oregon.

Distribution and Interpretation of Mapped Landforms and Sediment

The exact volume of sediment in Fall Creek Lake was not measured as part of this study; however, storage curves from 1988 and 2012 and a partial storage curve from 1965 (above about 217.5 m elevation) indicate that overall loss in storage for the full reservoir (254 m) is less than 1 %. Sediment accumulation since 1966 is concentrated in the lower portions of the reservoir near the dam, where it is susceptible to erosion during streambed drawdowns.

The relative areal coverage of geomorphic features varies systematically with pool elevation. Mapping (Figure 3) shows that the former Fall Creek valley and its forested hillslopes are now dominated by pelagic reservoir floor (42 % of reservoir area; Figure 3) and reservoir hillslope (35 % of reservoir area). The dominant substrate type overall is sand/mud (43 %). A nearly equal area is mapped as hillslope/pre-dam soil (42 %). Drawdown-associated landforms, including drawdown channels, distributary zones, and drawdown surfaces, account for about 5 % of the total mapped area; however, the total proportion increases substantially at lower pool levels, and 86 % of those drawdown landforms are found below minimum conservation pool. The presence of drawdown landforms above minimum conservation pool suggests formation during regular seasonal operations for flood mitigation rather than drawdowns for fish passage. During full streambed drawdowns, these features likely function as conduits for sediment and water, similar to pre-dam tributaries draining valley hillslopes to Fall and Winberry Creeks.

Below minimum conservation pool (222 m; Figure 1), pelagic floor and drawdown-associated landforms are prominent, occupying 59 % and 18 % reservoir area, respectively. There is a marked decrease in hillslope/pre-impoundment soils (7 %), and a greater proportion of the area is mapped as sand/mud (84 %).

The pool below 211 m is dominated by pelagic floor (47 %), drawdown surfaces (19 %), and wetted channel (18 %). Drawdown-associated landforms (including drawdowns channels, surfaces, and distributary zones) comprise 22 % of the mapped area in this small pool (1.5 % of total mapped area). Substrate at elevations below 211 m is almost entirely sand/mud (94 %). When pool levels are at or below this elevation, the majority of the drawdown landforms within the reservoir area are no longer directly interacting with the water surface, but they can continue to evolve through erosion and re-deposition in response to dewatering of the reservoir floor or precipitation events that generate runoff into the reservoir.

The main channel area cross-cuts all pool levels and acts as the primary active zone for water and sediment transport during full streambed drawdowns; landforms within this domain likely play a crucial role in exporting sediment to reaches downstream of the dam. Within this domain the wetted channel feature class makes up 49 % of the area. Channel banks and slumping banks account for an added 26 % of the mapped area. Aside from bars (10 %), bedrock (5 %), and drawdown surfaces (10 %), other mapped landforms are distinct to other domains such as reservoir floor or hillslope and account for less than 1 % of the area. Bar landforms are dominantly gravel (93 % by area), and the wetted channel area is 35 % gravel and 32 % bedrock. Although small in total area, the presence of bedrock channels within the reservoir suggests there is a relatively high transport capacity during regular seasonal drawdowns (most of this area coincides with a 2.5-km segment of the channel spanning the transition to minimum conservation pool). Bedrock outcrops also indicate erosion-resistant features that likely stabilize local channel position, hindering lateral migration of the wetted channel through reservoir floor deposits.

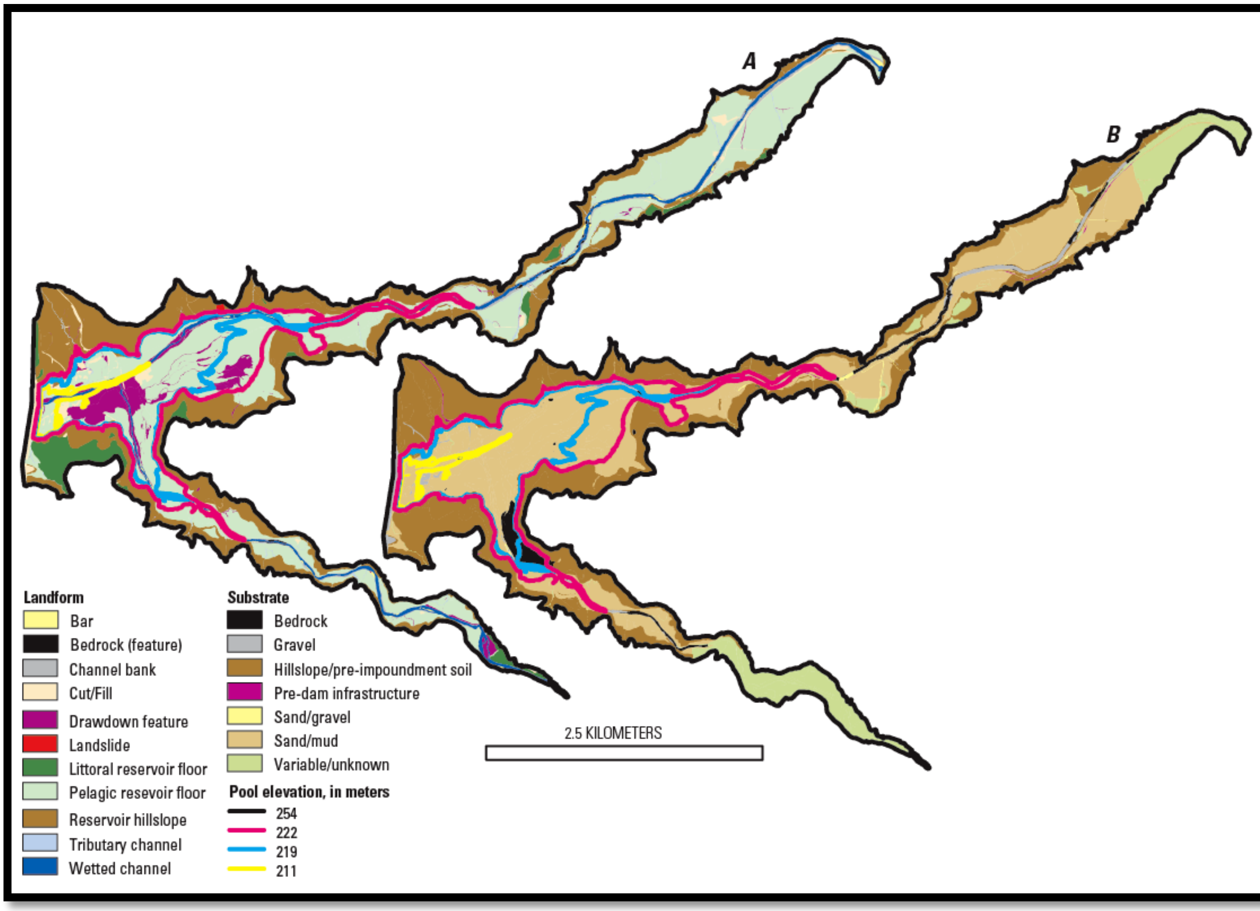

Figure 3. Landforms (A) and substrate (B) mapped within the Fall Creek reservoir, Oregon.

In the upper reservoir, a higher density of channel banks formed in pre-dam soils/hillslope material may indicate features that also functioned as channel banks prior to dam construction based on the presumed pre-dam location of the Fall Creek channel.

Drawdown surface landforms are 99 % sand/mud; though less extensive by area, other drawdown landforms (channels and distributary zones) are also dominantly sand/mud. The topographic signature and substrate type together suggest drawdown landforms primarily form in the finer reservoir-deposit sediment.

Overall, the mapping reveals a dynamic reservoir environment influenced by a blend of depositional processes that are active during lacustrine conditions at high lake levels and erosive processes that are active at lower lake levels when fluvial processes dominate. While the pelagic reservoir floor is mapped as a depositional environment, dominated by gradual deposition of suspended sediment, pre-dam topography is clearly visible in many areas despite more than 60 years of impounded conditions, suggesting relatively low rates of sedimentation and burial. Regular lake-level lowering during winter months for flood control, combined with full streambed drawdowns in the fall, creates erosive conditions that can cut drawdown channels and drawdown surfaces in reservoir deposits and re-distribute sediment within the reservoir. Drawing down lake levels also initiates fluvial processes within the main channel, whereby fine sediment deposits downstream of minimum pool are reworked and coarse sediment along the channel bed can mobilize to form gravel bars, and in some locations expose bedrock. In contrast, the reservoir hillslope is predominantly an erosional or sediment-neutral environment, as indicated by the presence of exposed, pre-dam hillslope, wave-cut terraces, and exposed root structures of relict stumps.

Magnitude of Erosion Related to Drawdowns

Within the area of interest for Fall Creek reservoir, 224,200 m^3 of erosion and 28,800 m^3 of deposition was calculated with GCD software for net erosion of 195,400 m^3 between January 2012 and November 2016 (Figure 4). This would suggest an annual average net erosion rate over 5 streambed-drawdown years of about 39,000 m^3/year. However, based on observations downstream in Fall Creek (Schenk and Bragg, 2014, 2015; G. Taylor, USACE, oral communication, 2017; Schenk, 2018), and downstream of other reservoirs during dam removals, which are a proxy for streambed drawdown responses (for example, Major and others, 2012 or Collins and others, 2017), it is more likely that larger amounts of sediment were eroded during earlier streambed drawdown periods (WYs 2012–13) than later drawdowns.

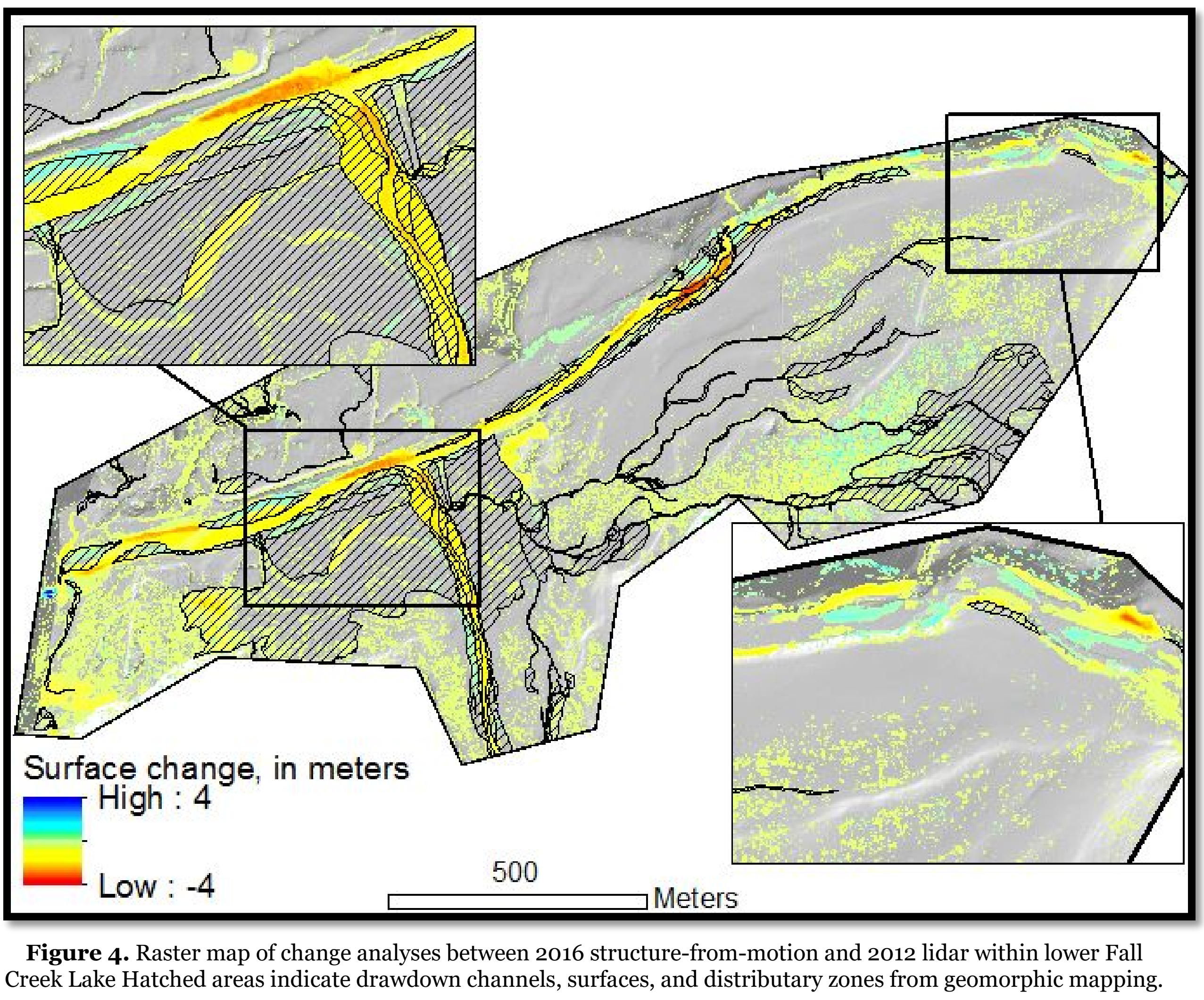

Figure 4. Raster map of change analyses between 2016 structure-from-motion and 2012 lidar within lower Fall Creek Lake Hatched areas indicate drawdown channels, surfaces, and distributary zones from geomorphic mapping.

The distribution of calculated erosion (Figure 4) was similar to that of mapped erosion features, such as drawdown channels and the main Fall and Winberry Creek channels through the reservoir. The largest amount of erosion (up to 3.8 m thick) was located in the main channel corridor. Some deposition (up to about 0.9 m) is likely the product of bars being reworked, slumping bank toes, or drawdown surfaces that have accumulated sediment. Localized areas with little variability of erosion or deposition can also be seen along the channel margins and often coincide with mapped drawdown surfaces. Within the reservoir floor, there are also prominent areas of erosion associated with drawdown surfaces, channels, and distributary zones. The large distributary zone near the confluence of Winberry Creek showed changes in elevation ranging from +0.32 m to -0.9 m, though the feature was dominantly erosional with large areas of no detectable change. Some of the drawdown channels showed incision of as much as 1.8 m near the confluences of the main Fall Creek and Winberry channels.

Controls on Drawdown-Related Erosion and Implications for Future Erosion

Multiple competing controls influence sedimentation and erosion at Fall Creek Lake as pool levels fluctuate seasonally for flood control and rapidly when temporarily drawn down to streambed. These can be generally categorized as direct or indirect controls that are closely tied to inherent physical or operational influences that affect timing, magnitude, and distribution of sedimentation and erosion. This framework for considering the relative roles of controls supports interpretation of future reservoir evolution under similar streambed drawdown management at Fall Creek Dam.

Annual streambed drawdown events since 2011, in combination with earlier intermittent streambed drawdowns, likely create the conditions necessary to maintain a well-defined and actively evolving channel in much of Fall Creek Lake. This channel constrains most coarse-grained sediment transport and re-deposition, whereas fine-grained deposition during lacustrine conditions has mainly occurred on the former pre-dam floodplain and terrace surfaces (presently, the reservoir floor) and areas of the reservoir closest to the dam. Drawdown-influenced erosion through the reservoir floor deposits is mainly limited to areas adjacent to the main reservoir channel, as most of the reservoir floor is topographically higher than or farther from the main reservoir channel and inaccessible to major erosion and reworking. In contrast, areas immediately upstream of the dam, where reservoir sedimentation has buried the pre-dam channel, are subject to more substantial downcutting and lateral migration of fine-grained material.

These observations suggest that a geomorphic framework for evaluating controls on reservoir sedimentation and erosion should consider different zones of the reservoir, their proximity to the main reservoir channel, and the different depositional and erosional processes activate by various dam management and streamflow scenarios. For example, in areas immediately upstream of the dam where fine-grained sediment accumulation is thick and readily accessible to fluvial erosion and transport, the direct controls on erosion are dam operations (predominantly lake level) and streamflow (a function of unregulated flow entering the reservoir). Sediment eroded from the area proximal to the dam and main streambed drawdown channel is more likely to be transported downstream of Fall Creek Dam during streambed drawdowns than sediment mobilized from reservoir margins. Upper elevations of the reservoir floor margins reflect pre-dam floodplain and terraces that indirectly influence streambed drawdown erosion; that sediment must be routed farther through the reservoir prior to export.

Patterns of sediment erosion and evacuation from Fall Creek Lake since WY2012 suggest that fine sediment erosion during streambed drawdowns will decrease in the future and tend to approach the rate of upstream sediment supply to the lower reservoir, because the streambed drawdown channel continues to reoccupy the main reservoir channel without widespread lateral erosion across floodplain deposits. Patterns of reduced sediment transport downstream of the dam are consistent with local suspended sediment loads calculated for WYs 2013–2017 (Schenk, 2018). Also, the majority of sediment deposited in Fall Creek Lake is fine-grained sediment stored in the main reservoir floor and is largely inaccessible to erosion during drawdown operations. This suggests 1) that the likelihood of fine-grained sediment on those surfaces entrained during streambed drawdown operations and subsequent transportation downstream of the dam is low, and 2) if that sediment is transported downstream of the dam, it would primarily travel as suspended load with limited impacts to habitat-related morphology.

Conclusions

Interpreting processes of sedimentation and erosion from reservoir landforms provides a basis for evaluating the evolution of Fall Creek Lake, Oregon, during typical lake conditions and streambed drawdowns. Geomorphic features and the distribution of sediment in the Fall Creek reservoir reflect a complex history of alternating depositional, transport, and erosional processes influenced both by reservoir operations and the morphology of the pre-dam valley and hillslopes. At Fall Creek Lake, pre-dam valley morphology acts as an indirect control influencing the distributions, processes, and magnitudes of reservoir sedimentation and streambed drawdown-related erosion, while dam operations directly control lake levels influencing the overall depositional or erosional regime. Unregulated streamflow entering the reservoir during streambed-drawdown period also directly influences the magnitude of erosion and sediment transfer within the reservoir. Overprinting of multiple processes creates a diverse array of landforms indicative of erosional and depositional processes. The erosion potential of sediment in Fall Creek reservoir is dependent on sediment grain size, reservoir morphology, and its exposure to removal processes. Combining lake level and reservoir morphology establishes the template for understanding processes active under particular operational conditions.

The overall study supports management operations at Fall Creek Lake for downstream fish passage and downstream sediment management. The sedimentation and erosion patterns and their underlying controls are specific to operations at Fall Creek Lake, but the approaches and findings from this study can support a broader understanding of reservoir drawdowns for other purposes, such as sediment management or construction. Furthermore, our findings help us understand the current conditions and predict the longer-term geomorphic responses downstream of Fall Creek Dam. While the underlying purpose for drawdown operations and the drivers of erosion at Fall Creek may differ from other reservoirs, the approaches described here that link process-based mapping and interpretation of erosional landforms to volumetric analyses could be modified to inform drawdown operations at other reservoirs to support sediment management for reservoir sustainability.

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