Appendix 4D

Bank Erosion Surveys

Pacific Watersheds Associates. June 2008. *Elk River Bank Erosion Void Assessment and Bank Erosion-Related Wood Inventory.* Prepared for North Coast Regional Water Quality Control Board and Sanborn.

Elk River Bank Erosion Void Assessment and Bank Erosion-Related Wood Inventory Humboldt County, California

June 2008

Prepared for:
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I. Introduction

A. Purpose/Background

Under the Clean Water Act Section 303(d), the Freshwater Creek watershed was listed by the North Coast Regional Water Quality Control Board (Regional Water Board) and the U.S. Environmental Protection Agency (EPA) as a sediment impaired water body. Space Imaging was granted a CMAS contract to conduct the sediment source analysis for the Freshwater Creek Total Maximum Daily Load (TMDL) sediment study. Space Imaging partnered with Pacific Watershed Associates (PWA) and landslide modeler Dr. Bill Haneberg to complete the work elements necessary to conduct the project. Subsequently, Sanborn was spilt from Space Imaging and assumed continued management of the project.

The original work plan submitted by Sanborn for the Freshwater Creek TMDL sediment source assessment included five main tasks. Task 1 involved compiling the historic aerial photography and LiDAR imagery and developing a comprehensive GIS library with the necessary GIS coverages and shape files required to run the landslide hazard and road surface erosion models.

Task 2 involved conducting a comprehensive landslide inventory using the 1987, 1997 and 2003 historic air photo sets. In addition, Task 2 work elements included a field verification study of a sample of air photo identified landslides to verify landslide type, size, sediment delivery and land use association. Finally, Task 2 included an air photo identified landslide and field inventoried landslide comparison study designed to determine how many landslides were not detected in the air photo analysis due to obstruction by the forest canopy within old-growth, mature second-growth (>30 years old) and “young” forest (≤30 years old) sample plots. Two sample plots for each timber age class category were analyzed for the air photo landslide and field identified landslide comparison study.

Task 3 included developing road surface erosion estimates using SEDMODL2. SEDMODL modeling was conducted by Kathy Dube in Freshwater Creek as part of the 2000 PALCO Watershed Analysis. As part of this project, SEDMODL2 was run on areas outside of the Freshwater Creek Watershed Analysis Area (i.e. Fay Slough and Ryan Slough planning watersheds. Road surface erosion estimates developed by Kathy Dube for the Freshwater Creek Watershed Analysis were combined with the road surface erosion estimates calculated as part of this study in order to provide an estimate of total road surface erosion for the entire Freshwater TMDL study area.

Task 4 involved conducting geologic slope stability modeling to identify varying landslide hazard throughout the Freshwater Creek TMDL study area. Geologic hazard models included: SHASTAB (Dietrich and Montgomery 1998); PISA-m – Probabilistic Infinite Slope Analysis (Haneberg 2001); and SMORPH (Shaw and Vaugeois 1999).

Task 5 involved a bank erosion void assessment and bank erosion-related wood survey using two published methodologies described in Reid and Dunne (1996) and Benda et al. (2002; 2004). The bank erosion surveys were conducted along three 3,000 m channel segments in each of three subwatersheds within the Elk River watershed. The three subwatersheds include: 1) a portion of the Little South Fork Elk River subwatershed located upstream from the turbidity station within a stand of late successional old growth redwood, 2) Corrigan Creek, and 3) South Branch North Fork Elk River. Both Corrigan Creek and South Branch North Fork Elk River represent second growth and recently timber harvested areas. The aim of the project was to develop and compare bank erosion estimates and yield rates for each of the study subwatersheds using the 2 methodologies.

The Freshwater Creek TMDL sediment source study was conducted in 2 phases. Phase I of the project consisted of Tasks 1, 2 and 3 outlined above. A final report detailing the methodologies and results for these tasks was provided to Sanborn and the North Coast Regional Water Quality Control Board in July 2006.

Tasks 4 and 5 were completed as part of the Phase II portion of the Freshwater Creek TMDL sediment source study. The slope stability modeling study was completed in April 2008 and a final report outlining the results was provided as a separate cover. This report details the methodology and results for Task 5 involving the bank erosion void assessment and bank erosion-related wood inventory.

B. Scope of Work

The scope of the work conducted as part of the bank erosion void assessment and bank erosion-related wood inventory for Phase II of the Freshwater Creek TMDL Sediment Source Assessment included the following:

- Review of pertinent literature regarding bank erosion estimates and the development bank erosion estimates from wood budgets and erosional void inventories.
- Compilation of existing GIS coverages necessary to develop stream sampling strategy and field maps for bank erosion surveys in Elk River.
- Select 9,000 m of sample stream reaches (3,000 m each) in Little South Fork Elk River, Corrigan Creek, and South Branch North Fork Elk River by Strahler stream order.
- Develop field dataform and relational database containing all attributes necessary to collect bank erosion data using methodologies outlined by Reid and Dunne (1996) and Benda et al. (2002).
- Conduct field based bank erosion void and bank erosion-related wood inventories.
- Digitize locations of bank erosion and wood inventory sites using ArcGIS.
- Derive bank erosion estimates for the three study subwatersheds using the bank erosion void method and wood budget method.
- Prepare final report and supporting maps outlining the study results.

The Freshwater Creek TMDL Sediment Source Assessment Phase II Bank Erosion Void Assessment and Bank Erosion-Related Wood Inventory report is organized into 5 sections. The first section provides the report introduction including the purpose, scope of work, background information and reference materials used in the study. Section 2 of the summary report describes the geologic characteristics and tectonic setting of the three study subwatersheds (Corrigan Creek, Little South Fork Elk River, and South Branch North Fork Elk River).

Section 3 describes the methodology used for the field based bank erosion void assessment and bank erosion-related wood inventory. In addition, Section 3 describes the results for the field assessment and is organized to: 1) describe the results for the field based bank erosion void assessment and bank erosion-related wood inventory and 2) derive volumetric estimates and rates of bank erosion by each analysis method for each of the three subwatersheds. Finally, Section 4 outlines the conclusions of the analysis.

C. Background Information/Reference Materials

Source and reference information for the bank erosion assessment and wood inventory included:

- Digital elevation model (1-m DEM) for Elk River based on LiDAR imagery from Sanborn.
- Geology of the Elk River watershed derived from "Maps and GIS data for the Elk River Watershed, Humboldt County, California, Watershed Mapping Series" prepared by the California Geological Survey in 2005.
- Timber harvest history for the North Fork Elk River and South Fork Elk River from "Sediment Source Investigation and Sediment Reduction Plan for the North Fork Elk River Watershed, Humboldt County, California" (PWA 1998) and PALCO Elk River Watershed Analysis (Hart Crowser 2001).
- Road construction history for the North Fork Elk River and South Fork Elk River from "Sediment Source Investigation and Sediment Reduction Plan for the North Fork Elk River Watershed, Humboldt County, California" (PWA 1998) and PALCO Elk River Watershed Analysis (Hart Crowser 2001).
- Bank erosion void field assessment methodology derived from Reid and Dunne (1996), PWA (1999), and PALCO (2007).
- Bank erosion-related wood budget methodology derived from Benda et al. (2002), Benda and Associates (2004)

II. Project Area

The Elk River bank erosion void assessment and bank erosion-related wood inventory study area is located in Humboldt County in the vicinity of Eureka, California (Figure 1). The study area is comprised of three small subwatersheds including Corrigan Creek (4.18 km^2), Little South Fork Elk River (2.91 km^2), and South Branch North Fork Elk River (4.99 km^2). The three subwatersheds were selected based on past turbidity studies and established turbidity stations at the subwatershed outlets (Manka 2005).

Land use histories developed for the North Fork Elk River Sediment Source Investigation (PWA 1998) and the PALCO Elk River Watershed Analysis (Hart Crowser 2001) were based on the analysis of historic aerial photography from the 1954, 1966, 1974, 1987, and 1997 air photo years. Timber harvesting in Corrigan Creek was first documented on the 1954 historic aerial photography in the lower portions of the subwatershed. During the 1966 air photo time period harvesting continued primarily by tractor clear cut methods, and only minor tractor harvesting was documented on the 1974 aerial photography. By the time of the 1987 historic aerial

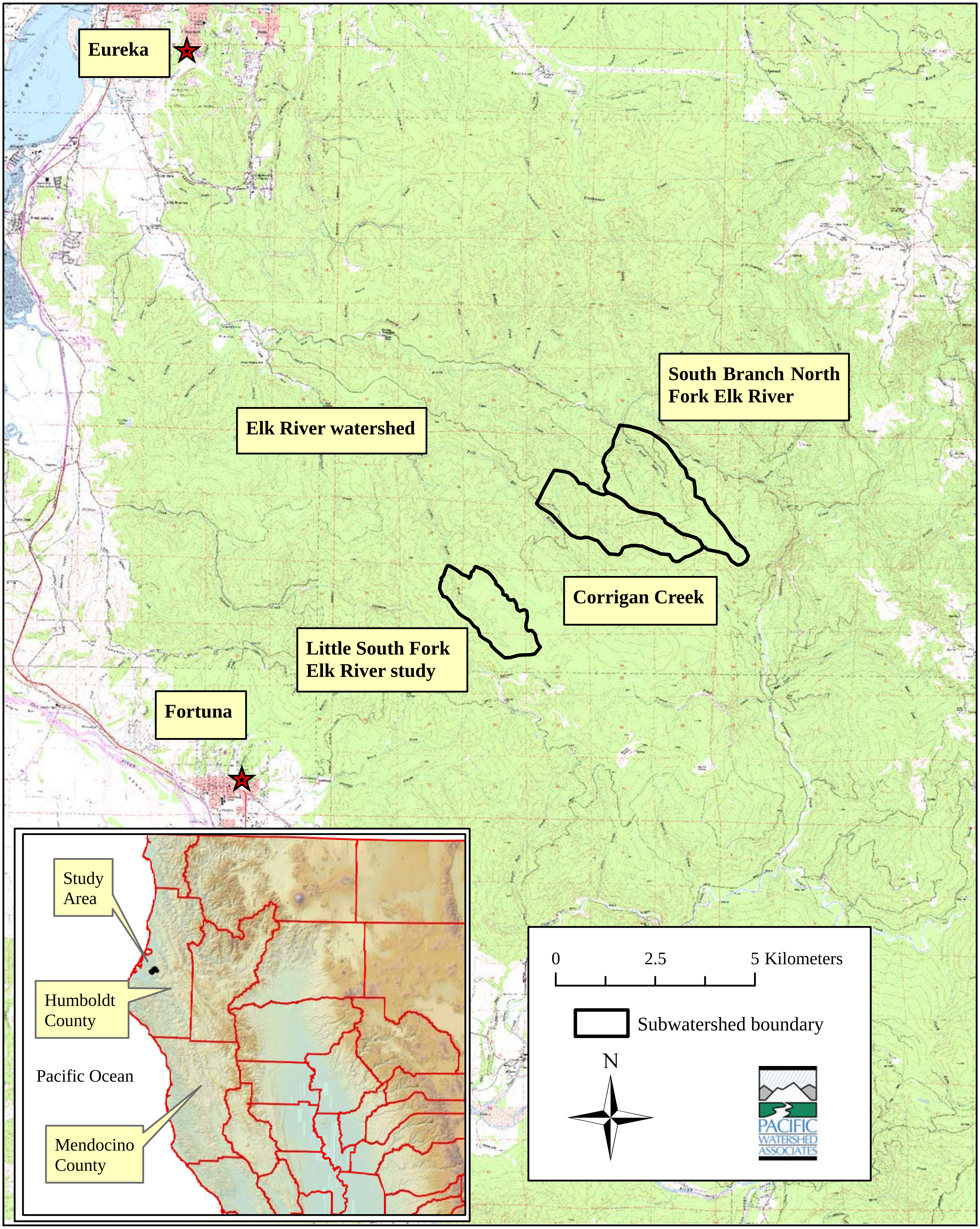

Figure 1. Elk River bank erosion void assessment and bank erosion related wood inventory study area

photography, the remainder of the middle portion and upper portions of Corrigan Creek were harvested primarily through tractor clear cut methods. During the 1997 air photo time period, only a few localized areas were tractor harvested, primarily in the upper portions of the watershed. The lower portion of Corrigan Creek has undergone recent, since 2000, harvesting. Approximately ¼ of the watershed was thinned with a few small clear cut units. The harvesting primarily used tractor yarding, although portions were cable yarded.

Timber harvesting was first documented in the lowermost portion of the South Branch North Fork Elk River by the time of the 1954 aerial photography. The remainder of the subwatershed appeared to be uncut until the 1974 air photo time period. During the 1974 air photo time period, heavy timber harvesting was documented in the lower portions of the subwatershed and extending to the upper ¼ of the subwatershed. Timber harvest methods during this time period were primarily by tractor clear cut methods. The remainder of the South Branch North Fork Elk River subwatershed (uppermost ¼) was harvested by the time of the 1987 and 1997 historic aerial photography.

The Little South Fork Elk River study area upstream from the turbidity station consists of late successional, old growth redwood. No harvesting had occurred in the study areas until the 1990's when a 2.3 km road ("Worm Road" or BLM R1 road) was constructed through a portion of the old growth stands. The road was constructed with a maximum width of 61 m (200 ft). After the Headwaters land transfer to the BLM in 1999, the "Worm Road" was permanently decommissioned between 2000 and 2003.

According to previous historic air photo analysis, road construction in the Corrigan Creek and South Branch North Fork Elk River developed concurrently with timber harvest activities in the subwatersheds. Road construction in the Little South Fork Elk Road was constrained to the development of the "Worm Road" (R1 road) in the uppermost portion of the subwatershed. Road densities in Corrigan Creek, Little South Fork Elk River, and South Branch North Fork Elk River study areas range from 0.80 km/km^2 to 4.2 km/km^2 (3.7 km/km^2, 0.80 km/km^2, and 4.2 km/km^2, respectively).

III. Geologic Setting of the Elk River Watershed

Coastal California north of Cape Mendocino lies within the tectonically active convergent margin of the North American plate. Since the Mesozoic Era, the geologic development of Northern California has been dominated by plate convergence. During the last 140 million years, subduction and the resulting continental accretion have welded a broad complex of highly deformed oceanic rocks to the western margin of the North American plate. These accreted rocks now comprise the Franciscan Complex, which constitutes the basement of the north coast region (Carver and Burke, 1992). Throughout the latest geologic period, major uplift of the Coast Ranges and erosional stripping of the regionally extensive forearc sediments are postulated to have resulted from the combined effects of the eastward subduction of the Gorda plate and the northward migration of the Mendocino triple junction (Nilsen and Clarke, 1987). Today, geologically youthful cover sediments are preserved in a series of structural settings such as those found within and around the greater Humboldt Bay region (Clarke 1992; Nilsen and Clarke 1987; Carver 1987).

The distribution of lithologic units within the Elk River bank erosion and wood inventory study area is illustrated in Table 1 and Figures 2a - 2c. The lithology for the study area was compiled from the "Maps and GIS data for the Elk River Watershed, Humboldt County, California, Watershed Mapping Series" prepared by the California Geological Survey (Marshall et al. 2005).

The Elk River bank erosion and wood inventory study area is comprised of Coastal Belt Franciscan lithologies. The Coastal Belt Franciscan is divided into two structural and lithologic terranes including:

Ty –The Yager terrane (y1 of McLaughlin et al. 2000) consists of well indurated and highly folded arkosic sandstone and argillite (Marshall et al. 2005). Sandstone within the Yager terrane develops sharp ridge crests and cliffs and well incised drainages (Maps 2a – 2c). The argillite component is highly sheared and prone to slaking and deep weathering. The Yager terrane can develop rotational debris slides in steep convergent topography that may channelize creating debris torrents along watercourses. Between 18% and 31% of the subwatershed area within Corrigan Creek, Little South Fork Elk River, and South Branch North Fork Elk River is underlain by the Yager terrane (26%, 31%, and 18%, respectively) (Table 1; Maps 2a – 2c)

QTwu – The undifferentiated Wildcat Group (included in QTw of McLaughlin et al. 2000) unconformably overlies the Yager Formation and consists predominantly poorly to moderately consolidated marine and non marine siltstone and fine grained silty sandstone with lenses of pebble conglomerate (Marshall et al. 2005). The undifferentiated Wildcat Group sediments weather into non plastic clayey silts and clayey sands that are prone to both deep seated rotational and translational mass wasting, as well as shallow debris landsliding on steep slopes (Marshall et al. 2005). Between 69% and 82% of the subwatershed area within Corrigan Creek, Little South Fork Elk River, and South Branch North Fork Elk River is underlain by Wildcat group sediments (74%, 69%, and 82%, respectively) (Table 1; Maps 2a – 2c).

Table 1. Lithology of the Elk River bank erosion void assessment and bank erosion-related wood inventory study area.

Lithology	Corrigan Creek		Little South Fork Elk River[1]		South Branch North Fork Elk River		Total	
	Area (mi^2)	% area	Area (mi^2)	% area	Area (mi^2)	% area	Area (mi^2)	% area
QTw	3.08	74%	2.02	69%	4.11	82%	9.21	76%
Ty	1.10	26%	0.89	31%	0.88	18%	2.87	24%
Total	**4.18**	**100%**	**2.91**	**100%**	**4.99**	**100%**	**12.08**	**100%**

[1] The Little South Fork Elk River subwatershed study area encompasses the drainage area upstream from the established turbidity station.

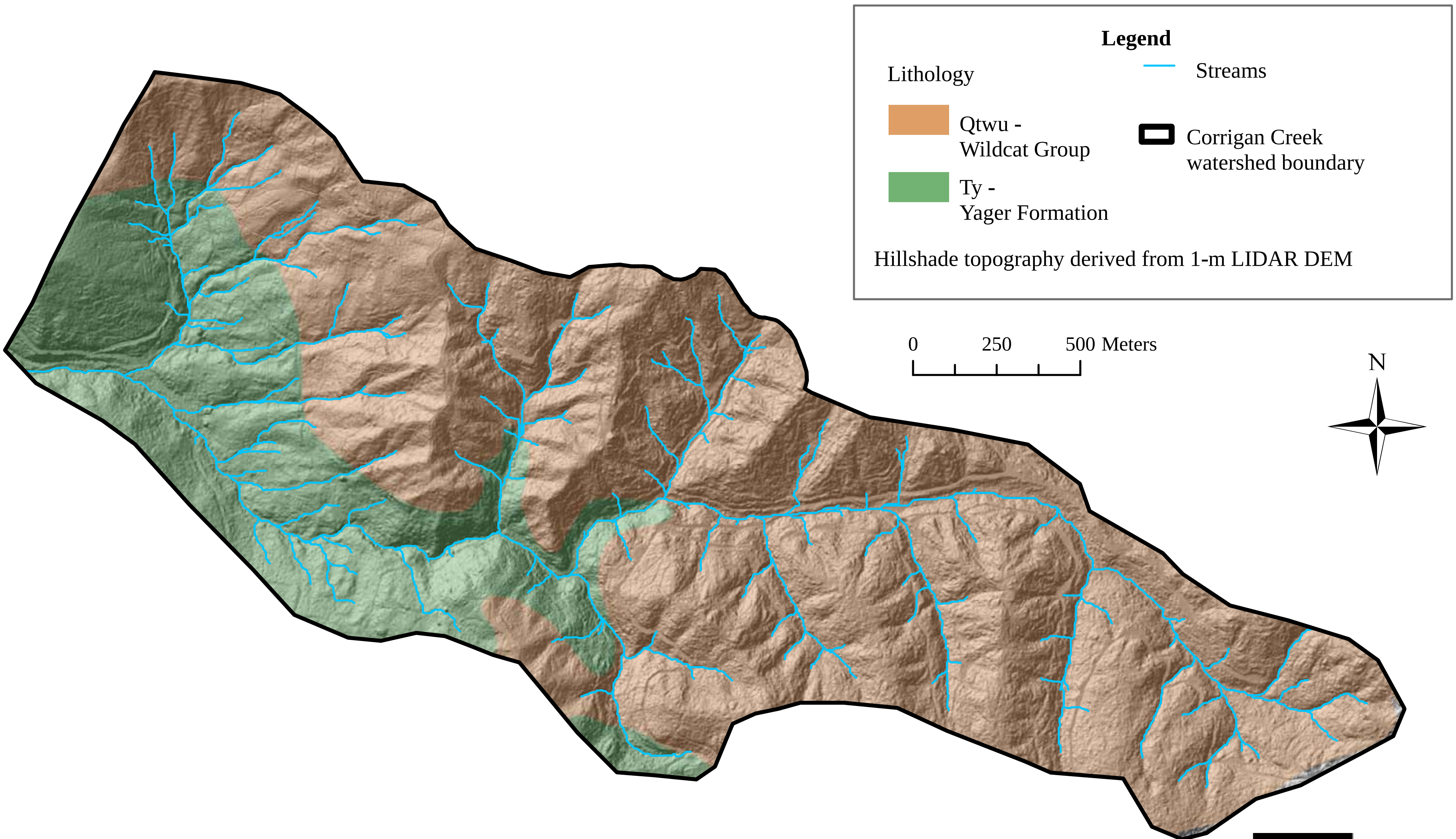

Figure 2a. Corrigan Creek Lithology, Bank Erosion Void and Bank Erosion-Related Wood Inventory, Elk River Watershed, Humboldt County, California.

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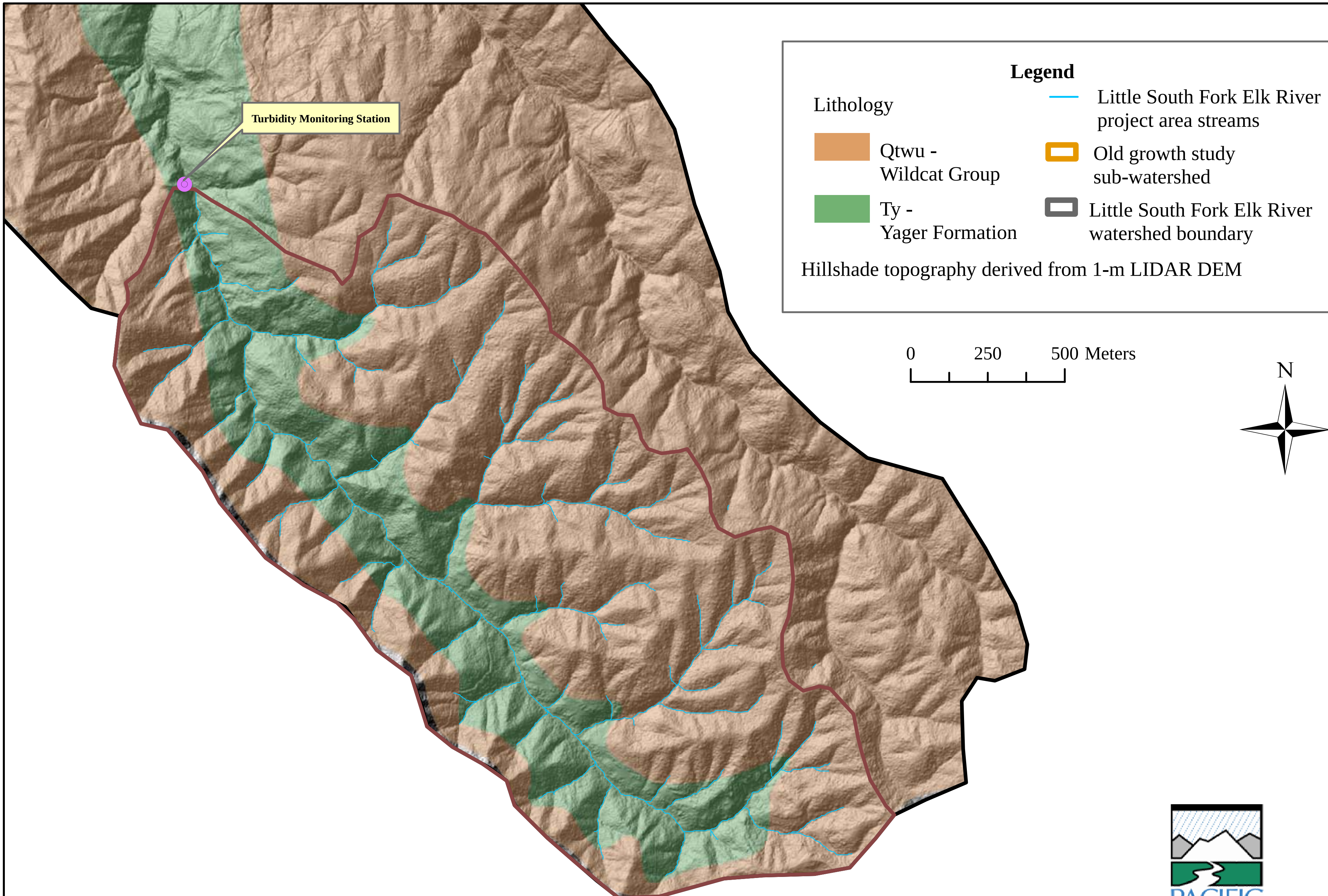

Figure 2b. Little South Fork Elk River Lithology, Bank Erosion Void and Bank Erosion-Related Wood Inventory, Elk River Watershed, Humboldt County, California.

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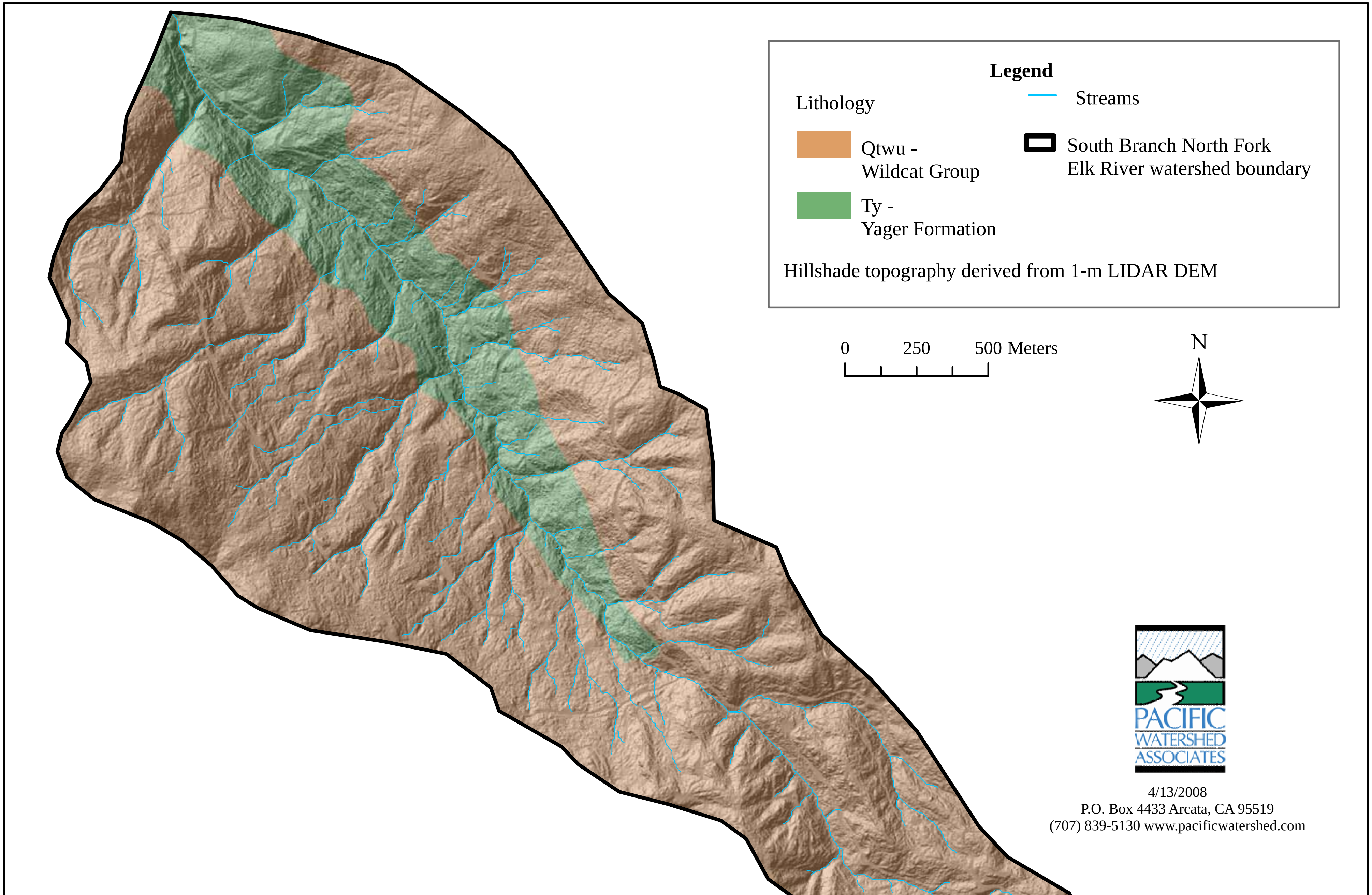

Figure 2c. South Branch North Fork Elk River Lithology, Bank Erosion Void and Bank Erosion-Related Wood Inventory, Elk River Watershed, Humboldt County, California.

IV. Bank Erosion Void Assessment and Bank Erosion-Related Wood Inventory

A. Methods

1. Field assessment methods

The field inventory of bank erosion voids and bank erosion-related wood was conducted on a random sample of tributary streams within 3 subwatersheds in the Elk River watershed, including Corrigan Creek, Little South Fork Elk River, and South Branch North Fork Elk River. PWA derived a GIS-based stream layer for the study areas using the Elk River 1-m LiDAR DEM generated for the North Coast Regional Water Quality Control Board (NCRWQCB). In order to develop a representative stream layer for the 3 subwatersheds, the Elk River 1-m LiDAR DEM was re-sampled as a 3-m grid. The 3-m grid was re-sampled back to a 1-m grid in order to reduce the topographic noise (i.e. topographic sinks, brushy areas, tree stumps, and other random errors). Using the 1-m grid, a stream layer was developed for each subwatershed assuming an 8,000 m^2 contributing area defining the location of stream inception. This stream layer was used to designate the Strahler order of all tributary channels within the three study subwatersheds.

Approximately 3,000 m stream channel reaches were randomly selected in each of the three study subwatersheds. Randomly selected stream reaches were selected to provide a proportional sample of 1^{st}, 2^{nd}, 3^{rd} and 4^{th} order and higher stream channels in each study subwatershed. Selected stream reaches were inventoried by stationing the selected stream reaches by 100-meter increments and inventorying bank erosion voids and wood deposited in the channel from bank erosion processes. For the purposes of this study, bank erosion is defined as stream bank erosion caused by lateral migration of stream flows (i.e. flow deflection or stream undercutting). Bank erosion does not include streamside hillslope failures (mass wasting), or stream channel incision (vertical down cutting) caused by fluvial processes.

Specific bank erosion void attributes were collected on field data forms for erosion features with sediment delivery >3.8 m^3 (>5 yds^3) and mapped on 1:1200 LiDAR based DEM shade relief field maps. The specific bank erosion attributes collected in the field are listed below. The locations of bank erosion sites <3.8 m^3 (<5 yd^3) were flagged in the field and mapped on the field maps, but data forms were not filled out for these smaller features.

Bank erosion-related wood was also inventoried and mapped along the sample stream reaches in the three study subwatersheds. To be considered bank erosion-related wood, wood pieces must show evidence of roots connected to the stream bank, or a root wad in the channel with evidence of adjacent bank erosion (Benda and Associates 2004) (Figure 3). Wood from other sources (i.e. natural mortality, landslides, wind throw, or other unknown processes) were not inventoried as part of this project. The minimum bank erosion-related wood size identified as part of this project was approximately 8 centimeters in diameter and 1.8 meters in length. Additional attributes that were collected for the bank erosion-related wood budget are also listed below.

The bank erosion void and bank erosion-related wood inventory attributes collected during the field inventory included:

General data attributes

- Unique identification number
- Sub-basin name
- Reach number
- Station number
- Field map number
- Observed geology

Bank erosion void attributes

- Location
    - Left bank
    - Right bank
- Bank erosion height (m)
- Bank erosion width (m)
- Bank erosion depth (m)
- Sediment delivery %
- Toe of deep seated landslide?
- Age of erosion (decade of erosion)
- Age indicators
    - Moss
    - Bare soil
    - Roots
    - Redwood sprouts
    - Wood sprouts

- Activity level
    - Active
    - Inactive
    - Waiting
- Activity indicators
    - Moss
    - Bare soil
    - Roots
    - Redwood sprouts
    - Wood sprouts
- Stream morphology
    - Inside bend
    - Outside bend
    - Straight reach
- Bank erosion causal mechanism
    - Natural flow deflection
    - Management flow deflection
    - Stream undercutting,
    - Landslide mass deflection

- Unstable geology
- Skid trail location
- Stand age
- <15 years old
- 15-30 years old
- >30 years old
- Old growth
- Geomorphic association
- Inner gorge
- Streamside

Bank erosion-related wood inventory attributes (based on Benda 2004 and Bigelow pers. communication):

- Tree type
- Conifer
- Deciduous
- Tree species
- Diameter at breast height (DBH) (m)
- Diameter at midpoint (m)
- In stream wood length (m)
- Total wood length (m)
- Age of recruitment (years)
- Decay class (based on Hennon et al. 2002)
- Needle or Leaf
- Twig
- Branch
- Primary branch
- Nub
- Hard
- Rotten

Figure 3. Example of bank erosion recruited wood in the Elk River watershed. Wood piece is connected to stream bank.

2. Methods to compute bank erosion volume and yield rate estimates

Using the bank erosion void assessment method (Reid and Dunne 1996; PWA 1999; PALCO 2007), bank erosion volume estimates for erosion features >3.8 m^3 were estimated by measuring bank erosion height and root exposure depth along lengths of eroded stream bank. The volume of bank erosion was computed as the bank erosion height (ft) x root exposure depth (ft) and length of eroded channel (ft). Bank erosion sites <3.8 m^3 were tallied by stream order and erosion from these sites was estimated by multiplying the number of smaller features by an average delivery of 2 m^3 per site. Unit bank erosion (m^3/m) was determined for 1st, 2nd, 3rd and >4th order channels based on the total estimate of field inventoried bank erosion (>3.8 m^3 and <3.8 m^3 features combined) in each stream order. Unit sediment delivery was then extrapolated to the total length of stream in of the three subwatersheds by each stream order.

Bank erosion estimates using the wood budget method (Benda and Associates 2004) were calculated for 2nd order and higher streams. Bank erosion is less prevalent in 1st order stream channels due to the low stream power and small channel dimensions. As a result, erosion from 1st order channels was calculated from soil creep. Soil creep estimates were not calculated for 2nd order and higher stream channels.

For 2nd order and higher streams, bank erosion rates were estimated using the following equation:

$$E = [I_{be}/N]/[\, B_L * P_{be}] \qquad (1)$$

where E is the mean bank erosion rate (m/yr), I_{be} is the annual wood supply to stream from bank erosion (m^3/km/yr), B_L is the volume of standing live biomass per unit area (m^3/hectare), P_{be} is the probability of tree fall from bank erosion processes, and N is 1 or 2 depending on whether one or both sides of the stream channel are forested (Benda et al. 2003). For the purposes of this study, bank erosion rates and estimates were derived for both stream channel banks (N=2). Estimates of standing biomass density for the three study subwatersheds were provided by PALCO. The standing biomass density was based on the volume in board feet per acre along Class I and Class II watercourses with a 10-m stream channel buffer. The Little South Fork Elk River standing biomass density data was derived from 1998 inventory information at the time this area was owned by PALCO. As a result, the estimate of B_L for Little South Fork Elk River may represent a minimum biomass density value.

Annual wood supply to the stream from bank erosion (I_{be}) was calculated using the following equation:

$$I_{be} = [V_{be}/L]/\Delta T \qquad (2)$$

where V_{be} is the volume (m^3) of bank erosion recruited wood, L is the total stream reach length (m), and ΔT (yr) is the weighted mean age of bank erosion recruited wood (Benda and Associates 2004).

The fraction of stem length of fallen trees that is deposited into the channel (P_{be}) is based on a random geometric tree fall model (Van Sickle and Gregory 1990) and assumes a hypothetical uniform stand of trees within a designated distance normal to the stream bank (Benda and Associates 2004). Based on field observations by Benda and Associates and other studies, P_{be} assumes 100% fall probability towards the stream channel (Benda and Associates 2004; Murphy et al. 1989; Martin et al. 2001). P_{be} was calculated for each study subwatershed using a probability calculator provided by Paul Bigelow (Benda and Associates). The calculation of P_{be} is dependent on average stream width (m) and average tree height (m). For the purposes of this study, average stream width was derived from field observations, and average tree height for Corrigan Creek and North Branch South Fork Elk River was estimated as 34 m, and average tree height for the Little South Fork Elk River was estimated as 80 m.

The weighted mean average of bank erosion recruited wood (ΔT) was derived using the wood decay class and the recruitment age of bank erosion-related wood. The weighted mean average ΔT is calculated by summing the product of the mean recruitment age for each decay class the proportion of wood within each decay class.

Bank erosion rates developed for 2nd order and higher streams were then applied to the following equation to develop bank erosion sediment delivery:

$$\text{BE sediment delivery} = [E*N*\text{Bank height}*\text{Drainage density } (m/km^2)] \qquad (3)$$

where bank height refers to the average "entrenched" bank height for 2nd order and higher stream channels. Over geologic time, stream channels in the Elk River watershed have incised as a result of uplift and stream down cutting. In higher order streams, this results in "entrenched" stream channels where the bank full height (2 yr flood recurrence interval) is below the point where the top of the stream bank intercepts the hillslope (Figure 4). The entrenched bank height was used to determine bank erosion estimates for this study, because it is assumed that bank erosion occurring at the bank full height will result in undercutting of the entire entrenched stream bank. Drainage density refers to the average drainage density for 2nd order and higher stream channels for each of the three study subwatersheds.

For 1st order streams, erosion estimates were calculated using Equation 3, and substituting a soil creep rate for the bank erosion rate (E). The soil creep rate used in this study was estimated at 1.6 mm/yr and was derived from the Surface Erosion Module of the PALCO Upper Eel River Watershed Analysis (PALCO 2007). Swanston et al. (1995) estimated creep rates from 1.0 to 2.5 mm/yr in Redwood Creek, which is approximately 55 kilometers north of the watershed in this study. The PALCO Upper Eel River watershed analysis used an average soil creep rate of 1.6 mm/yr for North Coast California watersheds (PALCO 2007). This appeared to be an adequate estimate for the Elk River bank erosion void and wood inventory study due to the lack of pertinent soil creep data for the three study areas. The average bank heights used for the 1st order stream channel refer to the average bank full stream bank height, not entrenched bank height. First order streams do not exhibit entrenched stream channels due to low stream power (Figure 4).

Figure 4. Fifth order stream exhibiting stream channel entrenchment caused by a combination of channel down cutting and geologic uplift. Bank full height is located approximately 1 m below entrenched bank height. The photo point was taken looking downstream at the turbidity station on Corrigan Creek

Figure 5. First order stream in Little South Fork Elk River exhibiting bank full dimensions, but no stream channel entrenchment. Bank full height is approximately 5 cm – 8 cm (<2”).

B. Results

Figures 6a – 6c and Table 2 show the distribution of randomly selected stream reaches and the entire stream network according to Strahler stream order for Corrigan Creek, Little South Fork Elk River and South Branch North Fork Elk River. A total of 8.89 km of stream channel were inventoried as part of the bank erosion void and bank erosion-related wood inventory, with 3.01 km inventoried in Corrigan Creek, 3.0 km inventoried in Little South Fork Elk River, and 2.88 km inventoried in South Branch North Fork Elk River.

Table 2 describes the physical characteristics of the sample reaches for each study subwatershed. A total of 14 sample reaches were inventoried in the Corrigan Creek subwatershed with an average reach length of 215 m (Figure 6a). Approximately 750 m of stream reaches were inventoried in each of the 4 Strahler orders (1^{st}, 2^{nd}, 3^{rd}, and 4^{th} and higher) (Table 2). The dominant stream channel substrate within this subwatershed is primarily composed of a mixture of sand, gravel, and cobble (Table 3). The channel morphology of sample reaches within Corrigan Creek first order channels was observed as a mixture of bedrock cascades and channels that exhibited subsurface flow. Many of the first order channels within the Elk River watershed exhibit intermittent surface and subsurface flow. These first order channels typically show higher incidence of channel incision and vertical collapse due to subsurface flows.

Table 2. Stream length and average drainage density by Strahler order

Subwatershed	Strahler order				Total
	1	2	3	4	
Total channel length in Corrigan Creek (km)	15.59	6.65	1.83	4.87	28.95 km
% of total channel length, by order	54%	23%	6%	17%	100%
Length sampled (km)	0.75	0.75	0.75	0.76	3.01 km
Length sampled (%)	5%	11%	41%	16%	10%
Average drainage density (km/km^2)	6.76	2.80	1.24	0.07	--
				Study area	4.2 km^2
				Stream density	6.89 km/km^2
Total channel length in Little South Fork Elk River (km)	9.63	4.49	2.65	2.34	19.11 km
% of total channel length, by order	50%	24%	14%	12%	100%
Length sampled (km)	0.90	0.59	0.75	0.76	3.00 km
Length sampled (%)	9%	13%	28%	32%	16%
Average drainage density (km/km^2)	5.36	2.83	1.57	0.7	--
				Study area	2.91 km^2
				Stream density	6.57 km/km^2
Total channel length in South Branch North Fork Elk River (km)	18.01	11.33	4.59	2.88	36.81 km
% of total channel length, by order	49%	31%	12%	8%	100%
Length sampled (km)	0.62	0.75	0.75	0.76	2.88 km
Length sampled (%)	3%	7%	16%	26%	8%
Average drainage density (km/km^2)	7.34	3.80	1.45	0.58	--
				Study area	4.99 km^2
				Stream density	7.38 km/km^2

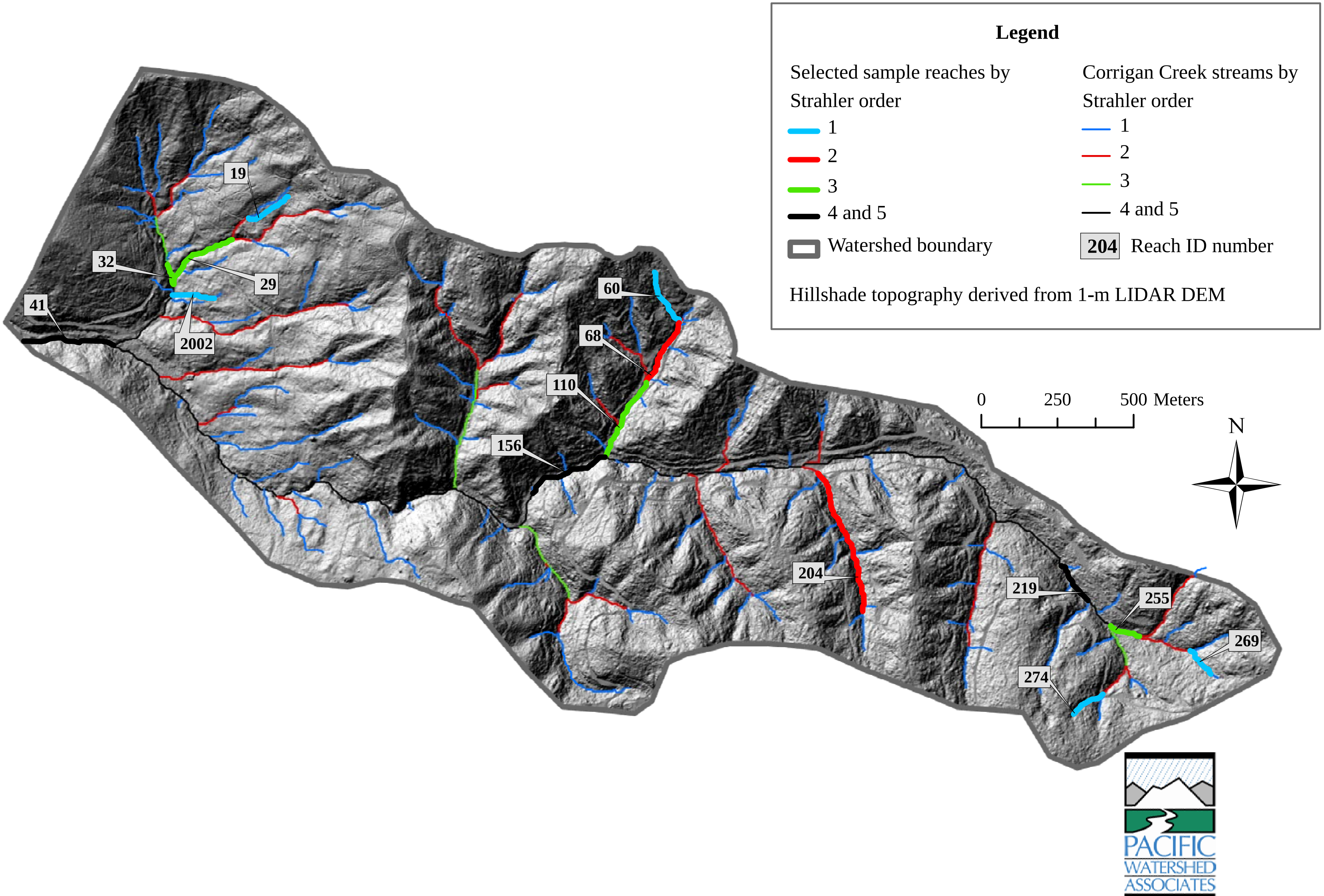

Figure 6a. Corrigan Creek selected inventory stream reaches, bank erosion void and bank erosion-related wood inventory, Elk River Watershed, Humboldt County, California.

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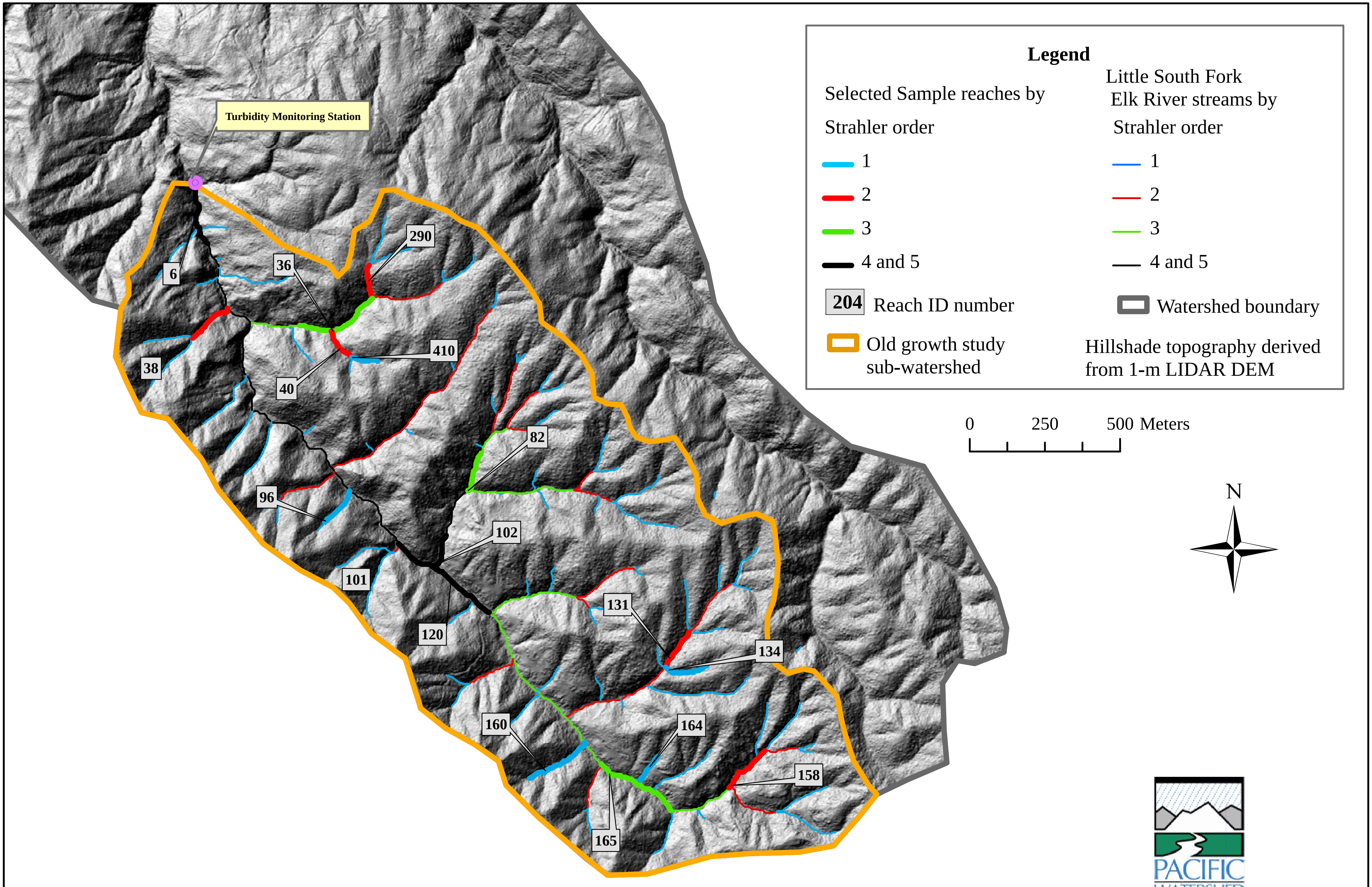

Figure 6b. Little South Fork Elk River Selected Inventory Stream Reaches, Bank Erosion Void and Bank Erosion-Related Wood Inventory, Elk River Watershed, Humboldt County, California.

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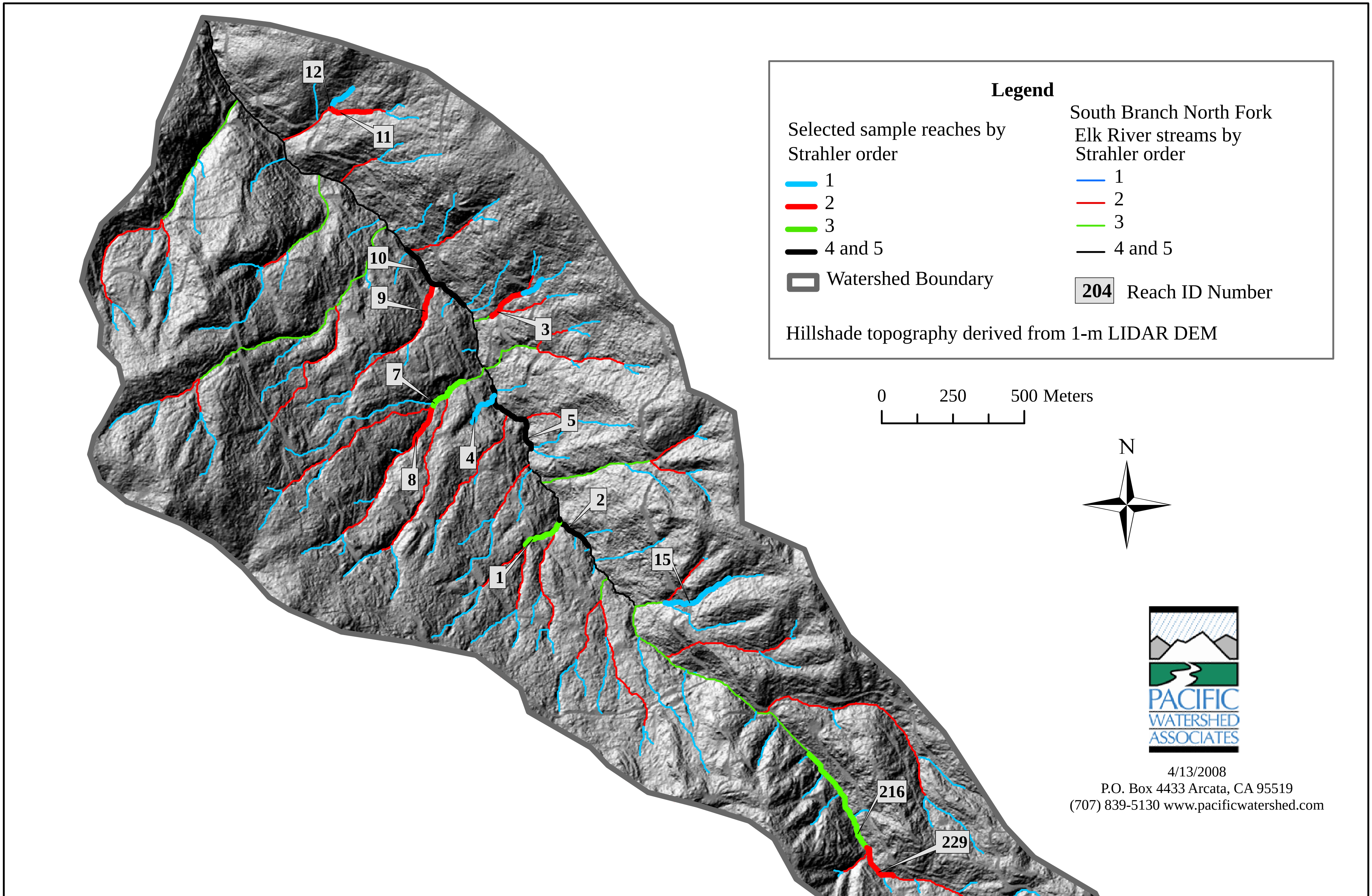

Figure 6c. South Branch North Fork Elk River selected inventory stream reaches, Bank Erosion Void and Bank Erosion-Related Wood Inventory, Elk River Watershed, Humboldt County, California.

Table 3. Physical characteristics of the selected sample stream reaches in Corrigan Creek, Little South Fork Elk River and South Branch North Fork Elk River

Subwatershed	Strahler stream order	Reach No.	Drainage area change over reach length (km^2)	Reach Length (m)	Average slope gradient (%)	Average channel width (m)[1]	Dominant channel substrate	Dominant channel morphology[2]
Corrigan Creek	1	19	0.003	162.5	39	0.58	Sand	CAS
	1	60	0.018	206.1	10	0.6	Sand	SSF
	1	269	0.006	113.2	38	0.6	Gravel	CAS
	1	274	0.006	128.1	30	NM	NM	SSF
	1	2002	0.003	142.3	25	1.2	Gravel	CAS
	2	68	0.138	233.7	10	1.6	Sand	CAS / SSF / LGR
	2	204	0.144	518.1	5	0.68	Sand	LGR/CAS/HGR/STP
	3	29	0.042	273.1	27	0.9	Gravel	CAS
	3	32	0.006	72.4	5	1	Gravel	HGR
	3	110	0.096	298.6	3	0.88	Sand	SRN / LGR
	3	255	0.017	108.8	6	0.64	Gravel	HGR/SSF
	4	156	1.595	293.1	4	1.6	Sand	LGR
	4	219	0.042	155.3	2	0.76	Gravel	LGR
	5	41	0.101	307.4	3	6	Cobble	LGR
Little South Fork Elk River	1	96	0.009	141	33	0.3	Sand	SSF/CAS
	1	134	0.009	154.5	15	0.3	Sand	SSF
	1	160	0.032	238.8	20	0.5	Sand	SSF
	1	164	0.006	126.3	35	0.3	Sand	SSF
	1	410	0.008	93.3	18	0.4	Sand	SSF
	2	131	0.014	147.7	14	1	Cobble	SSF
	2	38	0.012	166.8	27	0.6	Sand	SSF/CAS
	2	40	0.019	119.8	14	0.6	Sand	SSF
	2	158	0.060	185.2	5	0.9	Sand	STP/Road excavation
	2	290	0.022	120.6	34	0.4	Sand	CAS/SSF
	3	36	0.183	300.9	16	0.6	Sand	SRN
	3	82	0.017	143.6	10	0.4	Sand	SRN
	3	165	0.155	303.3	8	1.2	Sand	SRN
	4	102	0.019	128.4	7	1	Sand	HGR
	4	120	0.076	254.6	2	0.89	Sand	LGR
	5	6	0.191	228.4	4	4	Gravel/Cobble	LGR
	5	101	0.499	143.9	2	2	Sand	LGR

Table 3. Physical characteristics of the selected sample stream reaches in Corrigan Creek, Little South Fork Elk River and South Branch North Fork Elk River

Subwatershed	Strahler stream order	Reach No.	Drainage area change over reach length (km^2)	Reach Length (m)	Average slope gradient (%)	Average channel width (m)[1]	Dominant channel substrate	Dominant channel morphology[2]
South Branch North Fork Elk River	1	4	0.007	142.9	36	NM	NM	SSF
	1	12	0.009	117.7	35	0.4	Sand	SSF
	1	15	0.022	268.6	15	0.7	Sand	HGR
	2	3	0.088	242.3	34	0.9	Gravel	CAS/HGR
	2	8	0.123	150.8	26	0.8	Gravel	CAS
	2	9	0.017	136.9	17	1.2	Gravel	HGR/CAS
	2	11	0.011	150.8	31	0.6	Gravel	SSF/CAS
	2	229	0.077	164.4	10	0.9	Sand	HGR
	3	1	0.080	167.8	23	1.2	Gravel	CAS/HGR
	3	7	0.197	174.5	14	1	Gravel	CAS/LGR
	3	216	0.141	411.5	3	0.55	Sand	LGR
	4	2	0.264	150.2	12	3.4	Cobble	HGR/CAS
	4	5	0.219	307.5	6	3.4	Cobble	CAS/LGR/HGR
	4	10	0.300	299	3	4.1	Gravel	LGR

[1] NM – Not measured
[2] LGR – Low gradient riffle, HGR - High gradient riffle, CAS – cascade, SSF - Subsurface flow, STP - Step pools, SRN - Step run

The 2nd order and 3rd order sample reaches in Corrigan Creek were a mixture of all channel types (bedrock cascade, low and high gradient riffle, step run) with a lower incidence of channels with subsurface flow. Fourth order and higher channels in this subwatershed were classified as low gradient riffles and are located in the mainstem of Corrigan Creek (Table 3 and Figure 6a).

Seventeen (17) randomly selected stream reaches were inventoried in the Little South Fork Elk River subwatershed upstream from the turbidity station (Figure 6b). Inventoried stream reach length within this study area averaged approximately 176 m. Approximately 900 m of 1st order, 590 m of 2nd order, 750 m of 3rd order, and 760 m of 4th order and higher stream reaches were inventoried in this subwatershed (Table 2). The dominant channel substrate observed in the Little South Fork Elk River inventoried stream reaches is composed primarily of sand with minor amounts of cobble and gravel. The channel morphology of 1st and 2nd order channels within this subwatershed were dominated by subsurface flow. The channel morphology observed in the 3rd and 4th order and higher inventoried stream reaches was dominantly low gradient riffle, with the 4th order and higher reaches located in the mainstem of the Little South Fork Elk River (Table 3 and Figure 6b).

Fourteen (14) sample reaches were inventoried in the South Branch North Fork Elk River with an average reach length of 206 m (Figure 6c). Approximately 620 m of 1st order, 750 m of 2nd order, 750 m of 3rd order, and 760 m of 4th order and higher stream reaches were inventoried in this subwatershed (Table 2). Similar to Corrigan Creek, the dominant channel substrate within the South Branch North Fork Elk River sample reaches was observed as a mixture of sand, gravel and cobble. The channel morphology of 1st order channels within this subwatershed was observed as primarily subsurface flow and high gradient riffle. Second (2nd) and 3rd order inventoried reaches exhibited less subsurface flow and were dominated by bedrock cascades and high gradient riffles. Finally, 4th order and higher order stream reaches within this subwatershed were located in the mainstem of South Branch North Fork Elk River and exhibited a mixture of channel morphologies including bedrock cascade, and high and low gradient riffles (Table 3 and Figure 6c).

Table 4 shows the percent distribution of sample and total stream length by lithology in the Corrigan Creek, Little South Fork Elk River, and South Branch North Fork Elk River. Overall for all three study subwatersheds, the Wildcat Group lithology is more prevalent in the 1st order and 2nd order stream channels and decreases substantially in the 3rd and 4th order and higher stream channels. As a result, the Yager Formation is more prevalent in the higher order channels where higher velocity stream flows have eroded through the Wildcat group terrane down to the underlying Yager Formation. For example, in the South Branch North Fork Elk River subwatershed the percent distribution of first order stream lengths underlain by the Wildcat Group and Yager Formation is 86% and 14%, respectively (Table 4). In contrast, the percent of 4th order and higher channels underlain by the Wildcat Group and Yager Formation is 0% and 100%, respectively.

Table 4. Percent sample reach length and total stream length by lithology

Subwatershed	Order	Inventoried sample stream length (%)			Total subwatershed stream length (%)		
		QTw (Wildcat Group)	Ty (Yager Formation)	Total sample	QTw (Wildcat Group)	Ty (Yager Formation)	Total length
Corrigan Creek	1	81%	19%	100%	66%	34%	100%
	2	100%	0%	100%	77%	23%	100%
	3	54%	46%	100%	41%	59%	100%
	>4	25%	75%	100%	43%	57%	100%
Total		65%	35%	100%	63%	37%	100%
Little South Fork Elk River	1	51%	49%	100%	66%	34%	100%
	2	42%	58%	100%	68%	32%	100%
	3	25%	75%	100%	31%	69%	100%
	>4	0%	100%	100%	0%	100%	100%
Total		30%	70%	100%	53%	47%	100%
South Fork North Fork Elk River	1	68%	32%	100%	86%	14%	100%
	2	61%	39%	100%	84%	16%	100%
	3	83%	17%	100%	60%	40%	100%
	>4	0%	100%	100%	0%	100%	100%
Total		52%	48%	100%	75%	25%	100%

1. Bank erosion void assessment

The following section summarizes the results of the field bank erosion void inventory using the bank erosion void assessment method and the estimation of bank erosion sediment delivery by Strahler stream order for the Corrigan Creek, Little South Fork Elk River, and South Branch North Fork Elk River subwatersheds. A total of 58 discrete bank erosion sites with >3.8 m^3 of sediment delivery were inventoried and field mapped along the 8.89 km of stream channel reaches in the three study subwatersheds (Figures 7a – 7c). In addition, 174 smaller bank erosion features <3.8 m^3were mapped and tallied in the field by stream order. Over the last 57 years, these 232 bank erosion sites (>3.8 m^3 and <3.8 m^3 combined) were estimated to delivery over 1,000 m^3 of sediment to Corrigan Creek, Little South Fork Elk River and South Branch North Fork Elk River (433 m^3, 137 m^3, and 439 m^3, respectively) (Table 5). The 57 year time period (1950-2007) is derived from the earliest age (1950 decade) assigned to bank erosion sites >3.8 m^3 identified in the during the field inventory.

Overall, Corrigan Creek and South Branch North Fork Elk River exhibited nearly the same unit bank erosion sediment delivery for the entire stream network within the subwatersheds (0.143 m^3/m and 0.144 m^3/m, respectively) (Table 5). The unit bank erosion sediment delivery calculated for Little South Fork Elk River (0.045 m^3/m) was approximately 69% lower than the unit sediment delivery derived for Corrigan Creek and South Branch North Fork Elk River (Table 5).

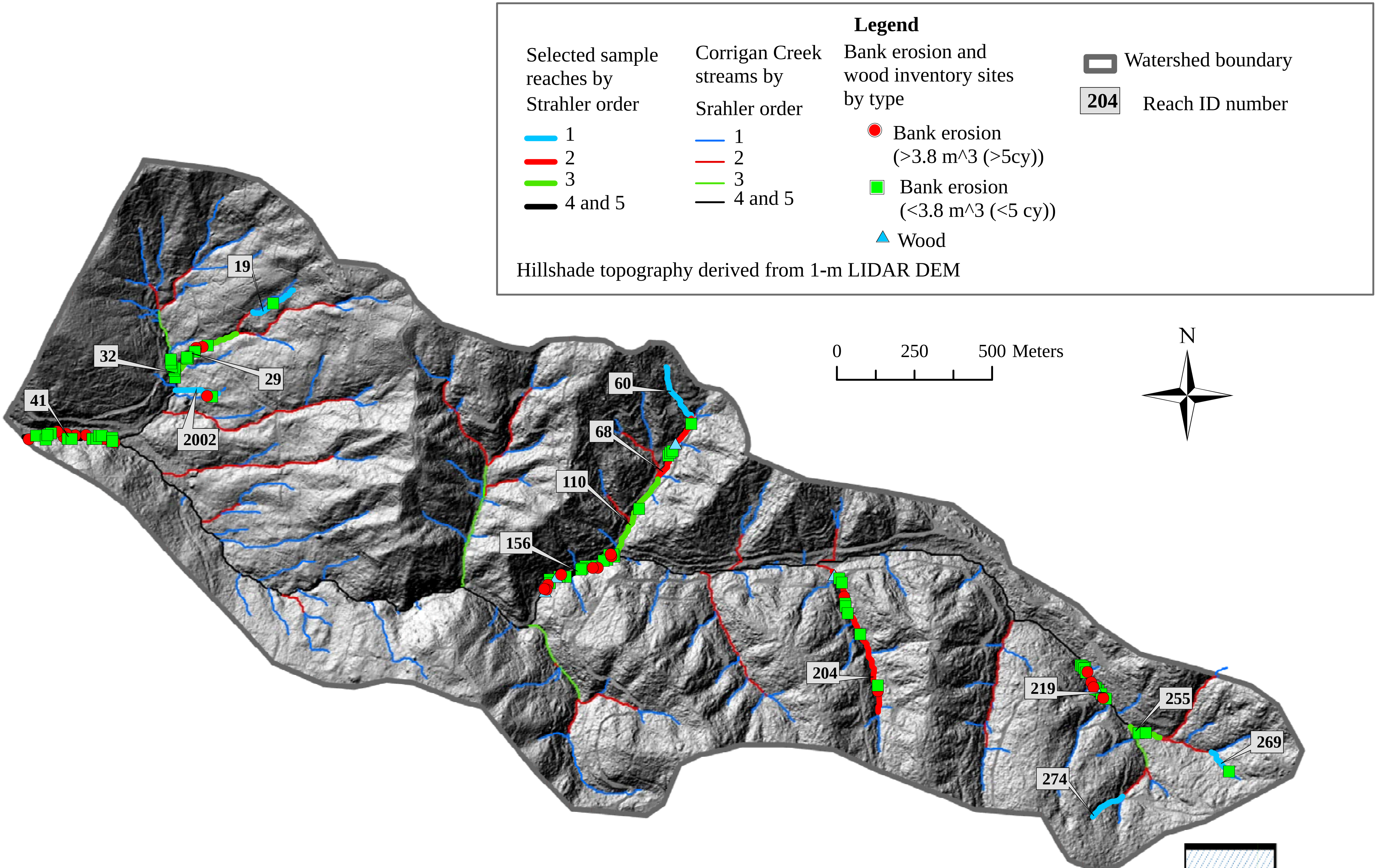

Figure 7a. Corrigan Creek site locations, bank erosion void and bank erosion-related wood inventory, Elk River Watershed, Humboldt County, California.

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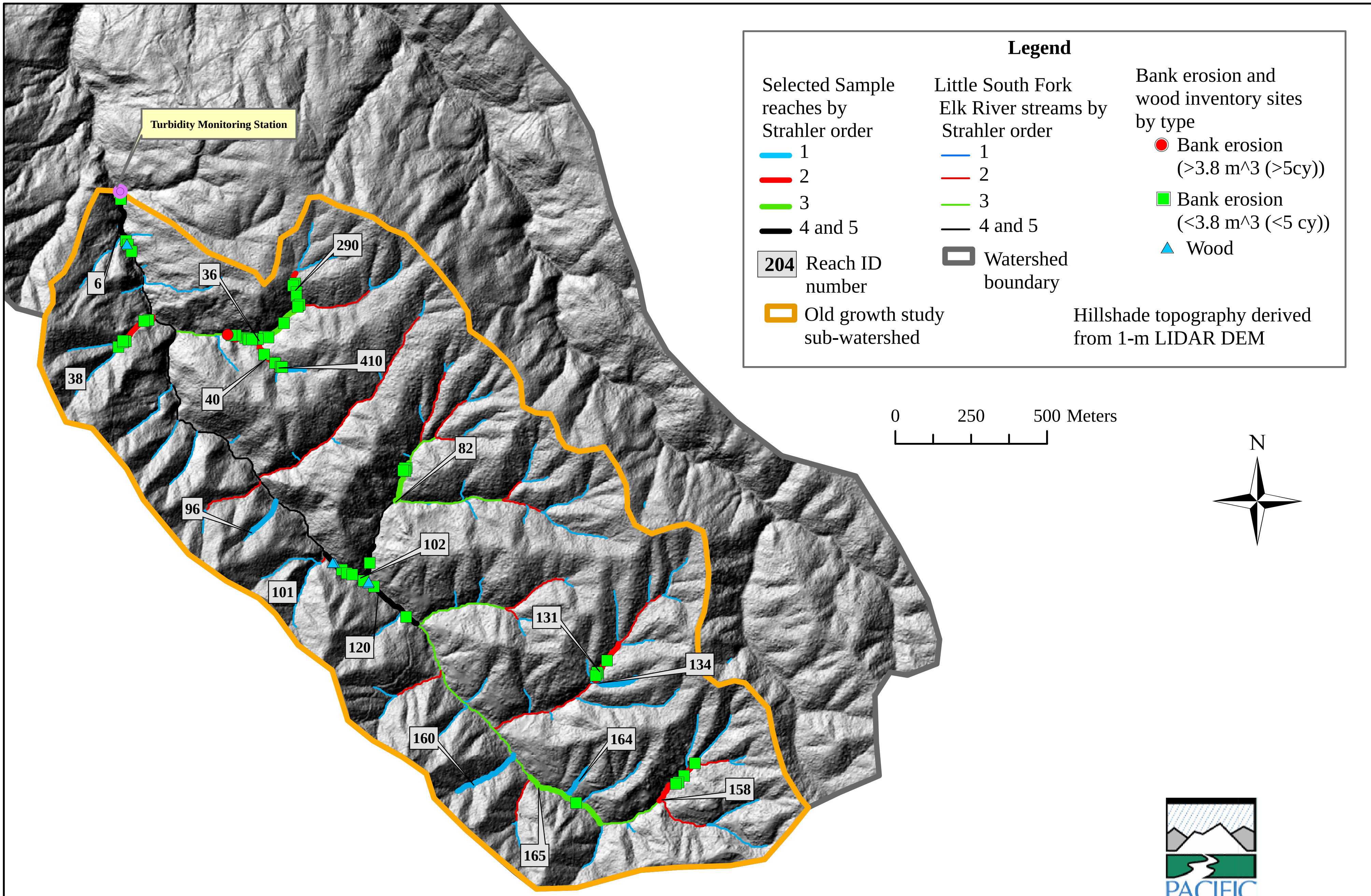

Figure 7b. Little South Fork Elk River site locations, bank erosion void and bank erosion-related wood inventory, Elk River watershed, Humboldt County, California.

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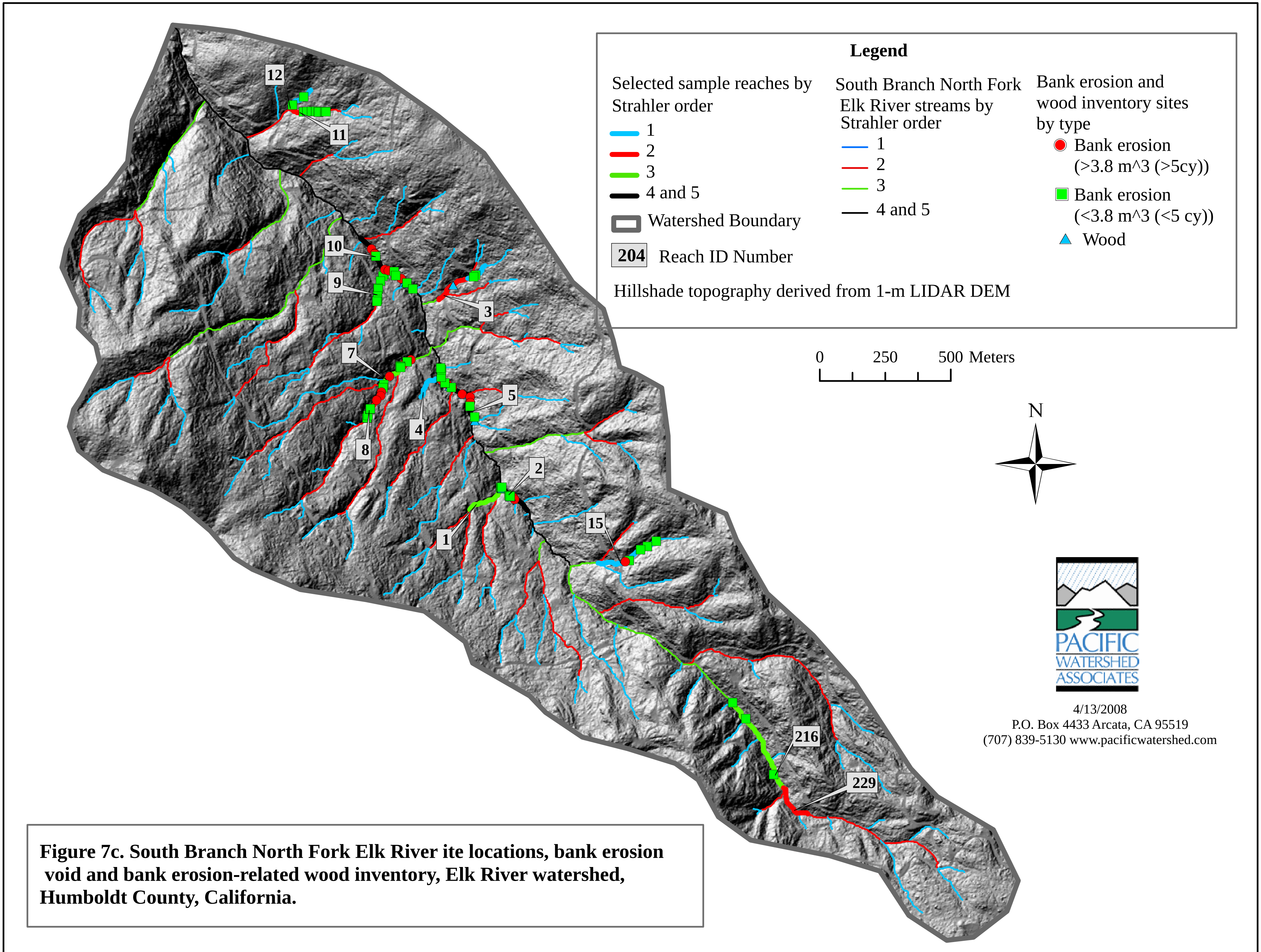

Figure 7c. South Branch North Fork Elk River ite locations, bank erosion void and bank erosion-related wood inventory, Elk River watershed, Humboldt County, California.

Table 5. Field estimated bank erosion from all inventoried bank erosion void features (>3.8 m³ and <3.8 m³)

Subwatershed	Strahler Order	Length of stream inventoried (km)	Bank Erosion	
			Sediment delivery (m^3)	Unit sediment delivery (m^3/m)
Corrigan Creek	1	0.75	17	0.022
	2	0.75	43	0.058
	3	0.75	59	0.078
	>4	0.76	314	0.415
	Total/Average	3.01	433	0.143
Little South Fork Elk River	1	0.90	14	0.018
	2	0.59	54	0.068
	3	0.75	43	0.057
	>4	0.76	27	0.035
	Total/Average	3.00	137	0.045
South Branch North Fork Elk River	1	0.62	76	0.099
	2	0.75	69	0.092
	3	0.75	30	0.040
	>4	0.76	263	0.347
	Total/Average	2.88	439	0.144

The highest unit sediment delivery for bank erosion (0.415 m^3/m) was observed in the 4th order and higher stream channels in the Corrigan Creek subwatershed, and the second highest unit bank erosion sediment delivery rate (0.347 m^3/m) was observed in the 4th order and higher stream channels in the South Branch North Fork Elk River (Table 6 and Figure 6). The South Branch North Fork Elk River exhibited higher unit bank erosion sediment delivery rates in lower order channels (1st and 2nd order) as compared with the other 2 study subwatersheds (Table 5).

Unit bank erosion sediment delivery by each stream order was extrapolated to the entire stream network for each of the three study subwatersheds in order to calculate the total bank erosion sediment yield. Table 6 lists the total volume of bank erosion (in m^3 and in metric tonnes) and estimate bank erosion yield rate (t/km^2/yr) by stream order for each of the three subwatersheds. Metric tonnes were calculated assuming a soil bulk density of 1,656 kg/m^3. This soil bulk density was used in the slope stability modeling conducted by Stillwater Sciences in 2007. Stillwater Sciences referenced Prellwitz et al. 2001, Hammond et al. 1992, and NAVFEC 1986 for the source of the soil bulk density value.

A total of 6,710 m^3 or 12,609 tonnes of sediment were delivered over the past 57 years (1950-2007) from bank erosion processes. The highest average bank erosion sediment yield rate (23.33 t/km^2/yr) was observed for all stream orders in the South Branch North Fork Elk River (Table 6 and Figure 8).The Little South Fork Elk River study subwatershed exhibited the lowest average bank erosion yield rate of 7.15 t/km^2/yr for all stream orders. This rate is 64% lower than the average bank erosion yield rate for Corrigan Creek (19.99 t/km^2/yr) and 69% lower than the bank erosion rate for South Branch North Fork Elk River (23.33 t/km^2/yr) (Figure 8)

Comparing bank erosion yield rates by stream order, the South Branch North Fork Elk River produced the highest bank erosion yield rate (21.68 t/km^2/yr) from 1st order stream channels. This rate is between 81% and 86% higher than the bank erosion yield rates observed in 1st order streams in the Little South Fork Elk River and Corrigan Creek (3.11 t/km^2/yr and 4.21 t/km^2/yr, respectively) (Table 6 and Figure 8). The second highest bank erosion rate (13.98 t/km^2/yr) by Strahler stream order was observed in 4th order and higher streams within the Corrigan Creek subwatershed (Figure 8).

Table 6. Extrapolated sediment delivery from bank erosion developed from the bank erosion void assessment

Subwatershed	Strahler Order	Total stream length (km)	Total drainage area (km^2)	Bank erosion sediment delivery[1]			
				Unit bank erosion (m^3/m)	Total bank erosion (m^3)	Total bank erosion (t)	Bank erosion rate (t/km^2/yr)
Corrigan Creek	1	15.59	2.36	0.022	342	566	4.21
	2	6.65	2.39	0.058	384	636	4.67
	3	1.83	1.73	0.078	143	237	2.40
	>4	4.87	4.2	0.415	2,021	3,347	13.98
	Total/ Average	28.95	4.2	0.143	2,890	4,786	19.99
Little South Fork Elk River	1	9.63	1.64	0.018	176	291	3.11
	2	4.49	1.61	0.068	305	505	5.50
	3	2.65	1.90	0.057	152	252	2.33
	>4	2.34	2.91	0.035	83	137	0.83
	Total/ Average	19.11	2.91	0.045	716	1,186	7.15
South Branch North Fork Elk River	1	18.01	2.39	0.099	1,784	2,954	21.68
	2	11.33	3.02	0.092	1,041	1,724	10.02
	3	4.59	3.26	0.040	183	303	1.63
	>4	2.88	4.99	0.347	1,000	1,656	5.82
	Total/ Average	36.81	4.99	0.144	3,104	6,637	23.33

[1] Assumes a soil bulk density of 1,656 kg m^{-3} (Stillwater 2007) and 57 year time period (1950 – 2007).

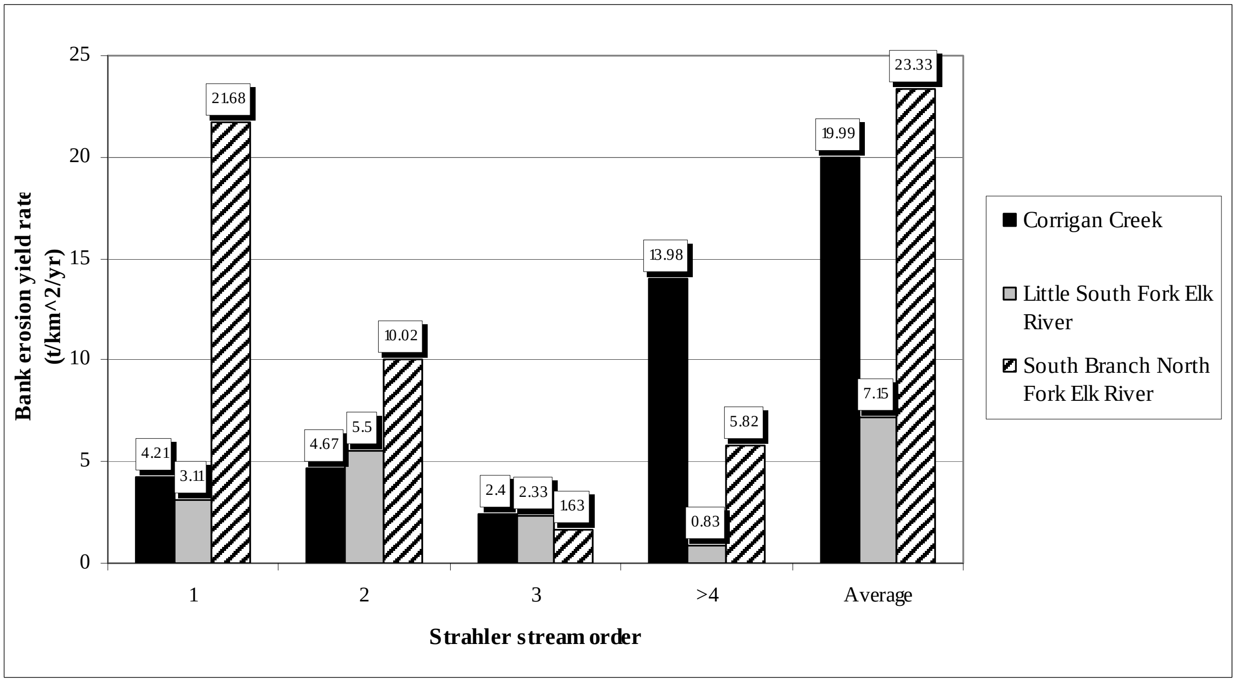

Figure 8. Bank erosion sediment yield rates by Strahler stream order and subwatershed developed from the bank erosion void assessment.

2. Bank erosion-related wood inventory

This section of the report summarizes the results from the field inventory of bank erosion recruited wood and the development of bank erosion sediment yield rates from 2nd order and higher stream channels and soil creep sediment yield rates for 1st order stream channels for each of the 3 study subwatersheds. Table 7 and Figures 7a – 7c show the results of the bank erosion–related wood inventory. Only 4 of the 14 sample reaches within each of Corrigan Creek and South Branch North Fork Elk River, and 4 of the 17 reaches in Little South Fork Elk River, contained wood recruited from bank erosion processes. Wood recruitment from other processes (i.e. natural mortality, landslides, wind throw, or other unknown processes) was not inventoried or mapped in the field. A total of 26 pieces of bank erosion-related wood were identified along the 8.89 km of field inventoried sample reaches, with 5 pieces identified on 2nd and 4th order and higher channels in Corrigan Creek, 6 pieces identified on 2nd and 4th order and higher channels in Little South Fork Elk River, and 15 pieces identified on primarily 4th order channels in South Branch North Fork Elk River.

Twelve (12) of the 15 pieces of wood identified in the South Branch North Fork Elk River originated from two 4th order stream reaches (4 pieces from Reach #2 and 8 pieces from Reach #5) (Table 7). Reach #2 and Reach #5 produced more bank erosion-related wood in comparison to the other inventoried stream reaches producing bank erosion-related wood. According to the inventory results, the majority of stream reaches containing bank erosion-related wood only produced 1 or 2 pieces of bank erosion recruited wood per reach in each of the three study subwatersheds. The higher influx of bank erosion related wood in Reach #2 and Reach #5 in South Branch North Fork Elk River may be a result of channel morphology. These 2 reaches are located within bedrock cascade and high gradient riffle sections of the main stem. Higher stream velocities and complex channel morphology may result in an increase influx of bank erosion-related wood. The channel morphology of stream reaches yielding less bank erosion-related wood (1 to 2 pieces per reach) were primarily low gradient riffles or lower order stream channels exhibiting intermittent subsurface flow.

Table 7. Bank erosion-related wood inventory summary results

Sub watershed	Stream Order	Reach #	Station #	Tree Type	Tree species	Diameter midpoint (m)	Instream wood length (m)	Total wood length (m)	Recruit-ment age (yr)	Decay class	Volume of bank erosion wood (m3)
Corrigan Creek	2	68	432	Deciduous	Acer	0.15	3.40	3.40	30	7	1.60
	2	204	8	Conifer	Sequoia	0.20	1.50	11.00	5	1	0.94
	4	156	220	Deciduous	Alnus	0.10	2.00	12.00	10	5	0.63
	4	156	322	Deciduous	Salix	0.20	1.70	9.50	20	6	1.07
	4	219	76	Deciduous	Alnus	0.10	2.20	2.40	40	5	0.69
Corrigan Creek total											4.93
Little South Fork Elk River	2	131	6	Conifer	Sequoia rootwad	5.00	0.00	0.00	50	5	15.71
	4	120	231	Conifer	Sequoia	0.75	1.80	5.90	50	5	4.24
	4	120	229	Conifer	Sequoia	0.85	1.80	16.10	50	6	4.81
	5	6	184	Conifer	Sequoia	1.00	4.70	4.70	30	5	14.77
	5	101	224	Conifer	Sequoia	2.90	2.40	30.50	50	6	21.87
	5	101	119	Conifer	Sequoia	0.30	1.50	6.70	30	7	1.41
Little South Fork Elk River total											62.80
South Branch North Fork Elk River	2	3	169	Deciduous	Salix	0.09	4.90	9.80	10	2	1.39
	4	2	95	Deciduous	Alnus	0.15	1.75	19.68	10	1	0.82
	4	2	94	Deciduous	Alnus	0.27	1.45	12.20	25	1	1.23
	4	2	9	Deciduous	Salix	0.11	3.05	11.00	20	1	1.05
	4	2	8	Deciduous	Salix	0.20	1.78	13.10	10	1	1.12
	4	5	185	Conifer	Sequoia	0.14	1.80	8.00	5	1	0.79
	4	5	96	Conifer	Sequoia	0.19	5.40	7.50	5	1	3.22
	4	5	68	Deciduous	Salix	0.12	1.80	7.60	5	1	0.68
	4	5	332	Conifer	Sequoia	0.45	7.00	29.00	30	6	9.90
	4	5	203	Conifer	Sequoia	0.27	8.00	13.00	50	6	6.79
	4	5	176	Conifer	Sequoia	0.61	4.90	4.90	70	6	9.39
	4	5	183	Conifer	Sequoia	1.20	14.00	14.00	70	6	52.78
	4	5	119	Conifer	Sequoia	0.58	3.70	4.70	40	7	6.74
	4	10	211	Deciduous	Alnus	0.25	2.90	17.00	5	2	2.28
	4	10	220	Conifer	Sequoia	0.10	12.00	12.00	10	5	3.77
South Branch North Fork Elk River total											101.95

[1] Decay class: 1 - broad leafs or needles, 2 – twigs, 3 – secondary branches, 4 – primary branches, 5 – nubs, 6 – hard, 7 – rotten.

Three genera of deciduous hardwood and one conifer genera were identified in the field inventory including: Acer (Big Leaf Maple), Salix (Willow), Alnus (Alder), Sequoia (redwood) (Table 7). The wood recruited by bank erosion in Little South Fork Elk River was dominated by redwood (Sequoia), whereas a mixture of deciduous trees and redwood were present in Corrigan Creek and South Branch North Fork Elk River.

The average total length of wood pieces recruited by bank erosion processes ranged from 7.7 m – 12.2 m for Corrigan Creek, Little South Fork Elk River and South Branch North Fork Elk River (7.7 m, 10.7 m, and 12.2 m, respectively) (Table 7). This includes the entire length of wood pieces within and outside the stream channel. The length of bank erosion-related wood pieces within the stream channel ranged between 2.2 m and 4.96 m (2.2 m in Corrigan Creek, 2.0 m in Little South Fork Elk River, and 5.0 m in North Branch South Fork Elk River). The age of recruitment for bank erosion-related wood ranged from 5 – 70 years, with age of recruitment spanning 5 – 40 yr for Corrigan Creek, 30 – 50 yr for Little South fork Elk River, and 5 – 70 yr for South Branch North Fork Elk River.

The volume of each piece of wood was calculated as a cylinder using measurements of the diameter at the midpoint and in-stream length of each inventoried wood piece. A total 169.7 m^3 of bank erosion recruited wood was indentified in the three study subwatersheds, with 3% from Corrigan Creek, 37% from Little South Fork Elk River, and 60% from South Branch North Fork Elk River (Table 8). Volumes of bank erosion recruited wood were used in conjunction with total inventoried reach length and mean annual recruitment age to calculate the annual wood recruitment (I_{be}) for each inventoried stream reach.

Table 8 lists annual wood recruitment rate for 2nd order and higher stream channels by the 3 study subwatersheds. Overall, the South Branch North Fork Elk River yielded the highest annual bank erosion-related wood recruitment rate (1.8 $m^3/km^2/yr$) in comparison to the other 2 study subwatersheds (Table 8). Corrigan Creek yielded the lowest bank erosion-related wood recruitment rate (0.10 $m^3/km^2/yr$) which is 94% lower than the recruitment rate for South Branch North Fork Elk River. In addition, the Corrigan Creek wood annual recruitment rate was 84% lower than the rate calculated for the old growth portion of the Little South Fork Elk subwatershed (0.651 $m^3/km^2/yr$) (Table 8). As stated previously, the high influx of bank erosion recruited wood from the South Branch North Fork Elk River may be a result of the location of inventory stream reaches within more steep and complex channel morphology. These complex stream reaches may produce more bank erosion-related wood as compared to lower gradient, less morphologically complex stream reaches.

Another hypothesis for lower wood recruitment in the Corrigan Creek subwatershed may be due to a higher percentage of hardwood trees in the riparian zone as compared to redwoods. For example, within the 10-m buffer along Class I and Class II streams within Corrigan Creek the ratio of hardwood to conifer is 1:10. In comparison the ratio of hardwood to conifer in the South Branch North Fork Elk River is 1:38. Hardwood trees decompose at much faster rates than redwood, and as a result hardwoods that may have been recruited into the stream system a decade ago may not be present. This would result in a lower annual bank erosion-related wood recruitment rate.

Table 8. Annual bank erosion-related wood recruitment for 2nd order and higher stream channels by subwatershed

	Map reach length (m)	Volume of bank erosion recruited wood (m^3)	Weighted average recruitment age (yr)	Annual bank erosion-related wood recruitment rate (I_{be}) ($m^3/km^2/yr$)
Corrigan Creek	2,261	4.93	21	0.104
Little South Fork Elk River	2,243	62.80	43	0.651
South Branch North Fork Elk River	2,356	101.95	24	1.803

The mean bank erosion rate (E) was calculated for 2nd order and higher stream channels by study subwatershed using Equation 1 described in Section III-A-2 of the report. The mean annual bank erosion rate is calculated based on the annual bank erosion-related wood recruitment rate (I_{be}), the standing biomass density (B_L), and the probability of tree fall (P_{be}). Table 9 lists the parameters used to calculate mean bank erosion rate by study subwatershed. Overall, South Branch North Fork Elk River produced the highest mean bank erosion rate of 0.025 m/yr. This bank erosion rate is approximately 90% higher than the mean bank erosion rates calculated for Corrigan Creek and Little South Fork Elk River and (0.002 m/yr and 0.003 m/yr, respectively). The higher mean bank erosion rate observed in the South Fork Elk River is due to the high annual bank erosion-related wood recruitment rate. Other parameters (i.e. B_L and P_{be}) in the mean bank erosion rate equation could vary, but the annual wood recruitment rate obviously controlled the magnitude of the calculated mean bank erosion rate.

Table 9. Bank erosion yield rates for 2nd order and higher stream channels by subwatershed developed from the bank erosion-related wood inventory.

Subwatershed	**Parameters[1]**						**Bank erosion yield rate from 2 banks**	
	I_{be} ($m^3/km^2/yr$)	**B_L (m^3/ha)**	**P_{be}**	**E (m/yr)**	**Mean bank height (m)**	**Mean drainage density (m/km^2)**	**($m^3/km^2/yr$)**	**($t/km^2/yr$)**
Corrigan Creek	0.104	261.73	0.13	0.002	0.98	2,310	11.5	22.9
Little South Fork Elk River	0.651	2075.39	0.05	0.003	0.88	2,330	21.3	42.6
South Branch North Fork Elk River	1.803	271.97	0.13	0.025	0.54	3,140	143.2	286.4

[1] Parameters used to calculate bank erosion yield rates include: 1)I_{be} – annual wood recruitment rate, 2) B_L - Standing biomass density, 3) P_{be} – Probability of tree fall, 4) E – mean annual bank erosion rate for 2 banks..

The estimated bank erosion sediment yield rate for 2nd order and higher stream channels within each of the 3 study subwatersheds was computed using Equation 3 described in Section III-A-2 of this report. Estimated bank erosion yield rate ($m^3/km^2/yr$) was calculated using the following variables: 1) mean bank erosion rate, 2) average stream bank height, and 3) average drainage density of 2nd order and higher channels (Table 9). The South Branch North Fork Elk River produced the highest bank erosion sediment yield rate (286.4 $t/km^2/yr$) for 2nd order and higher stream channels in comparison to Corrigan Creek and Little South Fork Elk River (22.9 $t/km^2/yr$ and 42.6 $t/km^2/yr$, respectively) (Table 9). The bank erosion sediment yield rate for South Branch North Fork Elk River was 92% higher than the rate calculated for Corrigan Creek and 85% higher than the rate calculated for Little South Fork Elk River. The high rate of bank erosion sediment yield for South Branch North Fork Elk River is due to the high mean annual bank erosion rate coupled with high mean drainage density of 2nd order and higher stream channels. Corrigan Creek yielded the lowest bank erosion sediment yield rate of 22.9 $t/km^2/yr$.

As discussed in the methodology section of the report, bank erosion was not calculated for 1st order stream channels. First order stream channels in the study subwatersheds exhibited intermittent subsurface flow, low stream power, and poorly defined stream banks. To address sediment yield from hillslopes adjacent to 1st order stream channels, an average soil creep rate of 1.6 mm/yr was employed. The soil creep yield for each of the study subwatersheds was calculated using Equation 3 and substituting average annual soil creep rate for annual bank erosion rate (refer to Section III-A-2 of this report). South Branch North Fork Elk River produced the highest soil creep yield of 2.15 $t/km^2/yr$, in comparison to Corrigan Creek and Little South Fork Elk River (1.75 $t/km^2/y$ and 0.81 $t/km^2/y$, respectively) (Table 10).

Table 10. Soil creep yield rates for 1st order stream channels by subwatershed developed from the bank erosion-related wood inventory.

Subwatershed	Parameters			Soil creep yield rate ($m^3/km^2/yr$)	Soil creep yield rate ($t/km^2/yr$)
	Soil creep rate (m/yr)	Mean bank height (m)	Mean drainage density (m/km^2)		
Corrigan Creek	0.0016	0.14	2,310	1.06	1.75
Little South Fork Elk River	0.0016	0.07	2,330	0.49	0.81
South Branch North Fork Elk River	0.0016	0.13	3,140	1.30	2.15

3. Comparison of bank erosion sediment yield rates generated from the bank erosion void assessment and bank erosion-related wood inventory

Table 11 compares the bank erosion sediment yield rates for 2nd order and higher stream channels developed by the bank erosion void assessment method and the bank erosion recruited wood budget method. The bank erosion sediment yield rates for 1st order streams from bank erosion using the bank erosion void method, and soil creep using the wood budget method are presented in Table 11. , but should not be directly compared because bank erosion and soil creep are calculated using very different methodologies. The bank erosion void assessment method calculates 1st order stream bank erosion sediment yield rates using field collected void measurement data. Conversely, the wood budget method uses a calculated average soil creep rate derived from previous studies to generate soil creep yield rates for 1st order stream channels in each study subwatershed. Soil creep was used as an analog of bank erosion because it is often used to check estimates of bank erosion rates (Reid and Dunne 1996) and bank erosion is how soil creep usually expresses itself at the toe of the hillslope along stream channels.

Only the Corrigan Creek subwatershed showed similar bank erosion sediment yield rates for 2nd order and higher stream channels using the 2 different assessment and calculation methods (22.9 $t/km^2/yr$ using the wood budget method and 16.9 $t/km^2/yr$ using the bank erosion void method). Little South Fork Elk River and South Branch North Fork Elk River showed a great disparity between bank erosion sediment yield rates using the 2 different methodologies. The estimated bank erosion sediment yield rate for 2nd order and higher stream channels in the South Branch North Fork Elk River (286.4 $t/km^2/yr$) using the wood budget method was approximately 16 times greater than the rate generated using the bank erosion void method (17.5 $t/km^2/yr$). In addition, the bank erosion sediment yield rate generated for 2nd order and higher stream channels in the Little South Fork Elk River (42.6 $t/km^2/yr$) using the wood budget method was approximately 8 times greater than the rate generated using the bank erosion void method (5.1 $t/km^2/yr$).

Table 11. Comparison of bank erosion sediment yield estimates from bank erosion void assessment and bank erosion-related wood inventory methods

Subwatershed	Bank erosion void assessment method		Bank erosion-related wood budget method	
	Bank erosion yield rate ($t/km^2/yr$)		Bank erosion yield rate ($t/km^2/yr$)	Soil creep yield rate ($t/km^2/yr$)
	2nd order and higher channels	1st order channels	2nd order and higher channels	1st order channels
Corrigan Creek	16.9	4.2	22.9	1.75
Little South Fork Elk River	5.09	3.1	42.6	0.81
South Branch North Fork Elk River	17.5	21.7	286.4	2.15

The extreme difference between wood budget derived bank erosion sediment yield rates for 2nd order and higher order stream channels in Corrigan Creek and South Branch North Fork Elk River (22.9 $t/km^2/yr$ and 286.4 $t/km^2/yr$, respectively) is puzzling. These watersheds are located directly adjacent to each other, and have the same underlying geologies and similar slope topography. In addition, these watersheds experienced very similar timber harvest methods during the 1970s and 1980s, and have similar road densities. There is no obvious reason why these 2 subwatersheds display such significantly different wood recruitment rates, and as a result produce such different bank erosion sediment yield rates. The rates derived from the bank erosion void assessment appear to be more realistic, with nearly equivalent rates of bank erosion sediment yield observed in the Corrigan Creek and South Branch North Fork Elk River (16.9 $t/km^2/yr$ and 17.5 $t/km^2/yr$, respectively), and a lower rate of bank erosion sediment yield in the old growth portion of the Little South Fork Elk River.

4. Limitations and confidence in analysis

The bank erosion sediment yield rates generated by the bank erosion void assessment method and the bank erosion-related wood budget method did not correspond very well among all 3 of the study subwatersheds (Table 11). There are a variety of possible reasons for the disparity between the results of the 2 methodologies.

1) The two methods rely upon very different parameters for the volumetric calculations. The bank erosion void assessment method requires the field estimation of actual bank erosion voids that are used to develop mean bank erosion rates, whereas the wood budget method relies on the field estimation of wood recruitment, as well as other wood budget parameters to generate mean bank erosion rates. Because the 2 methodologies incorporate such different field data and parameters, it is not surprising that the results do not correspond well.
2) Both methodologies require a representative stream network and a statistically rigorous sample of stream reaches that best represent the distribution of stream orders within each subwatershed. The scope and budget for the Elk River bank erosion void assessment and bank erosion-related wood inventory project included the field inventory of approximately 3 km of stream within each of the 3 study subwatersheds (9 km total). Combined, the total length of streams was estimated at 84.87 km (28.95 km (34%) in Corrigan Creek, 19.11 (23%) in Little South Fork Elk River, and 36.81 km (43% in South Branch North Fork Elk River). This results in a sample of only 11% of the total stream network. Actual stream lengths surveyed in each subwatershed were 10% of the streams within Corrigan Creek, 16% of the streams within Little South Fork Elk River, and 8% of the streams within South Branch North Fork Elk River. Extrapolation of bank erosion rates based on only 8-16% of the total sample stream network does not provide adequate confidence in the final estimation of bank erosion sediment yield rates. Regardless of sample size, high variability is expected between stream reaches because of differences in reach channel morphology and bed load characteristics, and land use history. Larger sample sizes determined by the appropriate confidence interval and confidence level would have provided a more statistically robust result, but this was beyond the scope of the project.
3) The bank erosion void assessment method relies upon field-based bank erosion void measurements per unit stream reach length that are then extrapolated to the entire stream network. The field inventory of bank erosion can be difficult depending on the age of the past bank erosion. Bank erosion can be difficult to identify in areas where bank erosion has historically occurred along long sections stream bank. In this case, areas of bank erosion may not show typical “scalloped” shape erosional voids that exhibit exposed roots. Instead, long sections of older bank erosion may appear grown over with no evidence of past erosion. This may result in an underestimation of field estimated bank erosion and extrapolated bank erosion sediment yield. In addition, the depth of bank erosion is difficult to determine in the field if exposed roots are not present. The depth of

the exposed roots may or may not be apparent in a bank erosion void, and as a result depth may be over or under estimated at each field site.

4) The assumption that all wood showing evidence of originating from the stream bank is bank erosion-related may be incorrect. Some trees that are growing within the riparian zone or within the 10-m buffer used in this study may have originated from other sources (i.e. natural mortality or wind throw). Because channels are dynamic there may be no evidence that lateral migration of the stream channel or flow deflection caused the recruitment of the "bank erosion-related" wood. Unless there is evidence of flow deflection or lateral channel migration, there may be no reason to assume the wood has been incorporated by bank erosion processes. This may result in an overestimation of annual bank erosion-related recruitment rates and bank erosion sediment yield rates.
5) The wood budget method only identified wood recruited by bank erosion processes. Any wood within the channel that did not show evidence of recruitment by bank erosion was not included in the wood budget. Some of the wood within the channel may have been recruited by bank erosion processes, but was not included due to the lack of evidence of connection to the bank. As a result, this may result in an underestimation of the annual bank erosion-related wood recruitment rate.
6) The biomass density used in the wood budget equations calculating bank erosion sediment yield rates are rough estimates. The PALCO data was based on a 10-m buffer on Class I and Class II streams. The classification of Class II streams is very broad and may incorporate some first order streams. This may result in an overestimation of biomass density for 2^{nd} order and higher order streams. The scope and budget of the project did not allow for the development of an independent biomass density estimate by stream order.

We estimate a moderate confidence in analysis using the bank erosion void assessment methodology. Although there are limitations to the estimation of the dimensions and age of bank erosion voids and the sample size of stream reaches is statistically small, this methodology provides actual field based evidence of the magnitude of bank erosion processes within a subwatershed. In addition, the bank erosion void assessment allows for the analysis of bank erosion by different attributes such as stream order, stream class, geology, management allocation, and stream channel morphology. This can be a powerful analysis tool for characterizing bank erosion in different areas exhibiting different land uses.

Our confidence is comparatively low in the bank erosion rates and estimate of bank erosion sediment yield rates derived from the bank erosion-related wood budget. The estimation of bank erosion rates from the volume of bank erosion recruited wood relies on a variety of general assumptions that may not be statistically valid and measurements that contain significant uncertainties. In addition, the estimation of bank erosion using the wood budget method does not allow for further in depth analysis of other geomorphic or land use attributes.

V. Conclusions

Developing accurate estimates of bank erosion at the watershed or subwatershed scale can be a difficult and laborious task. In order to provide accurate estimates of bank erosion, full field-based bank erosion assessments of the stream channel network should be conducted with qualified professionals able to recognize field evidence of the location, age and magnitude of past bank erosion. Field surveys can be a time-intensive and expensive process, and potentially beyond the scope and budget of many watershed assessments. A variety of methodologies have been devised to provide estimates bank erosion sediment yield that are based on a sample of stream reaches within a larger watershed or sub-watershed. This sample bank erosion rate is then extrapolated to the unsampled stream reaches within the watershed. Such sampling reduces labor requirements but introduces additional uncertainty into the erosion estimates.

For this study, we developed bank erosion sediment yield rates using 2 field-based methodologies. These included a bank erosion void assessment (Reid and Dunne 1996) and a bank erosion-related wood inventory (Benda et al. 2002; 2004). The bank erosion study was conducted along 3 km of sample stream reaches within each of three subwatersheds of Elk River: Corrigan Creek, Little South Fork Elk River, and South Branch North Fork Elk River subwatersheds. The aim of the study was to develop and compare estimates of bank erosion sediment yield rates by stream order and subwatershed using the two methodologies.

The results of the study showed a significant difference between the estimated bank erosion sediment yield rates even though the methodologies were employed on the same study reaches in each subwatershed. Thus the bank erosion sediment yield rate derived from the wood budget method for the Little South Fork Elk River (42.6 t/km^2/yr) was 8 times higher than the bank erosion sediment yield rate derived from the bank erosion void assessment (5.09 t/km^2/yr). In addition, the bank erosion sediment yield rate derived from the wood budget method for South Branch North Fork Elk River (286.4 t/km^2/yr) was 16 times higher than the bank erosion sediment yield rate derived from the bank erosion void assessment (17.5 t/km^2/yr) for the same study reaches.

The disparity between the bank erosion sediment yield rates derived from the 2 methodologies may be due to the widely divergent input parameters and assumptions on which the methodologies are based. Even using the two measurement techniques the study may have produced more comparable results if a larger, more statistically robust sample (>20% of the total stream network and within each stream order) was inventoried using both methodologies. Budget limitations precluded this expanded assessment. Finally, the wood budget methodology may have produced improved results using field based biomass density estimates based on stream order instead of stream class.

The void measurement technique has been widely used in geomorphic studies and brings with it a degree of acceptance in the literature. In spite of this, the method still has shortcomings related to the identification, interpretation and measurement of erosion rates. Although the wood budget method is newer and less well tested, it may have certain advantages in its application in forested settings. Further refinement of the input parameters for the wood budget methodology should be conducted before this method is used exclusively to derive watershed-wide values of bank erosion sediment yield. Significant differences in the bank erosion rates derived from the 2 methodologies suggests that further evaluation is needed before the methodologies can be used interchangeably.

VI. References

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