Development and Implications of a Sediment Budget for the Upper Elk River Watershed, Humboldt County[1]

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Abstract

A number of watersheds on the North Coast of California have been designated as sediment impaired under the Clean Water Act, including the 112 km^2 upper Elk River watershed that flows into Humboldt Bay just south of Eureka. The objectives of this paper are to: 1) briefly explain the geomorphic context and anthropogenic uses of the Elk River watershed; 2) develop a process-based sediment budget for the upper watershed, including an explicit assessment of the uncertainties in each component; and 3) use the results to help guide future management and restoration. Natural (background) sediment inputs are believed to be relatively high due to high uplift rates, weak Miocene-Pliocene bedrock materials, steep slopes, high rainfall, and resulting high landslide frequency. The primary land use in the upper watershed is industrial timberlands, and intensive logging in the 1980s and 1990s greatly increased sediment production rates and downstream aggradation. Road improvements and major changes in forest practices have caused anthropogenic sediment inputs to drop by roughly an order of magnitude since the 1990s. Suspended sediment yields plotted against annual maximum peak flows indicate a decline since 2013, suggesting that the legacy pulse of sediment is now moving into the lower portions of the watershed and that improved management practices are having a beneficial effect. Recovery and restoration in the lower watershed is far more challenging as very low channel gradients cause sediment deposition, in addition to development of the floodplain for agricultural and residential use, forcing the river into a single-thread channel, and positive feedback loop between reduced flow velocities, aggradation, and dense vegetative growth in portions of the mainstem channels.

Introduction

The 152 km^2 Elk River watershed flows into Humboldt Bay just southwest of Eureka, California. It can conceptually be divided into a steep, forested upper watershed that comprises the majority of the basin (112 km^2) and a more developed lower watershed with a wide, low-gradient alluvial valley bottom and floodplain (fig. 1). Designated beneficial uses of particular concern include municipal and agricultural water supply, endangered coldwater fisheries habitat, and water contact recreation (TT 2015). Downstream flooding and high turbidity are critical concerns for the residents, and are believed by many of the residents to have been greatly aggravated by upstream forest management activities. These problems led the North Coast Regional Water Quality Control Board (NCRWQCB) to designate the entire Elk River watershed as impaired for sediment in 1998 under Section 303(d) of the Clean Water Act, and to identify an affected reach that spans the upper and lower watersheds (fig. 1).

There is considerable uncertainty and debate over the relative magnitude of past and current anthropogenic sediment inputs relative to natural erosion rates, and hence the extent to which past and present forest management activities are increasing downstream flooding and impairing the

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designated beneficial uses. It also is not clear to what extent flooding in the affected reach is exacerbated by human-induced changes to the main channels and valley floor. An assessment of natural sediment sources, anthropogenic sediment sources, and other modifications to the Elk River watershed has direct implications for the potential success of different watershed restoration options. Since an extensive hydrodynamic modeling study is underway to evaluate water and sediment conveyance in the affected reach and lower watershed (TT 2015), our focus is on the production and delivery of sediment from the upper watershed to the affected reach. The specific objectives of our ongoing study are to: 1) develop a sediment budget for the upper Elk River watershed, including inputs, outputs, and storage; 2) identify the greatest sources of uncertainty and how these might be resolved; and 3) discuss the implications of the sediment budget for downstream water quality, nuisance flooding, and future watershed recovery. This paper is an initial summary of our work.

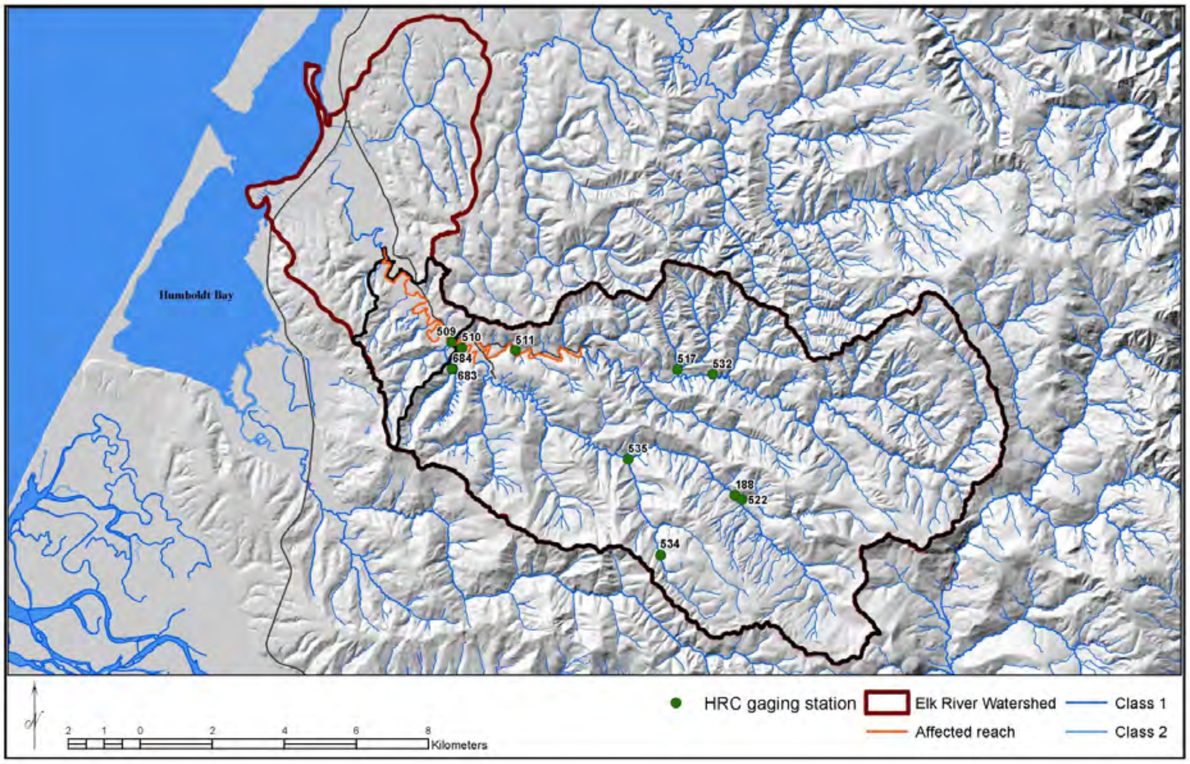

Figure 1—Map of the Elk River watershed with the affected reach in orange. The labelled green circles show the gaging stations that have been or are being operated by Humboldt Redwood Company. The upper watershed as defined in this paper is the area above the lowest gaging station (509), while the upper watershed for regulatory purposes is 8 km^2 larger as it includes all of the area draining to the affected reach.

Sediment Budget

A sediment budget is an accounting of sediment sources within a watershed, sediment outputs from the watershed, and changes in storage over a specified period of time (equation 1):

Inputs = Outputs + Change in storage.

For this paper the units for each component are mass (Megagrams or metric tons) per square kilometer per year, and multiple techniques are often needed to constrain and estimate each component. Each technique has an inherent spatial and temporal scale and uncertainty, so care must be taken to define the data and the extent to which these can be extrapolated in both time and space (Dietrich and Dunne 1978, Reid and Dunne 1996, Smith et al. 2011). We are fortunate because Humboldt Redwood Company has operated a minimum of 10 gaging stations in the Elk River watershed that measure both discharge and suspended sediment loads as part of their Habitat Conservation Plan. The gaging station that is furthest downstream (509) is on the mainstem just below the confluence of the North and South Forks, and this sets the downstream boundary for our sediment budget (fig. 1). Suspended sediment loads have been measured at station 509 since water year (WY) 2003, and the data from this station provides the output term in our sediment budget. The watershed area above station 509 is 112 km^2.

Sediment Inputs

For scientific and restoration purposes, sediment inputs in the upper Elk River watershed can be divided into: 1) natural (or background) sources; 2) inputs resulting from past timber management (1860s through the 1990s), which are designated as "legacy" sources in this paper, and 3) sediment inputs from forest management following major shifts in forest and road management practices beginning in 2000. Each of these sources is briefly discussed in the following sections along with their respective uncertainties.

Natural Sediment Sources

The magnitude of natural sediment sources is largely a function of the geologic and geomorphic conditions in the upper watershed. The majority of the upper watershed is underlain by the undifferentiated sedimentary Wildcat Group of Miocene-Pliocene age (fig. 2). This sequence of marine siltstones and fine-grained sandstones unconformably overlies Franciscan Complex bedrock, specifically the Jurassic-aged Central belt and the Late Cretaceous to Early Tertiary Yager terrane (Stillwater Sciences 2007). Undifferentiated Wildcat Group sediments are poorly indurated and considerably softer and more erodible than the low grade metamorphic sediment associated with the Central belt and Yager terrane. In the westernmost portion of the upper watershed the Wildcat Group is capped by the Hookton Formation. This is a non-marine, mid- to late-Pleistocene sedimentary formation that in the Elk River is dominated by silts intermixed with sands and clays. The Hookton Formation has a high propensity for natural failure and is highly erodible. Valley floors adjoining the main channels are mantled with a variably thick package of Quaternary-aged alluvial deposits (fig. 2).

Figure 2—Geologic map of the Elk River Watershed (TT 2015).

Estimates of natural or background erosion rates are extremely variable, but tectonic uplift, weak bedrock, and high precipitation rates all suggest that natural erosion rates should be relatively high. The proximity of the Elk River watershed to the Mendocino Triple Junction and Little Salmon Fault system produces uplift rates in the upper watershed that are on the order of 0.5 mm yr^{-1} (Balco et al. 2013, Stallman and Kelsey 2006). If erosion rates equal uplift rates, this uplift rate would convert to an erosion rate of roughly 1200 Mg km^{-2} yr^{-1} assuming a bedrock bulk density of 2.5 Mg m^{-3} (Bennet et al. 2015) and a 5 percent dissolution loss, which is comparable to the value in the nearby Eel River watershed (Milliman and Farnsworth 2011). This high erosion rate is consistent with the high mean sediment yields of 1100-3700 Mg km^{-2} yr^{-1} calculated for five North Coast watersheds with substantially unaltered flows (Andrews and Antweiler 2012). Alternatively, Stallman and Kelsey (2006) estimated a denudation rate of 0.10 mm yr^{-1} over the last 330 to 590 thousand years for the immediately adjacent Ryan Creek watershed, which converts to only about 250 Mg km^{-2} yr^{-1}.

Denudation rates over several thousand years also can be estimated using the cosmogenic isotope beryllium-10 (^{10}Be). Balco et al. (2011) presented a series of ^{10}Be data from a variety of watersheds along the North Coast, and denudation rates peak at more than 1 mm yr^{-1} between 40 and 41 degrees north latitude. This peak can be attributed to the northward propagation of the Mendocino Triple Junction. The centroid of the Elk River watershed is at 40.7^{o} N, which is at the leading edge of this peak. We have collected alluvial sand samples from the Elk River watershed for ^{10}Be analysis, but these data are not yet available. Mapping from the California Geologic Survey shows that most of the upper Elk River watershed is subject to mass movements (Marshall and Mendes 2005). While additional work is needed to better quantify the natural erosion rate, these data and a report from the California Geological Survey (Bedrossian and Custis 2002) strongly indicate that the long-term natural erosion rate is at least 3 to 14 times the values of 60 Mg km^{-2} yr^{-1} (about 0.024 mm yr^{-1}) estimated in the sediment TMDL (NCRWQCB 2016) and 94 Mg km^{-2} yr^{-1} estimated by HRC in their watershed analysis (HRC 2014) (table 1).

Legacy Sediment Sources

Estimates of legacy and current sediment sources are facilitated by the fact that nearly 84 percent of the upper watershed is industrial timberlands and another 15 percent is protected public lands. Only about 1 percent is in other private or public ownership, and land use for these parcels includes residences, agricultural use such as orchards or pasture, timber harvest, and unmanaged. Sediment source estimates have been made for the industrial timberlands from 1955 to 2011 (NCRWQCB 2013, TT 2015), but there are no comparable data for the other private lands.

Legacy sediments originate from materials deposited from forest management activities prior to 2000 that were stored within the watershed (e.g., in floodplains, terraces, or colluvial hollows), or sediment coming from sources that originated from management activities prior to 2000 (e.g., landslides that have not yet stabilized). This definition of legacy sources stems from the strong consensus that sediment production rates from forest management activities and roads greatly declined beginning around 1999 due to a marked shift in practices, particularly reduced logging on unstable slopes, stormproofing and decommissioning roads, restrictions on wet weather timber hauling, increased protection of riparian zones, and stronger controls on tractor logging operations (HRC 2014). In 2008 Humboldt Redwood Company, which owns 76 percent of the upper watershed, shifted from even-aged silviculture (clearcuts) to uneven-aged or selection harvesting (HRC 2014). About the same time the other major timber company began using shovel logging in areas suitable for ground-based timber harvest, and this generally minimizes ground disturbance and maximizes residual ground cover.

Table 1—Estimated sediment inputs to streams in Mg km^{-2} yr^{-1} from the sediment TMDL for three periods from 1988 to 2011 (TT, 2015), the values for 2001-2011 from the watershed analysis conducted by Humboldt Redwoods Company (HRC), and the estimated trends since 2011 relative to the HRC 2001-2011 values (upward arrow indicates an increase, an equal sign indicates little or no change, and a downward arrow indicates a decrease) (The values in parentheses in the column labelled HRC (2014) are the percentages that HRC apportions to legacy sources)

	Sediment TMDL (TT, 2015)			**HRC (2014)**	**Est. trend**
Natural sources	1988-97	1998-2003	2004-2011	2001-2011	2012-2016
Bank erosion	4	4	4	64	=
Streamside landslides	13	13	13		
Bank erosion: deep-seated	49	53	37		
Shallow landslides	15	15	15	2	=
Deep-seated slides	1	1	1	1	=
Creep	0	0	0	28	=
Sub-total (Mg/km2 yr)	**82**	**86**	**71**	**94**	=
Land use/management					
Low order channel incision	10	11	7	0	=
Bank erosion/streamside landslides	107	118	78	25 (89%)	=
Road-related landslides	150	6	12	20 (91%)	↓
Shallow landslides	98	42	2	0	↑
Untreated anthropogenic sites	32	27	19	0	↓
Post-treatment	0	4	12	0	↓
Skid trails	6	11	7	6 (100%)	↓
Road surface erosion	67	27	11	28 (63%)	↓
Surface erosion: harvest units	2	3	2	10 (77%)	↓
Sub-total (Mg/km2 yr)	**474**	**249**	**151**	**89 (81%)**	↓
Management related (%)	85	74	68	48	↓

It is extremely difficult to quantify or separate many of these legacy sources from natural sources, particularly: headwater incision of old sediment deposits; erosion from old skid trails, roads, and abandoned crossings; and subsurface erosion from soil pipes under or through the anthropogenic sediment deposited in headwater areas. A report from the adjacent Freshwater Creek watershed suggested that the first cycle of logging did increase drainage densities and channel scour, and estimated that this generated approximately 15,000 Mg km^{-2}, primarily from first- and second-order streams (PWA 1999). The HRC 2014 Watershed Analysis estimated that legacy sources are equivalent to 80 percent of background sources or about 80 Mg km^{-2} yr^{-1}.

Sediment From Current Management Activities

Process-based studies indicate that improved management practices have reduced sediment inputs from the industrial timberlands by at least a factor of four for 2004 to 2011 relative to 1988 to 1997 (NCRWQCB 2016, TT 2015) (table 1). The actual reduction in management-related sediment sources is almost certainly larger for several reasons. First, streamside landslides and bank erosion accounted for 52 percent of the anthropogenic sediment sources in the sediment TMDL (TT 2015), but this value was based in large part on the assumed threefold-difference in drainage densities between managed areas and unmanaged areas; field investigations have documented that drainage densities in managed areas are about 6 km km^{-2} rather than the 10 km km^{-2} that was used for calculations in the TMDL. An extensive survey of more than 40 km of different-order streams in 2012 found that erosion voids left by streamside landslides and bank erosion were due to unstable geology and natural flow deflection (i.e., deep seated features being eroded at their toes and large woody debris, respectively) (SHN 2013). The conclusion was that “causal mechanisms due to recent management were virtually non-existent” (SHN 2013, p. 6). These and other data suggest that the vast majority of the bank erosion and streamside landslides that were attributed to management should in fact be considered part of the natural sediment load (table 1).

Second, landslide occurrence has greatly decreased (table 1). Landslide-related sediment loads for 2003 to 2011 were heavily influenced by the numerous landslides in water year (WY) 2003 resulting from the record 24-hour rainfall of 172 mm at Eureka. Annual helicopter surveys and aerial photograph analyses show a continuing decline as the mean sediment delivery from landslides (table 1). From WY 2010 to WY 2016 mean sediment delivery from landslides further decreased to less than 1 Mg km^{-2} yr^{-1}. Notably, this period did include two drought years, and nearly all of the recent landslides are road-related rather than from harvested areas (table 1). Third, road sediment production and delivery has been greatly reduced by continuing efforts to upgrade road crossings, rock and disconnect roads, and road decommissioning (table 1), with HRC spending an estimated $7 million since 1999 to decommission more than 20 percent of their roads and stormproof nearly 80 percent of the remaining 340 km. Fourth, surface erosion and sediment delivery from harvest units has been largely eliminated by the changes in harvest techniques and increased protection of riparian zones; these have greatly reduced the amount of bare ground, soil compaction, and surface disturbance.

The net result is that sediment inputs from forest management have further declined since 2011 and are probably only about 20 to 40 Mg km^{-2} yr^{-1} (HRC 2014), plus perhaps another 20 Mg km^{-2} yr^{-1} of short-term inputs as a byproduct of treating those legacy sites that are accessible and feasible to rehabilitate (TT 2015) (table 1). The latter inputs should be considered as a short-term cost in exchange for eliminating both chronic legacy sources and legacy sources that might fail and cause much larger sediment inputs.

Sediment Outputs and Sediment Storage

The overall quality of the discharge, turbidity, and suspended sediment data are very good. In each year about 100 to 450 suspended sediment samples are collected at each gaging station from stage-triggered automated pump samplers. Annual suspended sediment yields are calculated by multiplying discharge times storm-specific turbidity-suspended sediment relationships (Lewis and Eads 2009). From WY 2003 to 2016 the mean annual suspended sediment yield at station was 260 Mg km^{-2} yr^{-1} with a high interannual variability (c.v. = 1) and a range from 960 Mg km^{-2} yr^{-1} in the WY with the highest peak flow on record (2003) to just 20 Mg km^{-2} yr^{-1} in the WY with the second lowest peak flow on record (2014). Most of the annual sediment load is transported during the largest one or two storms, and 83 percent of the annual variability in suspended sediment yields can be explained by the instantaneous annual maximum peak flow (fig. 2). There are no bedload data, but bedload in five North Coast rivers was estimated to range from 1 percent to 10 percent of the calculated suspended loads (Andrews and Antweiler 2012). Data from Caspar Creek, which is the closest analog to Elk River with reliable bedload data and has similar geology to the upper portions of the Elk River watershed, indicate that bedload equals about 50 percent of the suspended load (Cafferata and Reid 2013). If we assume that bedload is half of the suspended load, the total annual sediment yield at station 509 would be around 400 Mg km^{-2} yr^{-1}, or a watershed-scale denudation rate of 0.14 mm yr^{-1}.

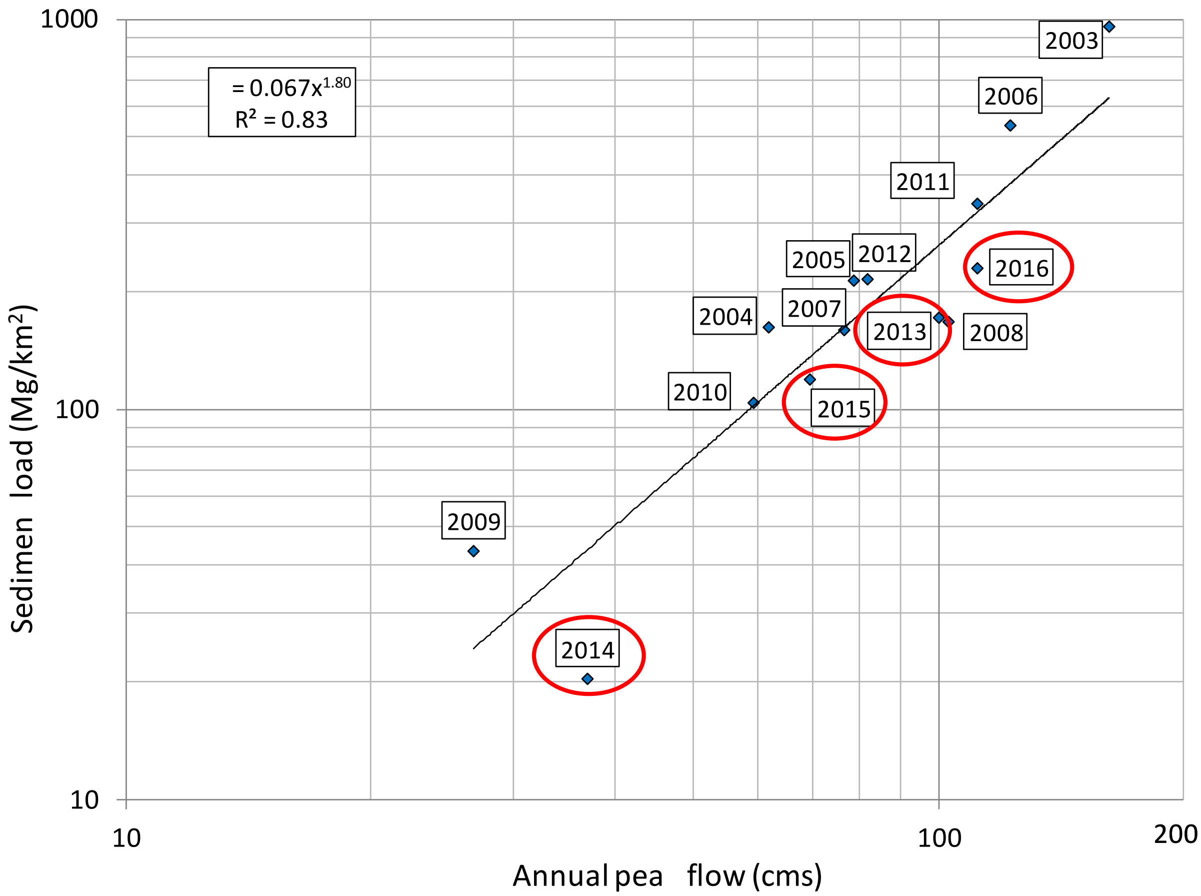

Figure 2—Plot of the annual suspended sediment loads at station 509 versus the annual instantaneous maximum peak flow. Note that each year since 2013 falls below the regression line developed with all the data, indicating a reduction in the annual sediment load for a given peak flow.

The difference between sediment inputs and outputs is sediment storage (equation 1). Storage from natural, legacy, and current sediment sources is very difficult to quantify and hence another major source of uncertainty in the sediment budget. Simply rearranging equation 1 to calculate storage as the difference between sediment inputs and outputs also is problematic given the uncertainty in sediment inputs.

Ferrier et al. (2005) noted relatively low mean sediment residence times and hence low storage capacities in Redwood Creek and the North Fork of Caspar Creek. Conversely, the 2012 survey of streambank erosion and streamside landslides in the upper Elk River watershed noted that "stream valleys tend to have broad cross sections with wide valley bottoms" and that this is in contrast to the steeper, more incised valleys in the upper Eel, Bear, and Mattole watersheds (SHN 2013, p. 5). The lower portion of the main channels in the Elk River watershed are clearly depositional zones as indicated by the sharp change in gradient and associated widening of the valley bottom. The valley bottoms along the mainstem and extending up the North and South Forks are in the 100-year flood zone (fig. 4). Technical documents supporting the sediment TMDL estimated that 640,000 yd^3 or nearly 500,000 m^3 of sediment had accumulated in the affected reach since the late 1980s or early 1990s (NCRWQCB 2013, TT 2015), but this value is highly uncertain given the large spatial extrapolation from very limited data and probably substantially overestimated given more recent analyses of the cross-sectional changes over time and measured sediment yields at station 509.

The magnitude of storage is of critical concern for determining the potential for watershed recovery. While the high interannual variability of suspended sediment yields makes it difficult to identify statistically significant trends in the 14-year record, the suspended sediment yields for each of the last 4 years fall below the regression line shown in fig. 3. Qualitative observations and some of the monitoring data on bed material particle size and residual pool depth (MacDonald 2014) indicate a coarsening of the streambed in the upper portions of the affected reach. If these trends are confirmed, this would suggest that the pulse of legacy sediment is finally starting to be removed from the upper watershed (Trimble 1999). Alternatively, if these trends are not confirmed, the bulk of current sediment yields are due to some combination of natural and legacy sediment sources given the generally recognized reduction in current anthropogenic sources (TT 2015) (table 1).

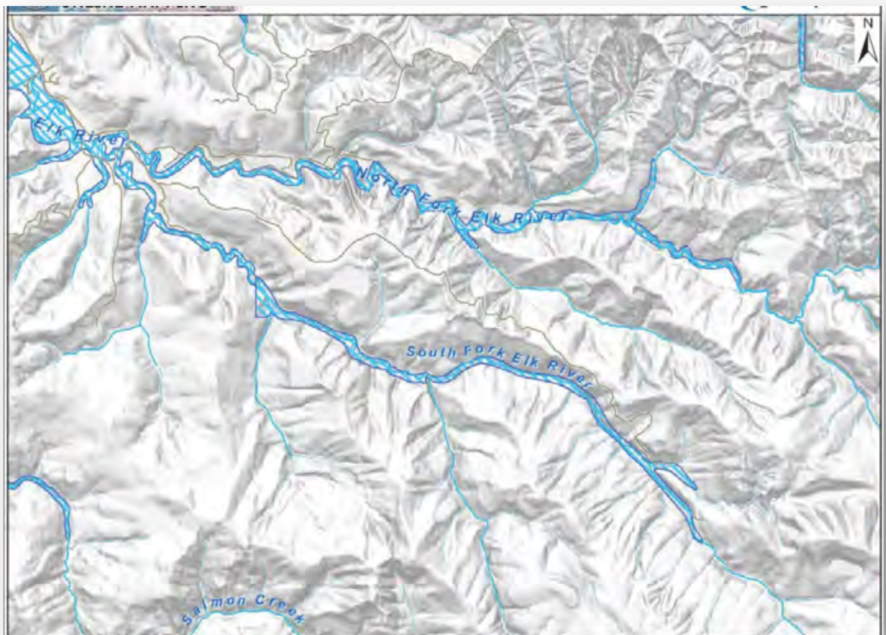

Figure 3—Map of the 100-year flood zone in the North and South Forks of the Elk River as mapped by the Federal Emergency Management Agency.

Implications for Restoration and Management

The three issues of greatest concern to resource management agencies and the local residents are: 1) the high turbidity and suspended sediment concentrations that limit the use of the Elk River for domestic and agricultural water supply during the winter months; 2) nuisance flooding of road access and residences; and 3) the effects of high turbidity and fine sediment deposition on salmonid spawning, feeding, and rearing. Data indicate that each of these issues has been exacerbated to some degree by human activities in the watershed, and the following will address each of these in turn.

First, the high natural erosion rates and fine-grained, weak rocks in the upper Elk River watershed lead to inherently high turbidity levels during the winter wet season compared to many other forested landscapes, even in the absence of any human disturbance. For example, turbidity levels in the undisturbed Little South Fork of the Elk River exceed the unfiltered drinking water standard of 5 NTU at least 10 times per year, and the mean duration of these exceedences is 31 days per year. Turbidity data from other undisturbed watersheds envelope the values from the Little South Fork (Klein et al. 2012). Extensive gravel filtration was required to maintain water quality when the Elk River was used as the major source of water for Eureka (Springer 1995). These data indicate that the Elk River will never be, and almost certainly never has been, able to meet the turbidity criteria for unfiltered municipal water supply. Industrial forest management, including the extensive road network, has increased turbidity levels in the rest of the Upper Elk River watershed, but the sediment budget indicates that this anthropogenic increase in sediment inputs is primarily due to legacy and stored sediment rather than current forest management (table 1). It is not clear to what extent the turbidity and associated suspended sediment concentrations limit agricultural pumping since agricultural users primarily pump river water during the growing season rather than during the winter (B. Alexandre, 2016, personal communication).

The most frequent nuisance flooding is associated with a 60-m section of road that dips below the bankfull channel on the North Fork ("Elk River flood curve"). Floodwaters begin encroaching on the roadway at about 20 $m^3 s^{-1}$, which is only about one-third of the estimated bankfull flow and mean annual flood. Hence this section of road is inundated approximately three to four times a year, which is a major concern because this road is the only access for some residents. While there are no data on aggradation over time at this location, this frequent flooding appears to be at least as much a function of poor road layout as any human-induced channel aggradation.

Flooding of residences and roads in the remainder of the lower basin is a function of both the inherent characteristics of the watershed along with human-induced alterations to the stream channel and valley floor. There is a very sharp decrease in channel gradient from the upper watershed to the affected reach, and the geologic map indicates that the valley bottoms are filled with Quaternary alluvial deposits. Nearly all of the valley bottom along the affected reach falls within the 100-year flood zone as designated by the Federal Emergency Management Agency (fig. 3). According to the classic text by Dunne and Leopold (1978, pages 599–608) "The channel is formed and maintained by the flow it carries but is never large enough to carry without overflow even discharges of rather frequent occurrence….The floodplain is indeed part of the river under storm conditions." Hence much of the valley bottom along the affected reach is by definition an active floodplain and naturally subject to flooding.

Historical accounts and aerial photos indicate severe human-induced changes to the main channel of the Elk River and adjoining floodplain (HRC 2014, MacDonald 2016). These include a loss of overflow channels and wetlands; confining the river to a single-thread channel; forcing the river through a tight series of unnatural right-angle bends; and dense vegetative growth within the channel. These changes probably have led to a positive feedback loop in which the reduced velocities and the subsequent aggradation facilitate vegetative growth in the channel, which further reduces channel capacity. Our preliminary estimate is that the stage associated with the historic bankfull flow of a little over 60 $m^3 s^{-1}$ has increased by around 0.8 m between 1967, when the gaging station operated by the U.S. Geological Survey ceased operating, and 1999 when HRC began cross-section measurements at nearly the same location. Annual cross-section data from 1999 through 2016 show a small increase in bankfull cross-sectional area and 0.4 m of thalweg incision since 1999. Given the biogeomorphic processes of deposition and colonization by vegetation and all the downstream changes, it is not clear whether further reductions in sediment inputs from legacy and current forest management will induce sufficient channel incision to reduce nuisance flooding.

Efforts to dredge the channel and/or remove some of the vegetation within or adjacent to the channel will be harmful to the threatened fish populations, and are ultimately short-term solutions given the low gradients and high natural sediment yields. Prior to European settlement the lower portion of the watershed was almost certainly a wetland with the Elk River flowing through a complex network of channels (HRC 2014) that would periodically avulse in response to aggradation. Restoration of the Elk River will necessitate a tough choice between maximizing conveyance, with the associated adverse effects on fish, or allowing a mechanism for the Elk River to reclaim part of the valley bottom while still protecting life and property and allowing some economic use.

Conclusions

The upper Elk River watershed has been designated as impaired for sediment due to the high turbidities, suspended sediment loads, and observed or inferred channel aggradation that has exacerbated nuisance flooding. The extent to which these problems can be eliminated depends in large part on how much of the high sediment loads are due to natural versus anthropogenic sediment sources. Natural erosion rates are believed to be relatively high given the uplift rate of around 0.5 mm yr^{-1}, and that the weak geology and high annual precipitation induces debris flows, landslides, and deep-seated earthflows. Nearly 84 percent of the upper watershed is designated as industrial timberlands and intensive logging—particularly the tractor-based logging in the 1980s and 1990s—greatly increased erosion rates and induced downstream aggradation.

Sharp changes in logging practices and a wide range of road improvements mean that sediment inputs from roads and current forest management have dropped by more than an order of magnitude. Both legacy sediment inputs and sediment storage are extremely difficult to quantify, but the recent drop in sediment yields as normalized by peak flows and the minimal aggradation over the last 15 years indicate that the legacy sediment pulse has at least partially passed through the 509 gaging station and is now moving downstream into the lower watershed. The implication is that sediment inputs from current forest management practices have declined to the point that water quality conditions are improving. Achieving the designated beneficial uses in the lower portions of the Elk River will be much more difficult given the extensive agricultural and residential use and the associated large alterations to the main channel and floodplain. Dredging and riparian vegetation removal may produce a localized, short-term increase in conveyance, but this will almost certainly have a negative impact on water quality and the endangered salmonids.

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