APPENDIX C
SEDIMENT BUDGET REPORT

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C.1 INTRODUCTION

A sediment budget for the Tucannon River watershed was developed to provide data on the input and transport of bedload and fines in the river system. Understanding the amount and timing of both bedload and suspended sediment movement through the proposed habitat restoration areas is an important aspect to ensuring the long-term success of enhancement projects.

Bedload, the coarse-grained portion of the sediment load that moves along the bed of the river, is the basis for channel geomorphology and channel substrate that provides spawning, rearing, and hiding habitat for fish and aquatic organisms. In the Tucannon River, bedload consists of cobble, gravel, and sand-sized particles. Suspended load, the fine-grained portion of the sediment load that moves in suspension, affects turbidity (water clarity). High levels of fine-grained sediment (sand, silt, and clay) can also degrade aquatic habitat by filling the pore spaces between cobble and gravel particles on the bed and reducing the oxygen flow to incubating fish eggs and reducing macroinvertebrate habitat.

The sediment input budget considers the amount and timing of sediment delivered to the channel from different erosion processes and sediment sources. Based on a review of past studies in the watershed and field and aerial photograph analysis, the following erosion processes appear to be dominant in the basin:

- Surface and rill erosion on unvegetated soil.
- Streambank erosion due to channel migration of the mainstem Tucannon River.
- Stream entrenchment (incision) in some tributaries, particularly Pataha Creek and Smith Hollow.
- Periodic gullying of some swales during extreme rainfall events. Mass wasting (landsliding) does not appear to be a dominant erosion process (USFS 2002).

Sediment inputs related to these processes were categorized for each of the following sources of sediment:

- Land Use – surface and rill erosion
  - Agricultural and range land
  - Timber harvest

- Wildfire – surface and rill erosion
- Road Erosion – surface erosion from un-surfaced (gravel/dirt) roads
- Streambank erosion – channel migration along the mainstem Tucannon
- Colluvial erosion and debris flows – Gullying in steep, bedrock-lined swales
- Channel incision – entrenchment along Pataha Creek and Smith Hollow

C.1.1 Past Studies

A number of past studies pertaining to sediment input and transport have been conducted in the Tucannon watershed. Comprehensive basin studies are summarized below; other process-specific studies are discussed in the appropriate sections.

The most comprehensive study was conducted for the National Resource Conservation Service (NRCS) in 1982 and included monitoring of water quality, suspended load, and bedload sediment at six locations in the Tucannon watershed as well as channel scour, inter-gravel flow, a study of changes to river form, and an aquatic habitat inventory (Hecht et al. 1982). Major findings of the 1982 study included the following points that are pertinent to this analysis:

- **Hydrology** – Relative to total average annual flow at the Starbuck gage, Pataha Creek contributed approximately 11% of the average annual flow, while the Tucannon basin upstream of Pataha Creek contributed approximately 85% of the flow during the 1980 water year. This is consistent with the partitioning of flow estimated by comparing U.S. Geologic Service (USGS) gaging records (see Appendix A).
- **Channel change** – The character of the mainstem Tucannon channel changed from a single, meandering thread in 1937 (aerial photographs) to a more braided pattern in 1978, with fewer large trees in the riparian zone. The change in planform resulted in an overall decrease in channel length and resulting increase in slope. The authors suggested that the channel changes were likely the result of increased peak runoff, removal of riparian forests, and a large flood that occurred in 1964.
- **Sediment load** – Suspended sediment load and bedload during 1980 were measured at several locations in the watershed. The 1980 annual suspended load and bedload at the Starbuck gage were 138, 270, and 565 tons, respectively. The majority of the suspended load came from Pataha Creek and the lower mainstem; there was little bedload movement in the Pataha drainage. Annual suspended sediment load from

other studies at the Starbuck gage was summarized; it varied greatly from over 3,000,000 tons/year to less than 10,000 tons/year (1963 to 1970 time period).

- **Scour and fill** – Scour and fill was measured at five locations in the mainstem Tucannon; maximum observed scour was 1.47 feet and maximum fill was 1.27 feet.

The USDA Forest Service (USFS) conducted an ecosystem analysis of the Tucannon watershed in 2002, concentrating on the upper Forest Service lands (USFS 2002). They found that the primary erosion process in the watershed is surface erosion (sheet and gully erosion), which is highest when rainfall events occur during times that the ground is frozen or saturated. The USFS inventoried landslides following the 1996 storm and found a total of only 21 slides on Forest Service land, supporting their conclusion that mass wasting is not a major sediment source in the watershed. They also investigated channel changes and found that the mainstem responded to the major flood by becoming more braided, wider, and shallower due to bank erosion and channel migration. The USFS has also been monitoring erosion following the School Fire in 2005. These results are discussed in Section C.2.4 – Wildfire.

C.2 METHODS AND RESULTS

The methods to estimate sediment inputs in this report were based on a field reconnaissance and historical aerial photograph analysis to help identify site-specific locations of past and current sediment sources and to provide information on erosion rates and delivery to streams. Erosion modeling was also used to extrapolate observations and measurements to other parts of the watershed. Estimates of sediment sources under current (2010) watershed conditions were made, as well as quantitative or qualitative estimates of sediment sources under historical conditions. Legacy sources of sediment, particularly coarse sediment (gravel and cobble), can continue to have an influence on stream conditions for decades or centuries as they are processed by the stream. Sediment inputs were calculated for each of 18 subbasins in the watershed to allow for analysis of sediment related to potential future habitat enhancement projects in different parts of the river. Due to uncertainties inherent in sediment budgeting techniques, the numerical results should be regarded as estimates of the relative magnitude of sediment from different sources, rather than a precise measurement of sediment inputs.

Figure 3 shows subbasins, roads, and stream gage/sediment sampling locations that are used in this report.

C.2.1 Aerial Photograph Analysis

A series of historic aerial photographs were viewed to look for past and current sediment sources and trends of disturbance through time. Table C-1 lists the photographs reviewed along with intervening large floods/storm events.

Table C-1
Aerial Photographs Reviewed for Sediment Source Analysis and Peak Flow Events

Date	Type	Scale	Source (Photo Set)
2/10/16	High flow (5,740 cfs) at Starbuck gage		
2/2/30	High flow (6,000 cfs) at Starbuck gage		
1937	B&W air photos, missing lower mainstem	Unknown, but large scale (24" x 24" prints)	NRCS (AAV)
8/18/54	B&W air photos	Unknown	NRCS (AAV)
12/22/64	High flow (7,980 cfs) at Starbuck gage		
7/24/74	B&W air photos, lower watershed and Pataha Creek	1:76,000	USGS (GS-VDPG)
8/30/76	B&W air photos, upper watershed	1: 80,000	USFS (41061)
1987	B&W air photos, WDNR transferred to orthophotos	1:24,000 (original scale 1:63,360)	WDNR
6/27/95	B&W air photos, parts of upper mainstem	1:12,000	WDNR (SE-P-95)
2/9/96	High flow (5,580 cfs) at Starbuck gage		
1996	B&W air photos, mainstem Tucannon	1:550 (est.)	CCD (BPA-TUCA)
2010	Color air photos, mainstem Tucannon	Electronic	CCD

Notes:
cfs = cubic feet per second
NRCS = National Resource Conservation Service
USFS = U.S. Forest Service
WDNR = Washington Department of Natural Resources
CCD = Columbia Conservation District
USGS = U.S. Geological Service

All photos were reviewed to look for sediment sources and land use patterns. Photos covering the mainstem Tucannon River from 1954, 1974, 1976, and 1996 were scanned and geo-referenced in ArcGIS for analysis of channel migration patterns. The 1937 photos were not scanned because they were too large to fit in the portable scanner (photos could not be removed from the NRCS office). The resolution of the 1987 orthophoto sheets was inadequate to accurately determine the channel position.

C.2.2 Grain Size Sampling

Sediment sources were partitioned into three size classes for analysis: cobble and gravel (greater than 2 mm), sand (0.0625 to 2 mm), and fines (less than 0.0625 mm). Partitioning was based on riverbed samples taken during the summer of 2010 (described in Section 6.1 of the main report), grab samples of fine-grained bank material in the Pataha Creek watershed, and soil sample characteristics reported by the NRCS on their Web Soil Survey (NRCS 2009). Partitioning was different for each erosion process based on soil properties as well as the size of particles that could be eroded by that process. Table C-2 shows how total input from each sediment source was partitioned.

Table C-2
Partitioning of Sediment Sources by Grain Size Class

Sediment Source	Percent Cobble/Gravel	Percent Sand	Percent Fines
Land Use – sheet and rill erosion	10%	45%	455
Road surface erosion	5%	50%	45%
Wildfire – surface erosion	0%	50%	50%
Streambank erosion – Hartsock Grade subbasin	90%	9%	1%
Streambank erosion – lower subbasin	90%	9%	1%
Streambank erosion – Marengo subbasin	98%	1%	0%
Streambank erosion – Smith Hollow subbasin	85%	13%	2%
Streambank erosion – Starbuck subbasin	87%	12%	1%
Streambank erosion – gully/swale channels in loess	0%	70%	30%
Streambank erosion - gully/swale channels in volcanic bedrock	25%	15%	65%
Channel Incision – Pataha Creek and Smith Hollow	0%	70%	30%

C.2.3 Land Use – Surface and Rill Erosion

Land use activities that expose bare soil may increase the potential for erosion. In the Tucannon River watershed, agriculture and timber harvest are important economic activities that result in ground disturbance. The 2001 National Land Cover Database (NLCD 2001) data were used to represent land use for this analysis (Figure 2, main report). Primary land use types include: forested land in the upper watershed (24% of basin area); cultivated crops, primarily wheat and barley on the flat hilltops in the middle and lower watershed (32% of area); shrub/scrub on the drier slopes in the lower basin (20% of area); and grassland used for grazing on the side slopes in the middle basin (19% of area).

The fine-grained Palouse loess soils that provide such good agricultural lands and cover much of the lower watershed are extremely susceptible to erosion (Figure 4, main report). Erosion rates of fine-grained soils are particularly high if intense rainfall occurs on exposed soils when the soil is frozen or saturated. Many studies have been conducted to determine erosion rates on Palouse soils, as well as conservation methods that can reduce erosion rates.

The NRCS completed a cooperative river basin study in 1984 that concluded that soil erosion was a serious problem on croplands in southeastern Washington (NRCS 2004). They estimated erosion from cropland, rangeland, and forested areas for the Tucannon watershed and found surface erosion rates for cropland averaged 7 tons/acre/year; gully erosion from croplands was 0.1 tons/acre/year; erosion from rangeland was 0.5 tons/acre/year; 0.3 tons/acre/year from forested areas; and an average of 16% of eroded soil was delivered to streams. The NRCS concluded that changes to cropping systems could significantly reduce erosion; for example, converting to no-till farming could reduce erosion up to 95%.

Fu et al. (2006) developed a GIS-based version of the Revised Universal Soil Loss Equation (RUSLE) and a sediment delivery algorithm to estimate the effects of no-till farming practices in the Pataha Creek watershed. Their model results suggested that cropland erosion rates decreased 78% under the no-till system compared to conventional tillage systems.

Williams et al. (2010) measured erosion from conventional tillage and no-till dry land crop areas in northeastern Oregon from 2001 to 2005. They found an average of 67.5

kilograms/hectare/year (0.03 tons/acre/year) from conventional tilled lands and 2.5 kilograms/hectare/year (0.001 tons/acre/year) from no-till lands under below-normal precipitation levels. These values compared reasonably well with calibrated Water Erosion Prediction Project (WEPP) simulations they ran for the areas. They also report a range of erosion measurements from previous studies, including 0.05 tons/acre/year from traditional tillage land (Williams et. al 2009) and a long-term average of 1.11 tons/acre/year since 1963 on 5% sloped croplands on the Columbia Plateau (Nagel and Ritchie 2004).

In order to estimate surface and rill erosion resulting from land use in different parts of the Tucannon watershed, the WEPP model was used to calculate erosion for a series of land use/slope gradient combinations. These results were applied to the GIS gridded land use and slope gradient coverages to determine average annual erosion from each grid cell. Delivery of eroded sediment to streams was estimated based on the distance from each grid cell to the stream as follows: 100% delivery within 100 feet of a stream, 35% delivery for land between 100 to 300 feet from a stream, 10% delivery for land 300 to 1,000 feet from a stream, and no delivery for land more than 1,000 feet from a mapped stream (WDNR 1997).

The following parameters were used in the WEPP model. Table C-3 shows the WEPP modeling results:

- **Climate:** Pomeroy
- **Soil:** Walla Walla silt loam
- **Hillslope length:** 100 feet planar slope
- **Hillslope gradient:** varied from 2 to 80%
- **Treatments applied as appropriate for disturbance type:** winter wheat conventional till, winter wheat no-till, short grass 60% cover (rangeland), Rome or cattle grazing (pasture land), 20-year-old forest

Table C-3

WEPP Model Runs Used for Analysis

WEPP Model Condition	Applied to Land Cover	Average Annual Erosion Rate (tons/acre/yr) for Slope Category					
		0-5%	5-15%	15-30%	30-45%	5-65%	>65%
20-year-old forest	All forest types (deciduous, evergreen, mixed)	0	0	0	0	0	0
Short grass, 60% cover	Shrub/scrub, Grassland	0.004	0.022	0.102	0.165	0.218	0.258
Cattle grazing	Pasture/hay	0.009	0.032	0.278	0.619	1.05	1.511
Winter wheat conventional till	Cultivated crops	0.077	0.274	1.918	3.951	5.617	7.289
Winter wheat no till	Cultivated crops	0.018	0.028	0.061	.014	0.237	0.342

Two different tillage scenarios were run to represent conditions in the early- to mid-part of the 1900s, which assumes all conventional till, and the change to farming and stream buffer conservation practices that reduce erosion from croplands, which assumes 50% conventional till and 50% no till. Table C-4 shows the estimated sediment input from all land uses under the conventional till, no till, and 50/50 conventional/no till scenarios. Total sediment under the no-till scenario is approximately 11% of the conventional till scenario, consistent with reductions reported elsewhere.

Table C-4

Estimated Sediment Input from Land Use

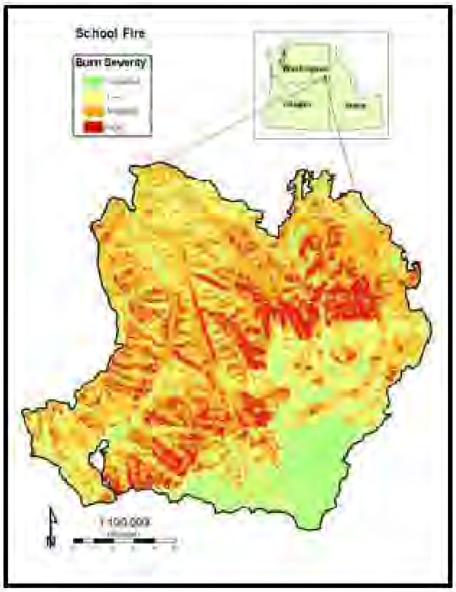
Subbasin	Land Use, Conventional (t/yr)			Land Use, No-Till (t/yr)			Land Use 50% conv. till, 50% no-till (t/yr)		
	Cobble/ Gravel	Sand	Fines	Cobble/ Gravel	Sand	Fines	Cobble/ Gravel	Sand	Fines
Headwaters Tucannon River	7	30	30	3	14	14	5	22	22
Panjab Creek	4	18	18	2	11	11	3	15	15
Little Tucannon River	44	198	198	20	92	92	32	145	145
Cummings Creek	21	94	94	7	31	31	14	63	63
Tumalum Creek	26	119	119	8	34	34	17	76	76
Hartsock Grade-Tucannon River	141	634	634	18	82	82	80	358	358
Town of Marengo-Tucannon River	64	289	289	18	83	83	41	186	186
Willow Creek	161	726	726	9	42	42	85	384	384

Subbasin	Land Use, Conventional (t/yr)			Land Use, No-Till (t/yr)			Land Use 50% conv. till, 50% no-till (t/yr)		
	Cobble/ Gravel	Sand	Fines	Cobble/ Gravel	Sand	Fines	Cobble/ Gravel	Sand	Fines
Upper Tucannon Total	**468**	**2,108**	**2,108**	**86**	**388**	**388**	**277**	**1,248**	**1,248**
Headwaters Pataha Creek	18	83	83	4	18	18	11	50	50
Bihmaier Gulch-Pataha Creek	173	777	777	19	87	87	96	432	432
Benjamin Gulch-Pataha Creek	106	475	475	13	58	58	59	267	267
Linville Gulch	290	1,305	1,305	22	99	99	156	702	702
Chard Gulch-Pataha Creek	103	464	464	19	83	83	61	274	274
Dry Hollow-Pataha Creek	66	298	298	11	52	52	39	175	175
Pataha Creek Total	**756**	**3,402**	**3,402**	**88**	**397**	**397**	**422**	**1,900**	**1,900**
Smith Hollow-Tucannon River	148	665	665	7	33	33	78	349	349
Town of Starbuck-Tucannon River	84	379	379	4	20	20	44	200	200
Kellogg Creek	266	1,197	1,197	14	64	64	140	631	631
Tucannon River	16	72	72	1	5	5	9	39	39
Watershed Total	**1,739**	**7,824**	**7,824**	**202**	**909**	**909**	**970**	**4,366**	**4,366**

C.2.4 Wildfire

In many areas of the western United States, wildfires are a natural component of the ecosystem and a mechanism for disturbance. Intense fires can burn vegetation and duff layers that protect the underlying mineral soil from erosion. In some cases this produces hydrophobic soil conditions that reduce infiltration and increase runoff and erosion. Less intense fires do not burn all vegetation or the duff layer, typically resulting in little surface erosion. Most fires result in patches of high, moderate, and low intensity fire within the burned area. Revegetation following natural fires is often rapid, especially in riparian areas where adequate moisture exists and in areas that are not intensely burned. The USFS analyzed the fire regime of USFS lands in the upper Tucannon watershed and characterized them as a mix of Fire Regime I (low severity, 0 to 35-year recurrence interval) and Fire Regime III (mixed high/low severity, 35 to 100+ year recurrence interval (USFS 2002).

In 2005, the School Fire burned approximately 50,000 acres in the upper Tucannon and Pataha drainages. As is typical with many wildfires, the School Fire left a mosaic of intensely, moderately, and lightly burned areas (Figure C-1). Based on observations made in the field and from the 2010 aerial photographs, the lasting effects of the School Fire from a sedimentation and geomorphology standpoint include a short-term input of sediment from erosion of the burned areas and a longer lasting effect of reduced canopy cover, bank stability, and long-term large wood inputs in areas of the mainstem Tucannon where there were more intense burns of the riparian zone (e.g., in patches between river mile [RM] 40 and 43). A smaller fire in the summer of 2010 in the upper Tucannon watershed in the vicinity of Hartsock Grade Road covered approximately 11,500 acres.



Source: USFS 2008

Figure C-1
Areas Burned in School Fire

The USFS has been measuring erosion and revegetation rates at several locations that were burned during the School Fire since 2006. Erosion data provided by the USFS reported an average of 0.05 tons/acre from untreated burned areas in 2008 and 0.04 tons/acre in 2008 (Clifton 2010). Based on an assumed exponential decrease in erosion rates with time after disturbance, the following erosion rates were applied to the area of the School Fire: 0.5 tons/acre in 2006, 0.05 tons/acre in 2007, 0.04 tons/acre in 2008, 0.03 tons/acre in 2009, and 0.02 tons/acre in 2010. Delivery rates used were the same as described for other land use sources based on distance from streams: 100% delivery within 100 feet of a stream, 35% delivery for land between100 to 300 feet from a stream, and 10% delivery for land 300 to

1,000 feet from a stream. Table C-5 shows the estimated average annual sediment input (2005 to 2010) from the School Fire.

Table C-5
Estimated Sediment Input from the School Fire

Subbasin	School Fire (t/yr)		
	Cobble/ Gravel	Sand	Fines
Headwaters Tucannon River	-	-	-
Panjab Creek	-	-	-
Little Tucannon River-Tucannon River	-	485	485
Cummings Creek	-	309	309
Tumalum Creek	-	123	123
Hartsock Grade-Tucannon River	-	40	40
Town of Marengo-Tucannon River	-	-	-
Willow Creek	-	-	-
Upper Tucannon Total	**0**	**957**	**957**
Headwaters Pataha Creek	-	167	167
Bihmaier Gulch-Pataha Creek	-	-	-
Benjamin Gulch-Pataha Creek	-	-	-
Linville Gulch	-	-	-
Chard Gulch-Pataha Creek	-	-	-
Dry Hollow-Pataha Creek	-	-	-
Pataha Creek Total	**0**	**167**	**167**
Smith Hollow-Tucannon River	-	-	-
Town of Starbuck-Tucannon River	-	-	-
Kellogg Creek	-	-	-
Tucannon River	-	-	-
Watershed Total	**0**	**1,124**	**1,124**

C.2.5 Road Erosion

A field reconnaissance of approximately 100 miles of roads within the watershed was conducted to determine hydrologic connectivity, road surfacing, width, cut-slope, and fill-slope characteristics. Roads visited included paved highways, graveled county roads, and smaller, unsurfaced forest roads.

The GIS stream delivery buffer layer (100, 200, and 1,000 feet) and Columbia and Garfield County road layers obtained from the Washington Department of Natural Resources (WDNR) website (see Figure 2, main report) were overlain to determine the lengths of road within each buffer boundary. Paved roads were excluded from the analysis because they have little erosion potential. For unpaved roads, the average road characteristics observed during the field reconnaissance were determined, and the data were entered into the Washington State Road Surface Erosion Model (WARSEM, Dubé et al. 2008) to estimate the average annual contribution of sediment to streams from roads in the watershed. Table C-6 shows the average annual sediment input from road surface erosion.

Table C-6
Estimated Sediment Input from Road Surface Erosion

	Road Surface Erosion (t/yr)		
Subbasin	**Cobble/ Gravel**	**Sand**	**Fines**
Headwaters Tucannon River	4	41	37
Panjab Creek	17	174	156
Little Tucannon River-Tucannon River	14	139	125
Cummings Creek	6	57	51
Tumalum Creek	3	29	26
Hartsock Grade-Tucannon River	2	21	19
Town of Marengo-Tucannon River	2	18	16
Willow Creek	4	39	35
Upper Tucannon Total	**52**	**517**	**465**
Headwaters Pataha Creek	22	215	194
Bihmaier Gulch-Pataha Creek	2	21	19
Benjamin Gulch-Pataha Creek	3	26	23
Linville Gulch	4	40	36
Chard Gulch-Pataha Creek	2	24	22
Dry Hollow-Pataha Creek	2	20	18
Pataha Creek Total	**35**	**346**	**312**

Subbasin	Road Surface Erosion (t/yr)		
	Cobble/ Gravel	Sand	Fines
Smith Hollow-Tucannon River	2	17	16
Town of Starbuck-Tucannon River	1	12	11
Kellogg Creek	3	31	28
Tucannon River	1	8	7
Watershed Total	**93**	**931**	**838**

C.2.6 Channel Erosion

Erosional processes associated with bedrock-lined swales and mainstem channel migration within the valley provide sediment directly to the stream channel. These sources are episodic; large quantities of sediment are added during major storms and peak flow events, with little sediment input during low or moderate flows. Field observations in the Tucannon watershed suggest that localized erosion and gullying of ephemeral, bedrock-lined channels located in steep, narrow swales occurs during major storms. This process has been documented by the USFS in a study of the effects of the 1996 flood event on forest land (Fitzgerald and Clifton 2007). In addition, analysis of historical aerial photographs shows that the mainstem Tucannon River actively migrates and erodes streambanks within its alluvial floodplain. A large amount of channel migration indeed occurs during large floods; however, observations by local residents suggest that channel migration is actively occurring in many locations throughout the study area during frequent flood events such as the 2-year event.

In order to estimate sediment input from these two types of channel processes, the GIS stream layer was overlain with the WDNR geology layer (WDNR 1997) to separate stream segments that are and are not underlain by alluvium. The alluvial stream segments are located in valley bottoms and are subject to channel migration. The non-alluvial stream segments are located in small, confined bedrock-lined valleys and on hillsides, and are subject to localized erosion and gullying.

C.2.6.1 Mainstem Channel Migration

An estimate of bank erosion along the alluvial channel lengths was made based on migration of the active Tucannon River mainstem channel observed on a series of historic aerial photographs. The photos used for this analysis were the 1954, 1974, 1976, 1996, and 2010 series. The active channel area was digitized on each photo series and overlaid to result in a series of polygons that represented unique areas of active channel on each set of photos. The area of each of these polygons thus represented new valley bottom areas that the active channel occupied between the previous and current photo years (i.e., the 1954 to 1974, 1976; 1974, 1976 to 1996; and 1996 to 2010 periods). The aerial photographs covered the mainstem Tucannon River between the mouth (RM 0) and just upstream of Cummings Creek (RM 38). Channel migration was evident along the mainstem between RM 38 and approximately RM 48 in the Little Tucannon River-Tucannon River subbasin, but could not be quantified due to the lack of complete aerial photograph coverage in this area. Therefore, estimates for sediment input from channel migration in this subbasin are unknown, but are likely of similar or smaller magnitude as the estimated amounts in the downstream Hartsock Grade-Tucannon River subbasin. A smaller amount of channel migration likely occurs in the Headwaters subbasin upstream of Panjab Creek, although the volume of contributed sediment is expected to be minor in comparison.

The unique active channel area for each photo period was multiplied by an average bank height of 3 feet (observed in the field) to yield the estimated volume of sediment added to the channel from channel migration. The total volume of eroded streambank for each photo period was divided by the number of years between photos to obtain an average annual sediment input rate. Figures D-1 and 2a through D-11a in Appendix D show the mapped active channel areas for the three photo periods.

C.2.6.2 Erosion in Bedrock Swales

Due to the small size of the bedrock-lined channels, they are not easily seen on aerial photographs and little information is available on the rates of erosional processes associated with these features. The two main sources of sediment to these drainages are colluvial erosion of soils that accumulate in the swales over time, and debris flows that remove these soils and carry them into the main river valley. Erosion from bedrock swale channels was estimated using a soil creep calculation and the assumption that the soil that gradually moves downhill via soil creep will enter the stream channel at the base of the hill by either bank erosion or gullying. Soil creep was calculated using the following formula (WDNR 1997):

Annual Sediment Yield from Soil Creep = Length of Stream Channel x 2 Banks x Soil Depth x Average Creep Rate x Soil Bulk Density

A creep rate of 1.5 millimeter/year (0.06 inches/year) and a soil depth of 1 meter (rounded to 3.25 feet) was used in the calculation. A bulk density value of 1.09 tons/cubic yard was used based on soil bulk density reported in the NRCS Web Soil Survey (NRCS 2009).

Table C-7 shows the estimated average annual sediment input from bedrock swales, as well as estimated input from channel migration in the mainstem for the three different aerial photograph periods studied. The inputs from migration of the mainstem channel vary greatly between photograph periods depending on whether a major flood occurred or not (e.g., 1954 to 1974 included the 1964 flood, and 1974 to 1996 included the 1996 flood).

Table C-7

Estimated Average Annual Sediment Input from Mainstem Channel Migration and Bedrock Swales

	Colluvial Erosion from bedrock swales (t/yr)			Channel migration 1954-1974/76 (t/yr)			Channel migration 1974-1996 (t/yr)			Channel migration 1996-2010 (t/yr)		
Subbasin	**Cobble/ Gravel**	**Sand**	**Fines**	**Cobble/ Gravel**	**Sand**	**Fines**	**Cobble/ Gravel**	**Sand**	**Fines**	**Cobble/ Gravel**	**Sand**	
Headwaters Tucannon River	132	99	429	U	U	U	U	U	U	U	U	U
Panjab Creek	109	82	356	-	-	-	-	-	-	-	-	-
Little Tucannon River-Tucannon River	342	259	1,113	U	U	U	U	U	U	U	U	U
Cummings Creek	163	122	529	-	-	-	-	-	-	-	-	-
Tumalum Creek	92	70	299	-	-	-	-	-	-	-	-	-
Hartsock Grade-Tucannon River	68	121	250	18,699	1,903	105	12,417	1,264	69	2,414	246	13
Town of Marengo-Tucannon River	50	81	182	58,231	760	256	24,852	324	109	9,262	121	41
Willow Creek	10	233	128	-	-	-	-	-	-	-	-	-
Upper Tucannon Total (see note below)	966	1,066	3,285	76,930	2,663	360	37,270	1,588	179	11,676	367	54
Headwaters Pataha Creek	181	136	590	-	-	-	-	-	-	-	-	-
Bihmaier Gulch-Pataha Creek	72	144	272	-	-	-	-	-	-	-	-	-

	Colluvial Erosion from bedrock swales (t/yr)			Channel migration 1954-1974/76 (t/yr)			Channel migration 1974-1996 (t/yr)			Channel migration 1996-2010 (t/yr)		
Subbasin	Cobble/ Gravel	Sand	Fines	Cobble/ Gravel	Sand	Fines	Cobble/ Gravel	Sand	Fines	Cobble/ Gravel	Sand	
Benjamin Gulch-Pataha Creek	37	74	141	-	-	-	-	-	-	-	-	-
Linville Gulch	63	162	256	-	-	-	-	-	-	-	-	-
Chard Gulch-Pataha Creek	44	113	178	-	-	-	-	-	-	-	-	-
Dry Hollow-Pataha Creek	42	138	181	-	-	-	-	-	-	-	-	-
Pataha Creek Total	440	767	1,617	0	0	0	0	0	0	0	0	0
Smith Hollow-Tucannon River	30	158	156	9,387	1,402	233	4,026	601	100	2,288	342	57
Town of Starbuck-Tucannon River	47	149	201	7,775	1,051	134	3,156	427	54	1,140	154	20
Kellogg Creek	51	248	256	-	-	-	-	-	-	-	-	-
Tucannon River	22	73	96	15,795	1,560	206	5,585	552	73	2,181	215	28
Watershed Total	1,556	2,461	5,612	109,887	6,676	934	50,036	3,167	406	17,286	1,078	159

Notes:

U= unknown; mainstem channel migration was observed in the Little Tucannon-Tucannon River subbasin, as well as a minor amount in the Headwaters subbasin, but the magnitude of sediment input in these areas could not be quantified due to the lack of complete aerial photograph coverage.

C.2.7 Channel Incision

Major areas of channel incision were observed along Pataha Creek and Smith Hollow. These streams flow through valleys filled with fine-grained silt and sand that originated as Quaternary loess deposits. These channels have been incised since at least the early 1900s; the incised areas are evident in the 1937 aerial photographs and mature trees can presently be observed within the incised channel areas in parts of Pataha Creek. It was not possible to determine the rate of ongoing incision or evolution of the channel cross-section within the incised areas with available data. However, continued erosion of the incised channel walls and bottom is occurring in Pataha Creek based on observations of erosion at bridge abutments along the creek.

Beechie et al. (2008) measured channel incision at several locations in Pataha Creek and provided the resulting measurements. Incision depths in Pataha Creek decreased in an upstream direction from 19 feet near the confluence with the Tucannon River to 6 to 7 feet near Pomeroy. Incision widths also decreased from 100 feet near the confluence to 34 feet near Pomeroy. Incision in Smith Hollow averaged 20 feet deep and 80 feet wide. Based on the field observations and a cross-section of lower Pataha Creek just upstream of the Highway 261 bridge taken from the LiDAR dataset (Figure C-2), it was estimated that 60% of the total width times depth of the incised area been eroded.

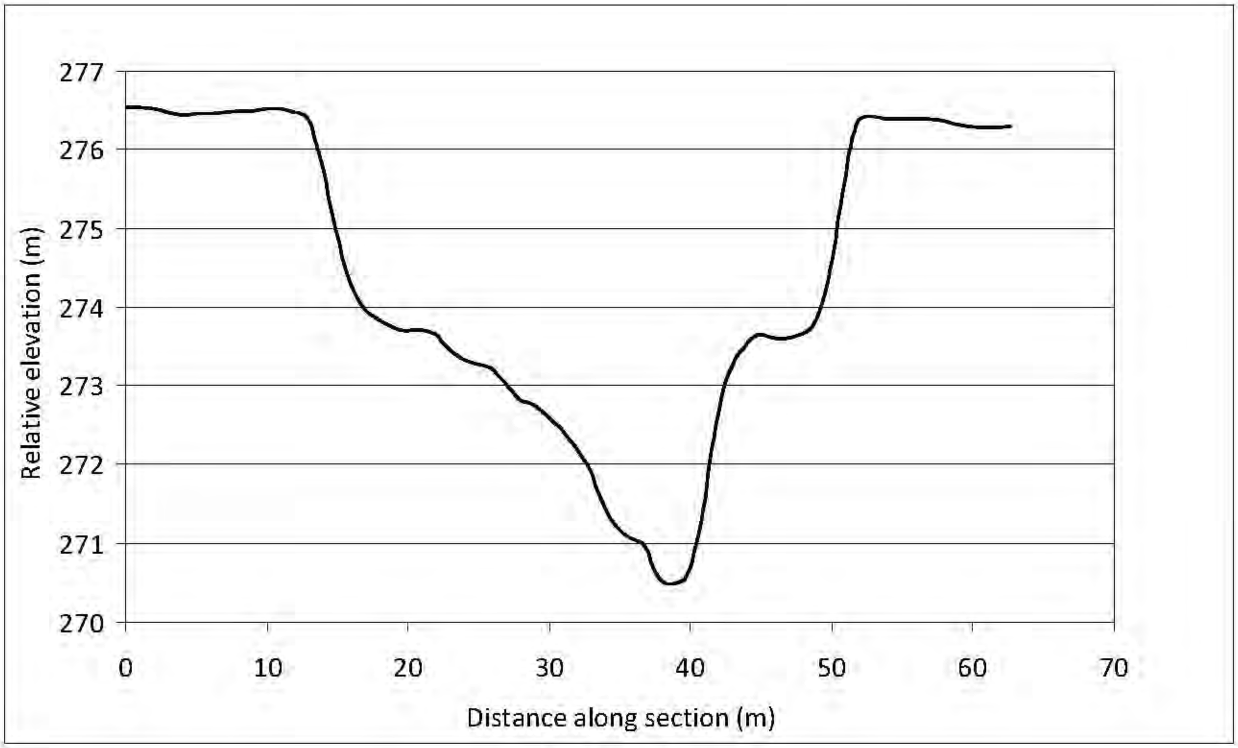


Figure C-2

Cross-Section of Pataha Creek Showing Channel Incision Profile

Note: Cross-section is located just upstream of the Highway 261 bridge crossing at a gravel sample site.

Observations and measurements of incision depth and measurements of the incised valley width from aerial photographs were used to estimate the total volume of sediment removed from the channels in the Pataha Creek and Smith Hollow subbasins (Table C-8). The rate of incision is not known; however, it is likely that incision is greatest during peak flow events. For sediment budgeting purposes, the total incised volume was divided by 100 years to provide an average annual input rate throughout the past century. It is possible that the channel incision started more than 100 years ago; therefore, the actual input rate from this source may be lower than estimated.

Table C-8

Parameters Used to Estimate Channel Incision Volumes

Subbasin	Length of Incised Channel (ft)	Average Incised Area (sq ft)	Total Incised Volume (cu yd)	Average Annual Erosion (t/yr over 100 yrs)
Bihmaier Gulch-Pataha Creek	55,611	126	259,519	2,855
Benjamin Gulch-Pataha Creek	41,055	176	267,620	2,944
Chard Gulch-Pataha Creek	68,793	722	1,839,585	20,235
Dry Hollow-Pataha Creek	28,857	880	940,538	10,346
Smith Hollow	8,026	960	285,355	3,139

C.2.8 Bedload Transport Modeling

Bedload transport modeling was conducted for the Tucannon River as part of this project (see Section 6.3 of the main report). The results of the bedload transport models were used to generate a bedload rating curve for two USGS gage locations in the Tucannon River: the Starbuck gage in the lower mainstem (USGS 13344500 Tucannon River near Starbuck, Washington) and the Marengo gage in the upper mainstem (USGS 13344000 Tucannon River near Pomeroy, Washington). The Starbuck rating curve was applied to the long-term mean daily flow records from the Starbuck gage to estimate total annual bedload transport capacity at that location. The mean daily flow at Starbuck was adjusted to 87% of the value and used to estimate annual transport at Marengo (Figure C-3).

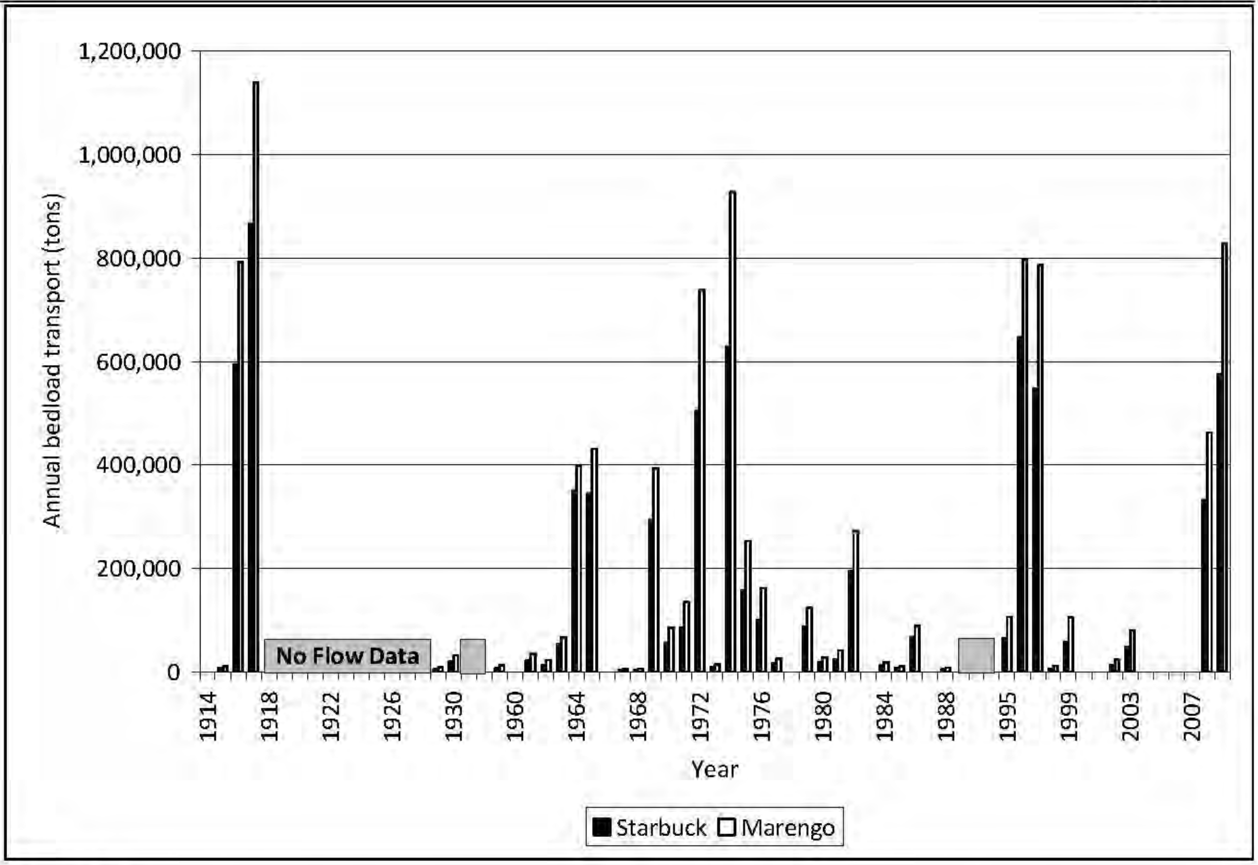


Figure C-3
Total Annual Computed Bedload Transport Capacity at the Starbuck and Marengo Gages

Bedload transport rates vary greatly between years because peak flows are needed to transport the cobble and gravel substrate in the Tucannon River. Little to no bedload movement is predicted to occur during years without peak flows that are high enough to initiate bedload transport (approximately 480 cubic feet per second (cfs) at the Starbuck gage). A transport capacity of more than 600,000 tons of bedload sediment is predicted during years with extreme floods (e.g., 1916 and 1996). Bedload transport capacity is different at the two gage locations due to differences in hydraulics, discharge, and typical substrate size.

As a check on the predicted bedload transport rates, the bedload transport rates computed by Hecht et al. (1982) for the 1980 water year based on measured bedload were compared with those computed using the bedload rating curve from our study. Hecht et al. (1982) reported 565 tons of bedload sediment at the Starbuck gage site and 1,079 tons downstream of the

Powers Road Bridge; we computed a transport capacity of 10,700 tons. These results indicate that bedload transport in the Tucannon River system is likely supply-limited, a common situation in gravel-bedded rivers.

Another comparison with bedload transport rates was made by comparing the estimated bedload input between aerial photo years with computed bedload transport for the same period. Estimated bedload transport capacity was higher than estimated input (Table C-9), also suggesting that the river is supply limited.

Table C-9

Comparison of Bedload Input and Transport Estimates

	Starbuck Gage		Marengo Gage	
Period	Estimated Average Annual Bedload Input (tons/year)	Estimated Average Annual Bedload Transport (tons)	Estimated Average Annual Bedload Input (tons/year)	Estimated Average Annual Bedload Transport (tons)
1954-1974	117,496	148,180	79,953	204,534
1974-1996	53,609	82,113	39,036	113,751
1996-2010	23,701	121,462	13,956	176,642

C.2.9 Analysis of ISCO Samples and Suspended Sediment Transport

In situ chemical oxidation (ISCO) sampling results from 2007 and 2008, which included daily measurements of total suspended sediment (TSS), were provided by the Columbia Conservation District (CCD) for several stations in the Tucannon River watershed. The data from the Fletcher and Territorial sites were chosen for analysis because they had relatively complete records. The Fletcher site is just downstream of the USGS Starbuck gage location, so those flow records were used to convert TSS to tons of suspended sediment/day. The Territorial site is just upstream from the Pataha Creek junction. Flows at this site were not gaged; a correction factor of 87% of the Starbuck gage flows were applied to the Fletcher site. It is likely that this slightly underestimates the discharge at the Fletcher site and thus results in slightly lower suspended sediment load than if actual discharge records were available at the site.

Figure C-4 shows the TSS (milligram per liter [mg/L]) measured at the Territorial and Fletcher sites, as well as the discharge at the Starbuck gage and rainfall at the Pomeroy weather station during the 2008 water year. Note that TSS at the Territorial site is generally higher than at the Fletcher site, which is upstream of Pataha Creek; this is consistent with the Hecht et al. (1982) study that found that the majority of fine-grained sediment that would be carried as suspended load came from Pataha Creek. Also note that while TSS increases during high flow events, it does not increase during rainfall events. This suggests that small to moderate rainfall events do not deliver eroded sediment directly to the mainstem river, but rather that the suspended sediment movement in the mainstem is related to high flows, particularly during spring snowmelt runoff.

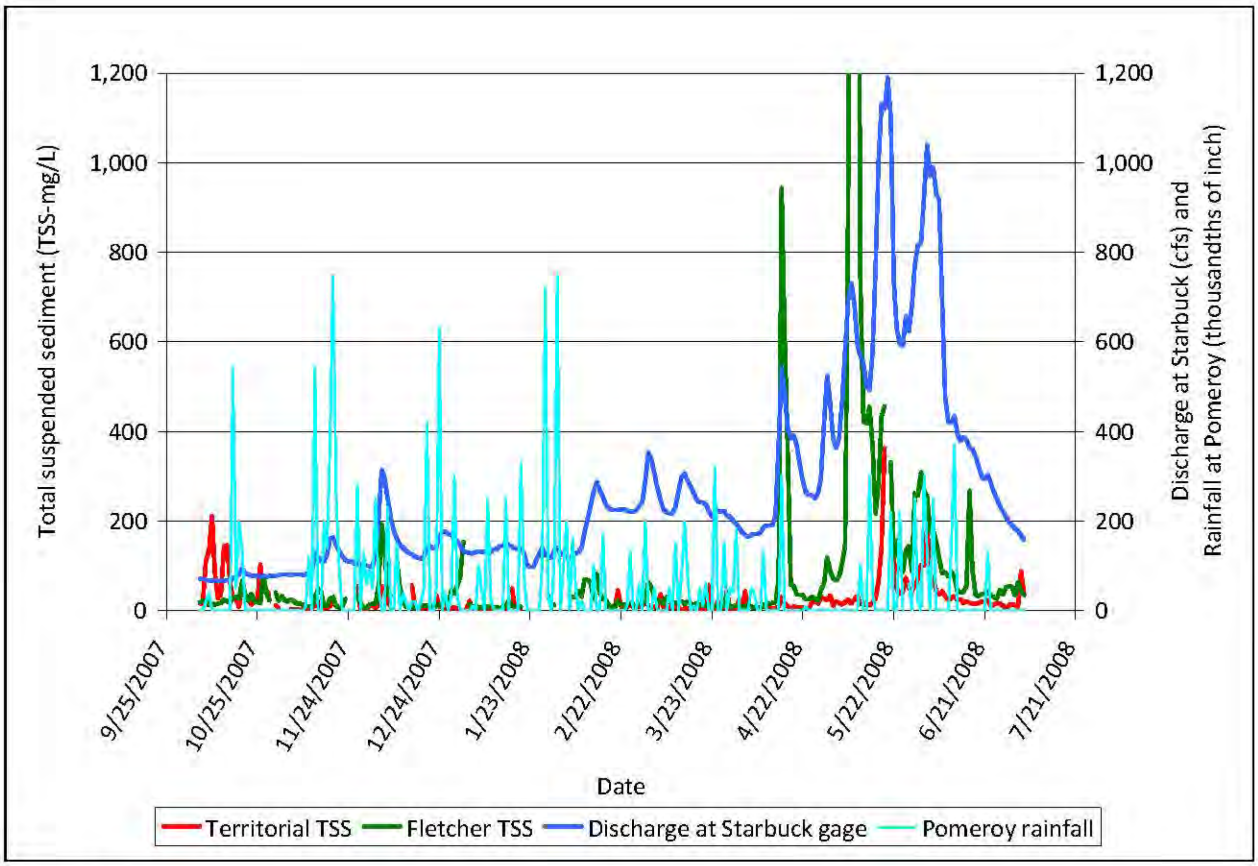


Figure C-4

Total Suspended Sediment, Discharge, and Rainfall, 2008 Water Year

Figure C-5 shows the correlation between TSS measured at the Fletcher site and discharge at the Starbuck gage for the 2007 and 2008 water years. There is a relatively good correlation between discharge and TSS.

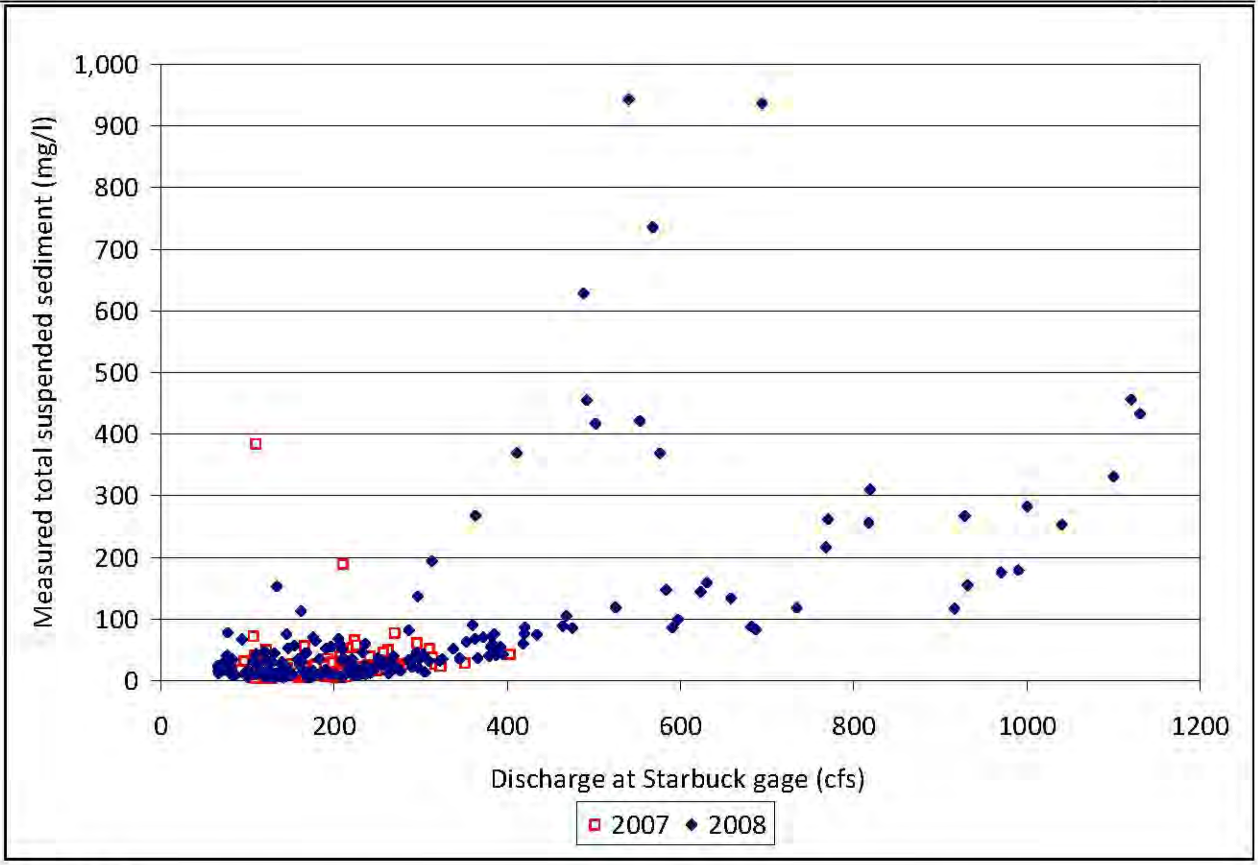


Figure C-5
Total Suspended Sediment at Fletcher vs. Discharge at Starbuck Gage

However, there is not a very good correlation between TSS and rainfall (Figure C-6). Previous researchers have suggested that overland flow does not normally occur in the deep, permeable loess soils that underlie much of the Pataha and Lower Tucannon watershed. Instead, they found that only extremely intense rainfall events or rainfall on frozen ground produced substantial overland flow and surface erosion (Williams et al. 2009). The rainfall/TSS record was reviewed to see if any data were available to support the hypothesis that rainfall on frozen ground results in a measureable increase in erosion/TSS. One storm was found (January 3, 2007) that met the criteria of relatively intense rainfall (0.65 inches/day) following freezing temperatures. Discharge during this period only increased from 137 to 210 cfs, but TSS increased from 20.4 to 1,015 mg/L, supporting the hypothesis the intense rainfall on frozen ground results in erosion and delivery of suspended sediment to streams.

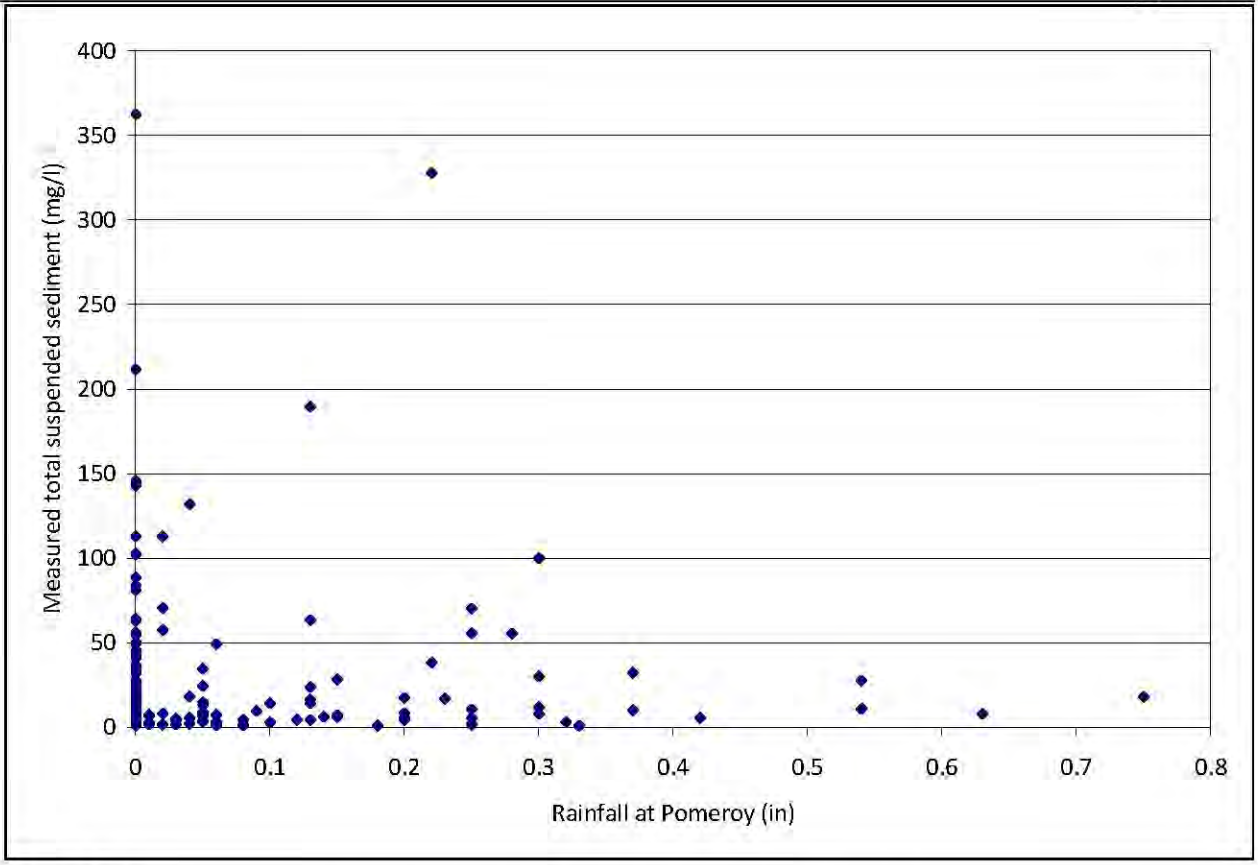


Figure C-6
Total Suspended Sediment at Fletcher vs. Rainfall at Pomeroy, 2008 Water Year

The daily TSS records at each of the sample sites were applied to the daily flow records from the Starbuck gage to obtain an estimate of total suspended load for the 2007 and 2008 water years. The total suspended load was adjusted for missing data by the proportion of missed flow to total flow for the water year. In addition to the 2007 and 2008 data, suspended sediment loads reported in Hecht et al. (1982) were compiled for comparison with the estimated sediment budget inputs. The portion of the total sediment input that travels as suspended load likely includes fines (silt and clay) and fine sand. Because the grain size that is carried as suspended load varies with discharge (e.g., more sand is carried during the higher velocity peak flows), all of the fines plus half of the sand-sized sediment input rates were used for comparison with the suspended load values.

Table C-10 shows a comparison of estimated sediment input and suspended sediment transport at the Starbuck and Marengo gages. Suspended sediment transport varies greatly between years; at the Fletcher/Starbuck site it ranges from 9,238 to 3,145,693 tons depending on whether or not there were large floods during a particular year. Estimated sediment input is based on average watershed conditions and is approximately 50,000 tons/year at the Starbuck gage. The estimated input values are in the range of transport values, but are lower than the average transport rate for the period measured, which included the largest flood on record (1965 water year).

Table C-10
Comparison of Suspended Sediment Input and Transport Estimates

Water Year	Fletcher Site/Starbuck Gage		Territorial Site/Marengo Gage	
	Estimated Average Annual Fines/50% Sand Input (tons/year)	Estimated Average Annual Suspended Transport (tons)	Estimated Average Annual Fines/50% Sand Input (tons/year)	Estimated Average Annual Suspended Transport (tons)
1963[a]	54,966[c]	399,275	9,395[c]	Not reported
1964		148,093		
1965		3,145,693		
1966		155,769		
1967		17,289		
1968		9,238		
1969		526,644		
1970		219,324		
Average 1963-1970		*577,666 w/1965* *210,805 w/o 1965*		
1980	52,269[d]	138,271	8,675[d]	
2007[b]	47,814[e]	13,423	8,086[e]	4,235
2008[b]		26,007-52,965[f]		8,094

Notes:
[a] 1963-1980 data reported in Hecht et al. (1982)
[b] 2007-2008 ISCO data compiled for this report
[c] 1954-1974 period
[d] 1974-1996 period
[e] 1996-2010 period
[f] Range in 2008 suspended sediment transport at Fletcher is with and without 5 days of anomalously high TSS data included

C.3 SUMMARY

The Tucannon River watershed sediment budget considered sediment inputs as well as suspended and bedload transport rates. Sediment inputs were determined by estimating erosion rates and delivery to stream channels and were partitioned by source and grain size category. Table C-11 and Figure C-7 show current (2005 to 2010) average annual sediment input rates by source. Note that these values should be regarded as estimates of the relative magnitude of sediment inputs rather than precise quantities due to the uncertainties inherent in calculating input rates.

The majority of recent sediment input to the Tucannon has come from channel-related sources, either by erosion/gullying in bedrock swales and mainstem channel migration during peak flows, or by channel incision in Pataha Creek and Smith Hollow. We estimated that 17% of recent sediment delivered to streams is from land use activities, including roads, agriculture, timber harvest, and wildfire. More soil is eroded from these land use activities, but not all of it reaches the streams. This is supported by recent ISCO sampling in the watershed that shows that suspended sediment levels are correlated with streamflow, but there is little correlation between high suspended sediment levels and rainfall events.

Table C-11
Average Annual Input from Current (2005 to 2010) Sediment Sources

Subbasin	Area (acres)	Colluvial Erosion in Bedrock Swales	Mainstem Channel Migration	Channel Incision	Road Erosion	Land Use	School Fire	Total	Average tons/acre
Headwaters Tucannon River	24,490	600	U	-	82	49	-	25,220	1.03
Panjab Creek	16,253	497	-	-	347	32	-	17,129	1.05
Little Tucannon River-Tucannon River (see note below)	22,073	1,558	U	-	277	322	970	25,201	1.14
Cummings Creek	12,717	740	-	-	113	139	618	14,328	1.13

Subbasin	Area (acres)	Colluvial Erosion in Bedrock Swales	Mainstem Channel Migration	Channel Incision	Road Erosion	Land Use	School Fire	Total	Average tons/acre
Tumalum Creek	10,268	419	-	-	58	170	246	11,161	1.09
Hartsock Grade-Tucannon River	12,700	398	2,673	-	42	795	80	16,688	1.31
Town of Marengo-Tucannon River	23,023	285	9,424	-	36	413	-	33,181	1.44
Willow Creek	19,118	337	-	-	77	853	-	20,385	1.07
Headwaters Pataha Creek	18,306	825	-	-	430	112	334	20,007	1.09
Bihmaier Gulch-Pataha Creek	23,790	443	-	2,855	42	960	-	28,090	1.18
Benjamin Gulch-Pataha Creek	17,937	229	-	2,944	51	592	-	21,755	1.21
Linville Gulch	19,207	438	-	-	80	1,560	-	21,285	1.11
Chard Gulch-Pataha Creek	20,616	305	-	20,235	48	609	-	41,814	2.03
Dry Hollow-Pataha Creek	18,419	328	-	10,346	40	389	-	29,522	1.60
Smith Hollow-Tucannon River	16,697	313	2,687	3,139	35	776	-	23,647	1.42
Town of Starbuck-Tucannon River	15,476	362	1,314	-	24	443	-	17,618	1.14
Kellogg Creek	22,088	504	-	-	63	1,402	-	24,057	1.09
Tucannon River	8,429	175	2,425	-	15	86	-	11,130	1.32
Watershed Total	**321,609**	**8,754**	**18,523**	**39,519**	**1,863**	**9,703**	**2,248**	**402,217**	**1.25**

Notes:

U= unknown; mainstem channel migration was observed in the Little Tucannon-Tucannon River subbasin, as well as a minor amount in the Headwaters subbasin, but the magnitude of sediment input in these areas could not be quantified due to the lack of complete aerial photograph coverage. The estimate of average tons per acre for these subbasins may be affected.

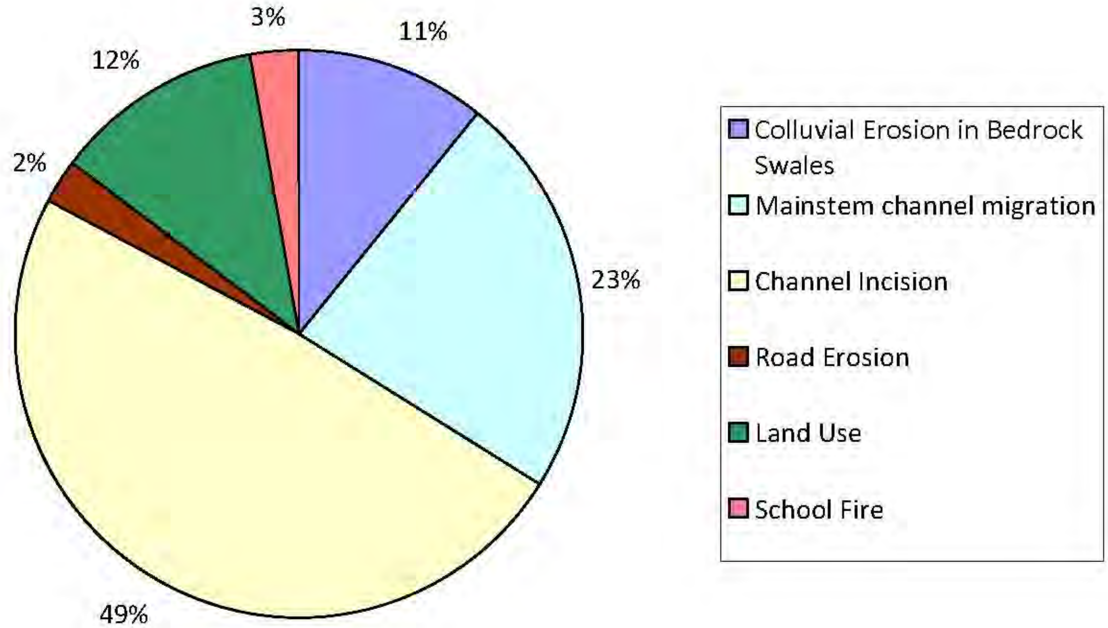


Figure C-7
Current Sediment Inputs by Source

The sediment input budget was also calculated for three different time periods based on available aerial photographs. Sediment inputs for the 1954 to 1974, 1974 to 1996, and 1996 to 2010 periods were estimated based on channel migration and land use changes. Table C-12 shows the sediment inputs by subbasin for each of these three periods. The primary differences between periods are higher inputs of bedload material (cobble/gravel) from channel migration during the large 1964 and 1996 flood events, and a decrease in erosion and sediment delivery from croplands through time as farming conservation efforts improved.

Table C-12

Tucannon River Watershed Sediment Input Budget (in Tons)

Subbasin	TOTAL 1954 to 1974			TOTAL 1974 to 1996			TOTAL 1996 to 2010		
	Cobble/ Gravel	Sand	Fines	Cobble/ Gravel	Sand	Fines	Cobble/ Gravel	Sand	Fines
Headwaters Tucannon River	143	170	496	143	170	496	141	162	488
Panjab Creek	131	274	530	131	274	530	130	270	526
Little Tucannon River-Tucannon River*	400	595	1,435	400	595	1,435	388	1,027	1,868
Cummings Creek	189	273	674	189	273	674	182	551	952
Tumalum Creek	121	217	444	121	217	444	112	298	525
Hartsock Grade-Tucannon River	18,910	2,679	1,007	12,628	2,039	971	2,563	785	680
Town of Marengo-Tucannon River	58,347	1,149	743	24,969	713	596	9,356	407	425
Willow Creek	175	997	889	175	997	889	99	655	547
Upper mainstem total	**78,416**	**6,354**	**6,218**	**38,756**	**5,279**	**6,036**	**12,971**	**4,154**	**6,009**
Headwaters Pataha Creek	221	434	866	221	434	866	214	568	1,001
Bihmaier Gulch-Pataha Creek	246	2,940	1,924	246	2,940	1,924	170	2,595	1,579
Benjamin Gulch-Pataha Creek	145	2,636	1,522	145	2,636	1,522	99	2,427	1,314
Linville Gulch	358	1,507	1,597	358	1,507	1,597	224	904	994
Chard Gulch-Pataha Creek	150	14,766	6,735	150	14,766	6,735	108	14,576	6,545
Dry Hollow-Pataha Creek	110	7,698	3,601	110	7,698	3,601	83	7,575	3,478
Pataha total	**1,231**	**29,982**	**16,245**	**1,231**	**29,982**	**16,245**	**897**	**28,646**	**14,909**
Smith Hollow-Tucannon River	9,567	4,439	2,012	4,205	3,639	1,879	2,398	3,063	1,520
Town of Starbuck-Tucannon River	7,907	1,592	725	3,288	967	646	1,232	515	431
Kellogg Creek	320	1,476	1,481	320	1,476	1,481	194	910	915
Tucannon River	15,834	1,713	381	5,624	704	248	2,213	335	170
Lower mainstem total	**33,628**	**9,220**	**4,600**	**13,438**	**6,787**	**4,254**	**6,037**	**4,823**	**3,036**
Total Tucannon Watershed	**113,275**	**45,555**	**27,063**	**53,424**	**42,047**	**26,535**	**19,905**	**37,624**	**23,955**

Note: *Mainstem channel migration was observed in the Little Tucannon-Tucannon River subbasin as well as a minor amount in the Headwaters subbasin, but the magnitude of sediment input in these areas could not be quantified due to the lack of complete aerial photograph coverage.

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