AN ABSTRACT OF THE THESIS OF

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Title: Stream Channel Stability and Sensitivity to Landscape History and Land Use Changes in Kelley Creek, Portland, Oregon.

Abstract approved:

Julia A. Jones

This study examines stream channel erosion processes in a small urbanizing watershed influenced by deposits of the Columbia Basin catastrophic floods: Kelley Creek, a 12-km^2 tributary of Johnson Creek, located just east of Portland, Oregon. Information on landscape history, stream channels, and sediment dynamics was compiled. The effects of future land use changes on stream channel response were projected. The likely effects of engineered solutions (stormwater management detention or infiltration facilities) are compared to land-use controls in mitigating the impact of future development on channel erosion.

The geology of Kelley Creek is shaped by volcanic processes and Missoula floods, leading to fine-textured soils and streambeds that are susceptible to erosion. Headwaters are buttes of the Boring Lava formation overlain by Springwater Formation mudflow deposits. Alluvial silts deposited during late Pleistocene catastrophic floods mantle the low-relief valley floor.

Land use in Kelley Creek transitioned from forestry to agriculture in the 20^{th} century, and more recently to urban expansion, increasing concerns of watershed managers about effects of development on sediment dynamics. Since 1930, land use on the valley floor of Kelley Creek has been dominated by nursery and berry agricultural production. Forested headwaters have been impacted by

roads, culverts, and timber harvest. Seven percent of watershed area is currently impervious, with housing and commercial uses projected to increase following the incorporation of Kelley Creek into Portland's metropolitan urban growth boundary.

Field surveys and engineering calculations were used to estimate sediment transport under current and future conditions in the watershed. Cross sectional geometry, slope and sediment size distributions were obtained from 15 locations in first to second-order channels in the watershed, and data were analyzed with sediment transport equations to simulate annual sediment transport rates given current and post-development flow patterns.

Results indicate that the stream channel is most sensitive to altered discharge patterns where gravel-sized (D_{50} > 10 mm) sediments currently are mobilized during annual peak events. In locations where fine (D_{50} < 5 mm) particles dominate the stream bed, particles mobilize throughout the year and changes in discharge patterns do not increase the duration of transport or overall bedload yields. Because most of the sensitive locations with gravel sediments are located within or near the forested headwaters, preserving these headwater forests will protect sensitive stream channels as effectively as engineered stormwater retention or infiltration approaches.

Kelley Creek's stream channel is still adjusting to recent mudflows and catastrophic floods, which provided abundant supplies of fine, erodible materials. Allowing this adjustment to continue without accelerating erosion in the face of rapid urban development poses an unusual challenge for managing geomorphic processes.

Stream Channel Stability and Sensitivity to Landscape History and Land Use Changes in Kelley Creek, Portland, Oregon

by
Yarrow M. Murphy

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APPROVED:

Major Professor, representing Water Resources Engineering

Director of the Water Resources Graduate Program

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Yarrow M. Murphy, Author

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INTRODUCTION

Since the mid-twentieth century, researchers have connected changes in fluvial systems to human activity, namely urbanization. Impervious areas associated with urbanization can influence the physical conditions controlling channel erosion; stream power, sediment availability and sediment characteristics. The last 50 years of research indicate that in temperate climates, stream channels enlarge by a factor of two to three as they adjust to development-induced changes in stream power and sediment sources (Chin 2006). Increased erosion, stream channel enlargement, channel incision and headward channel extension potentially threaten human safety, property values and aquatic and riparian ecosystems. Because of these impacts, land use planners must consider stream channel erosion in development planning.

Stream power, the amount of work done by flowing water, is proportional to the energy slope (channel or water surface slope) times discharge (Leopold, Wolman and Miller 1964). Development increases stream power mainly through altering discharge patterns. In an urban landscape, water and fine sediment are conveyed efficiently to the stream channel across impervious surfaces and through storm sewer infrastructure. In many cases in the temperate northwestern United States, this increased conveyance efficiency leads to higher peak stream discharges (Burges, Wigmosta and Meena 1998; Chin 2006). Magnified peak discharges increase frequencies of pre-development floods. As a major safety concern for infrastructure and people living along waterways, these floods gain attention from land managers.

Stream channel morphology changes in response to increased frequency of intermediate discharges which may not directly impact infrastructure. Flows exceeding a critical shear stress have competence to move bed material or cause bank erosion. Any increase in the duration of these competent flows increases the duration of sediment transport within the stream channel. Flows performing geomorphic work occur several times per year in many rivers (Leopold, Wolman et al. 1964). Urbanization particularly increases the duration of erosive flows (Walker 2000) and causes greater increases in flow frequencies for storm flows with shorter return periods (MacRae 1997). In the maritime northwest climate, Chang suggests that urbanization tends to increase total runoff following storm events (2007). Increased durations of moderate discharges lead to increased sediment transport and channel erosion rates. Intermediate flow durations can be increased further by stormwater detention facilities, which release stormwater below a regulatory threshold rate over an extended time period (Booth and Jackson 1997).

Increased flows can be attributed to reduced vegetation as well as impervious area. Throughout the process of human settlement, vegetation on the landscape is changed and reduced. In the American west, land has typically been cleared to make way for agriculture, decades prior to conversion to urban land uses. As noted by Booth, Hartley and Jackson (2002), in low density rural areas, clearing of forested areas in conversion to farmland can have a significant impact on hydrology, even with minimal impervious cover. Removing forest cover reduces transpiration by plants, which leads to increased total water yield (Dunne and Leopold 1978). Increases of some discharges are, therefore, unavoidable in order to accommodate the change in annual surface water discharge. Additional water yields contribute to channel erosion if they increase the duration of geomorphically effective flows.

Effects of urbanization on stream systems vary by region with climate, soils, vegetation and geology (Chin 2006). Landscape characteristics determine the potential for change in discharge patterns and a landscape's resilience to that change. Urbanization could lead to increased hydrologic sensitivity to intermediate storm events, which in our study area occur frequently. Ultimately, small changes in hydrologic response can translate to large increases in the duration of flows doing geomorphic work. This hydrologic change, coupled with abundant sediment sources could potentially drive up sediment yields to a destabilizing rate. Local geomorphologic context of surface water within the larger regional context informs land use, stormwater management and stream restoration efforts. As Levell and Chang (2008) conclude in their research of a restoration project in Kelley Creek, successful restoration must consider watershed and local scale geomorphology and hydrology.

This study focuses on the balance of the physical controls on sediment dynamics in Kelley Creek, a watershed located east of Portland, Oregon. Agriculture, low density housing and secondary forest dominate the current land use in this watershed. Much of the Kelley Creek catchment has recently been incorporated into the Portland metropolitan urban growth boundary and with this designation, land uses will change dramatically. This study aims to provide insight into potential impacts of land use changes in Kelley Creek in two ways; to 1) assess current fluvial sediment transport patterns and their major drivers in Kelley Creek and to 2) determine the stream channel's relative sensitivity to potential hydrologic perturbations brought about with land use changes and stormwater management approaches. The hypothesis is that sediment transport within the Kelley Creek's channel is most sensitive to changes in the intermediate annual discharge magnitudes, and least sensitive to increases in base flow discharges. Given current channel geometry, bed material size distributions and discharges, proposed hypothetical perturbations of the annual flow duration curves in Kelley Creek are used to test the sensitivity of sediment transport to the potential increases in stream discharge that result from reduced vegetation and increased impervious surfaces.

METHODS

Fluvial Audit

While the present work estimates rates of these processes, those quantitative results must be considered within their greater landscape context. The fluvial audit examines the watershed on a landscape scale, incorporating information about geology and soils, vegetation type and land use. These landscape characteristics, along with hydroclimate, drive sediment inputs to the channel and storage within the channel. The overview points to areas of likely active erosion or deposition, and guides more detailed field study. Background information for this fluvial audit includes the topography, geology, soils, historical land surveys, and aerial photographs.

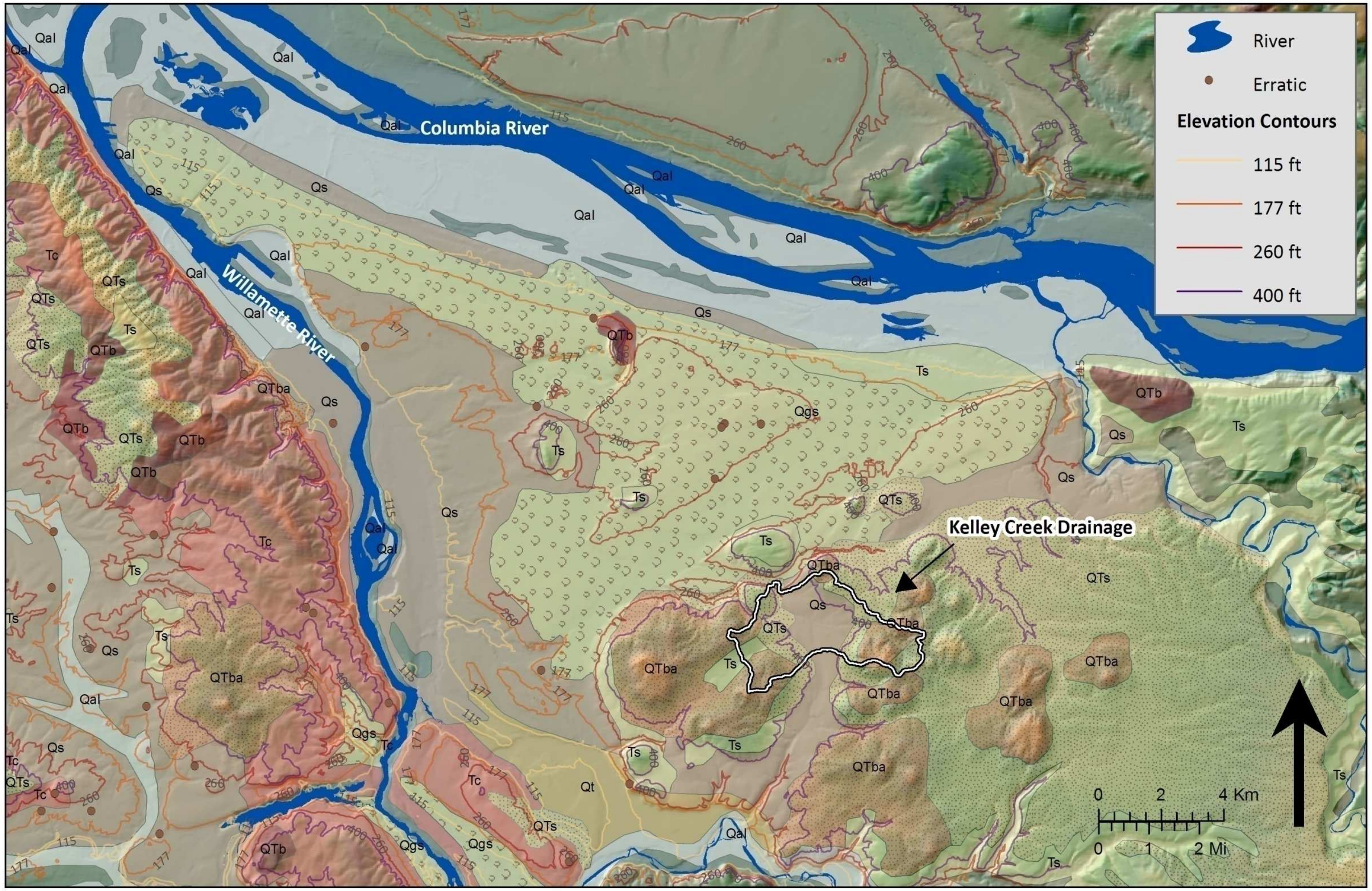
Site description

Kelley Creek drains 1215 hectares (4.69 square miles) east of Portland, Oregon and is part of the Johnson Creek watershed (Figure 1 and 2). Its northern tributaries include Jenne Creek and an unnamed tributary, referred to in the present study as Northern Tributary 2. Draining to Kelley Creek from the south are Clatsop and Mitchell Creeks and another unnamed tributary. The main channel of Kelley Creek is approximately 4.3 mi (7 km) long.

Three major geologic and topographic zones distinguish the landscape of the Kelley Creek drainage; its headwaters originate from a ring of basalt buttes rising to 240-340 m (800 to 1100 ft) elevation; between 90 and 120 m (300 and 400 ft) elevation, the central sections of channel flow through a low gradient valley and fine catastrophic flood deposits; and the lower end of the stream follows a fault through a steep canyon of coarse alluvium and basalt. Vegetation, soils and land use patterns correspond to the underlying geology and topography.

Figure 1. Study site location map.

Figure 2. Vicinity geology and Missoula Flood inundation depths. The Boring lava field buttes surround Kelley Creek.



Geologic Unit Descriptions

QTb	Pleistocene, Pliocene BASALT
QTba	Pleistocene, Pliocene BASALT and BASALTIC ANDESITE
QTs	Pleistocene, Pliocene SEDIMENTARY ROCKS
Qal	Holocene ALLUVIAL DEPOSITS
Qgs	Holocene, Pleistocene LACUSTRINE ALLUVIAL DEPOSITS: Coarse volcanic gravel with sandy matrix
Qs	Pleistocene LACUSTRINE and FLUVIAL SEDIMENTARY ROCKS
Qt	Holocene, Pleistocene TERRACE, PEDIMENT, and LAG Gravels
Tc	Miocene COLUMBIA RIVER BASALT GROUP and related flows
Ts	Pliocene, Miocene TUFFACEOUS SEDIMENTARY ROCKS and TUFF

Figure 3. LiDAR hillshade of Kelley Creek Basin. Note the inset floodplain, the deep, dead-end ravines and high drainage densities on the hillslopes.

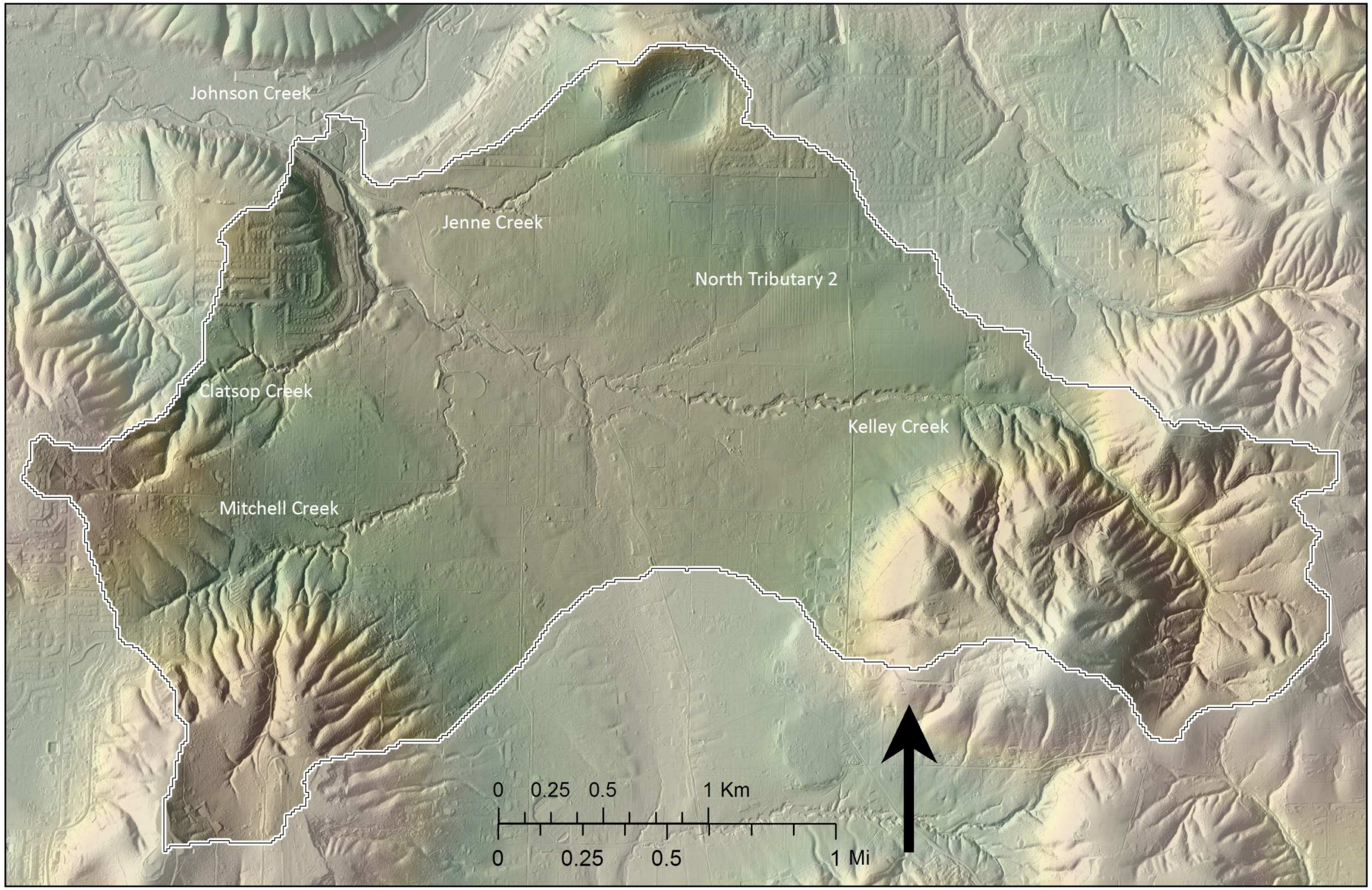


Figure 4. 1936 aerial image of Kelley Creek drainage.

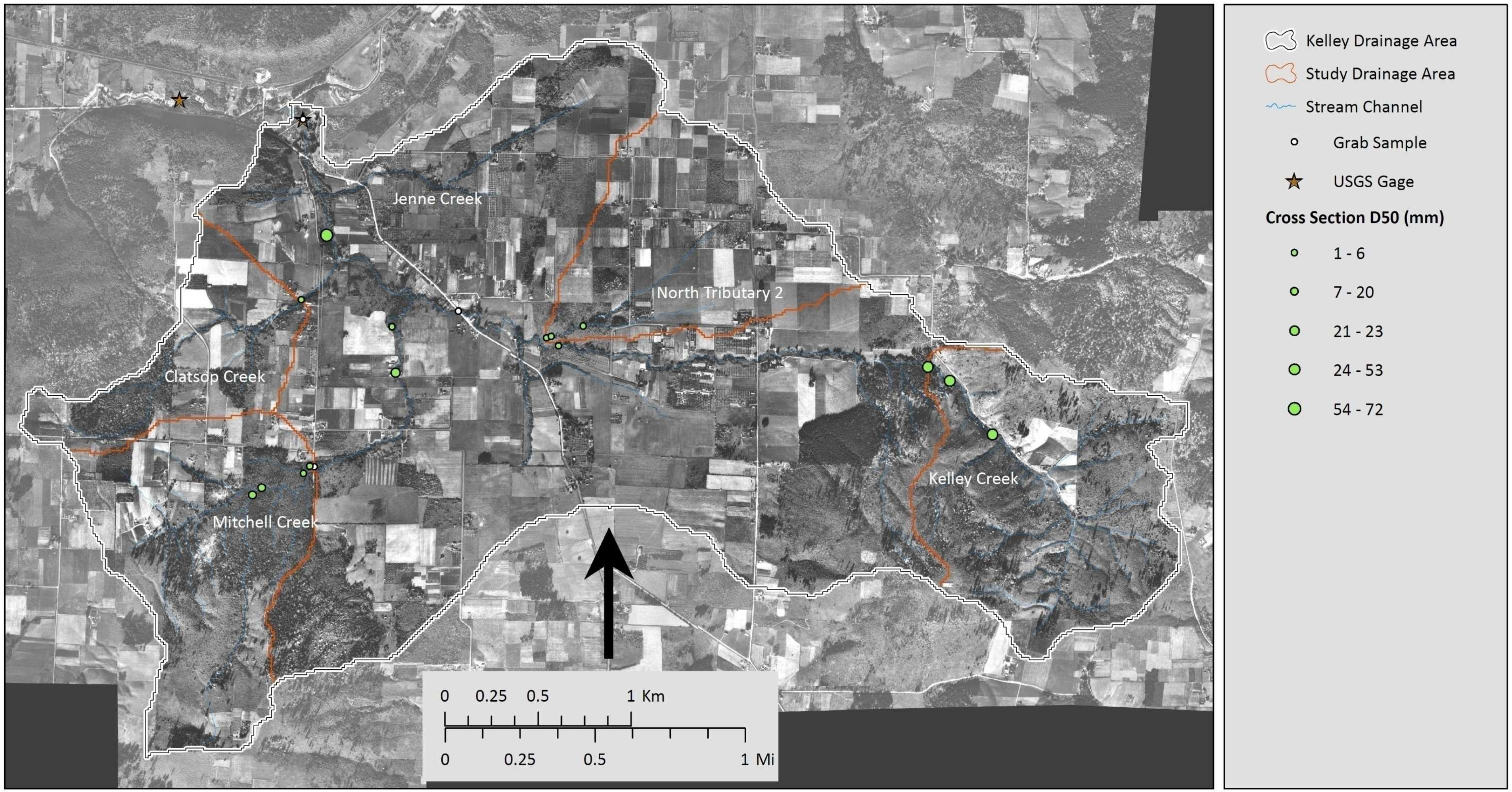


Figure 5. 2005 aerial image of Kelley Creek drainage.

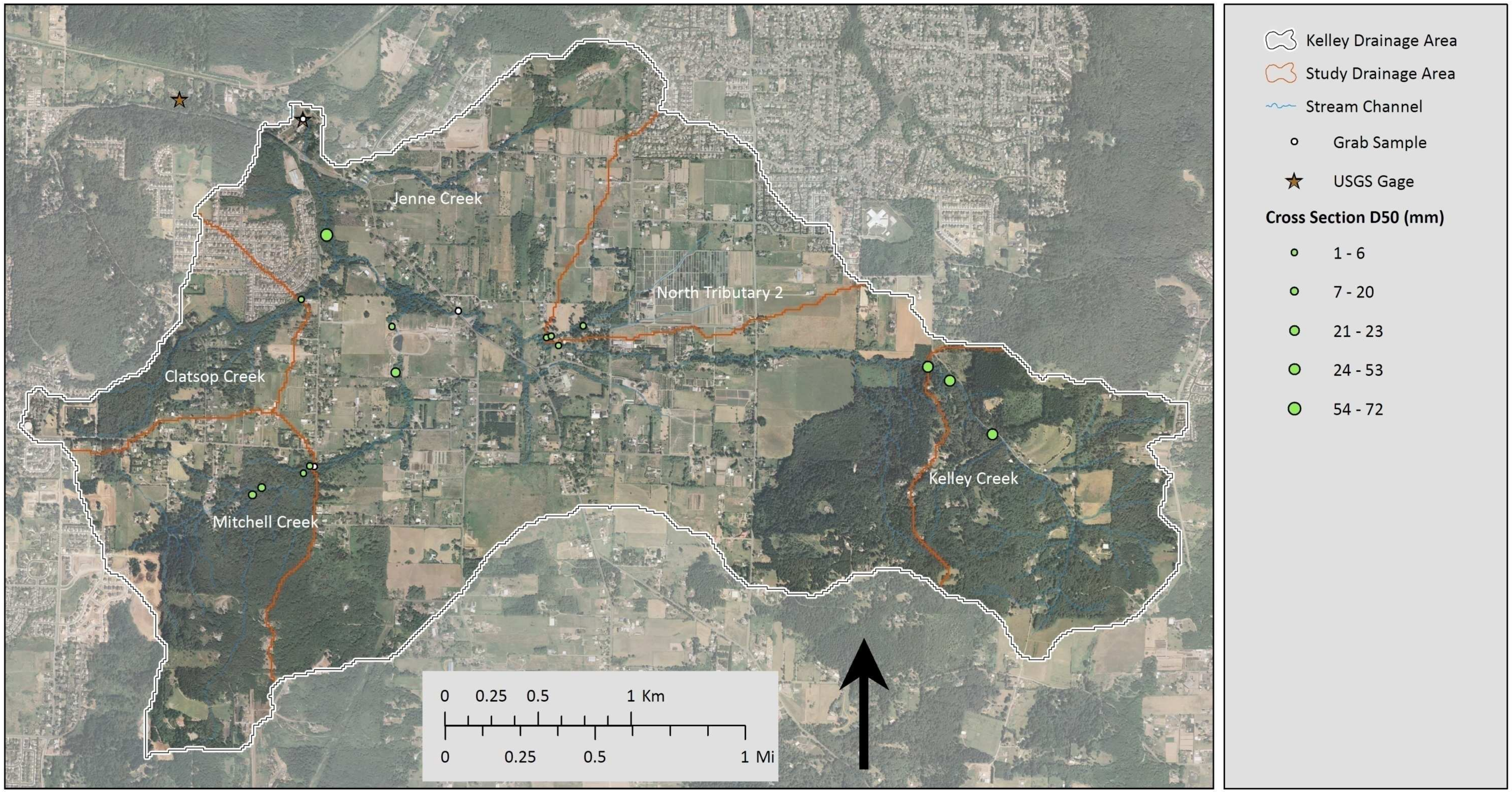


Figure 6. Soils of the Kelley Creek drainage area. Soils are generally silt loams.

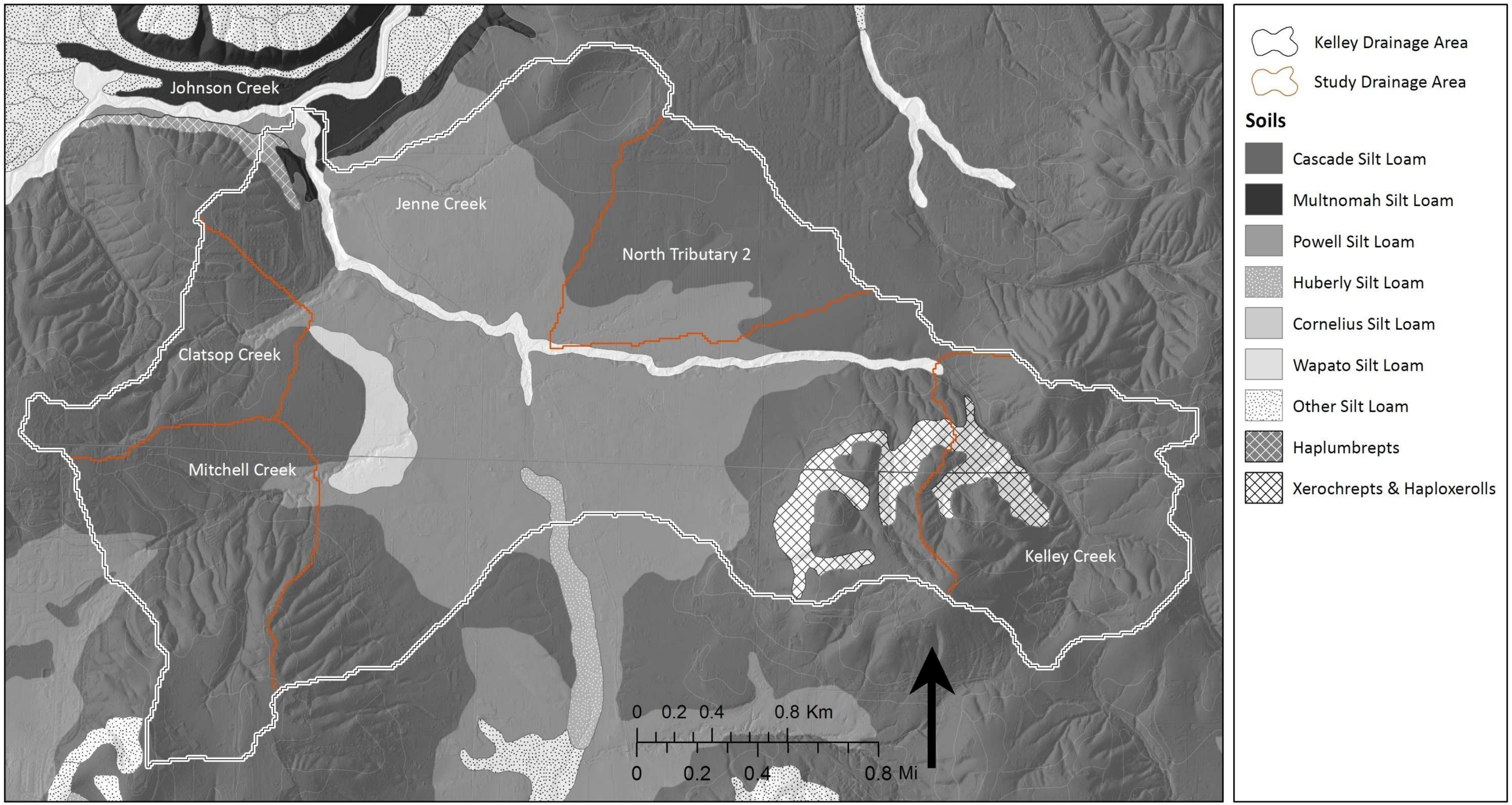
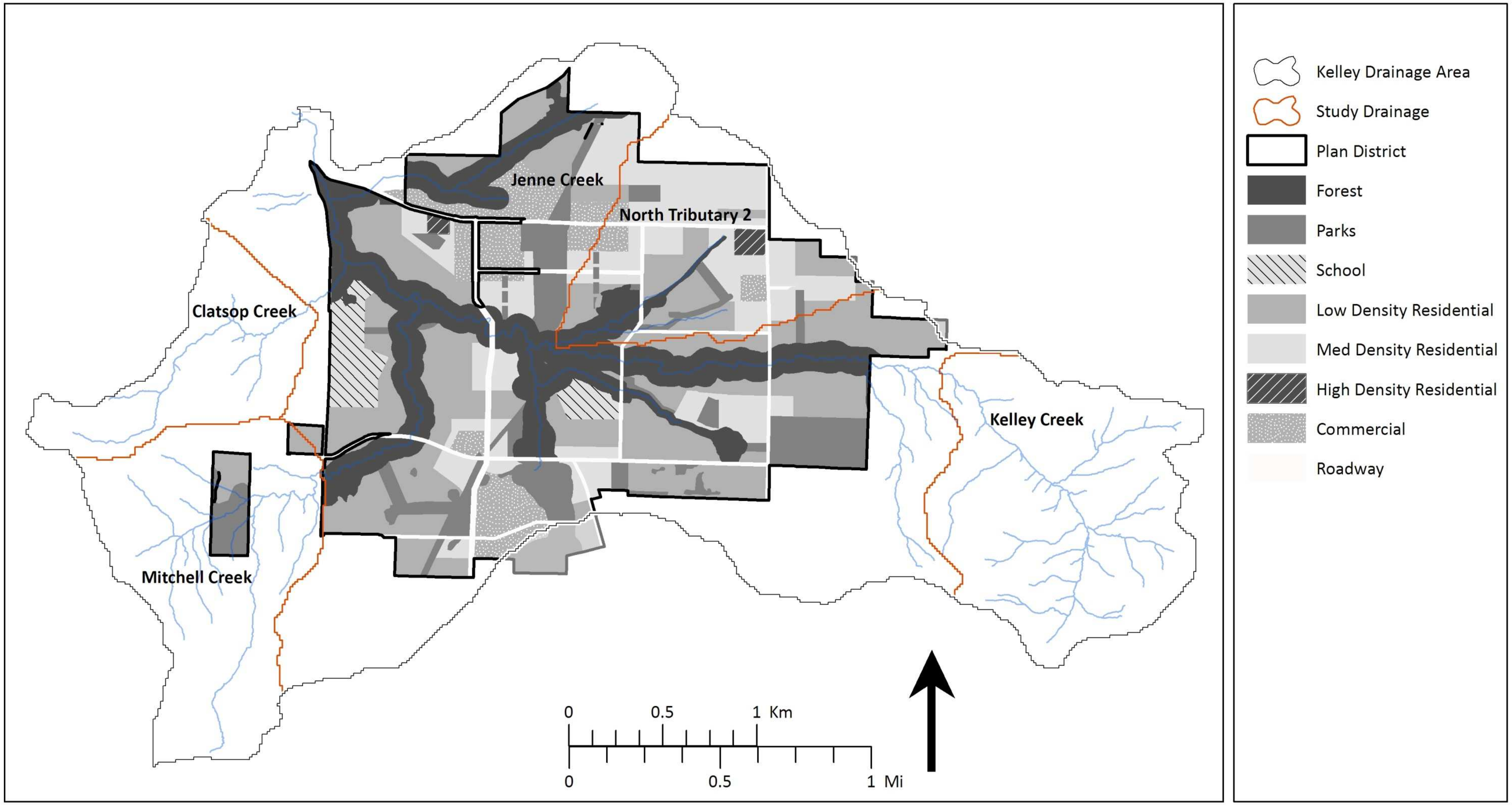


Figure 7. Future land use proposed by Pleasant Valley Planning District.



Earliest mapping of the Kelley Creek watershed occurred in 1854 by the General Land Office (Cartee 1854; Cartee 1855). These maps show the majority of Kelley Creek at that time covered by "burnt timber", with perhaps a small amount of coniferous forest on the eastern edge. Aerial photographs show most of the valley floor converted to agricultural production by 1935 with the surrounding hills forested. Photo records document hillside timber harvests in the watershed at least as late as the 1950s. These general land use patterns changed little through the last century, as illustrated in Figure 5. Changes that have occurred include increases in housing density throughout the watershed and a shift in agricultural focus from orchards, row crops and pastures to large-scale nursery plant production and Christmas tree farms.

Kelley Creek and its named tributaries flow from the remnants of six volcanic vents of the Boring Lava field (Allen 1975). These basalt buttes were formed during the Pleistocene, dating from less than one to 10 million years before present (Trimble 1963; Allen 1975; Madin 1994). The highest of these peaks reaches 344 m (1130 ft) in elevation. These basalts are overlain in areas by the Springwater Formation. Trimble (1963) describes the Springwater Formation as poorly sorted mudflow and alluvial gravel, cobble and boulder deposits originating from the Cascades. The Springwater Formation possibly reaches a maximum thickness of 225 ft and certainly exceeds 100 ft in places. The Springwater deposits were made during events throughout the Pleistocene up to 20,000 years before present (Madin 1994).

The upper main stem of Kelley Creek follows a fault at the interface between the Springwater and Boring Lava formations (Madin 1994). The upper 2800 m (9100 ft) of channel average 3.0% slope. With steeper slopes and basalt, Cascadian mudflow and coarse alluvium geologic materials, the channel of this section alternates between bedrock and coarse (50 mm) gravel. Second- and third-growth mixed coniferous and deciduous forest covers the hilltops surrounding Kelley Creek (Figure 5).

Mitchell Creek also originates from early Pleistocene Basalt of Mount Scott overlain by a Springwater Formation deposit (Trimble 1963; Madin 1994). The Springwater formation of Mitchell Creek has become deeply and densely dissected by fluvial erosion. Figure 3, the 1 m resolution hillshade image of the Kelley Creek watershed illustrates this weathering. The upper 800 m (2700 ft) of Mitchell Creek has an average slope of 4.3%. The stream bed in this upper portion of Mitchell Creek is gravel, like on the main stem of Kelley Creek, but in the range of 10-40 mm. During field reconnaissance, no exposed bedrock along the stream channel in Mitchell Creek was observed. The majority of land cover of the upper Mitchell Creek watershed is forest, which regenerated since being logged in the 1930s and 1950s.

Clatsop Creek is the steepest of the Kelley Creek tributaries, with the upper 1300 m having a slope of 8.3%. The stream channel is gravel above 120 m (400 ft) where the channel is accessible. Between 110 m (360 ft) and 195 m (310 ft) elevation, the channel's banks and bed are composed of clay, hardpan and silt. The 1936 aerial photo shows land along Clatsop Creek primarily in agriculture, with bits of forest adjacent to the channel (Figure 4). Most of this previously farmed land has since been abandoned to mixed forest and blackberry vines or developed to high density residential housing (Figure 5). Flow in Clatsop Creek is intermittent, perhaps due to summer withdrawals. Clatsop Creek is intermittently dry during summer dry periods.

The main valley floor of Kelley Creek meets the Boring Hills at approximately 120 m (400 ft) elevation. Alluvial silt deposits left by catastrophic floods occurring between 10,000 and 20,000 yr B.P. characterize the low relief valley floor (O'Connor, Sarna-Wojcicki, Wozniak, Polette and Fleck 2001;

O'Connor 2008). Today, this low gradient landscape hosts a variety of agriculture, including berries, nurseries and Christmas tree farms. The catastrophic flood silt deposits provide an unlimited supply of fine sediment to Kelley Creek and dominate the stream bank and bed materials throughout its middle section. The channel averages 0.62% slope as it drops 17 m (57 ft) over a distance of 2800 m (9300 ft). Both man-made impoundments and beaver dams create ponds along the channel on the valley floor. Between ponds, the stream has carved a steeply walled channel approximately 10 m deep. An inset floodplain above Kelley Creek's confluence with Northern Tributary 2 is apparent in the LiDAR hillshade (Figure 3).

Northern Tributary 2 is a low gradient tributary located on the valley floor, below 425 feet elevation. Its lower 870 m (2900 ft) the stream bed drops 1.5 m per 100 m horizontal distance. Landowners along this channel refer to it as a ditch, but it appears to be an historic, naturally occurring geographic feature visible on LiDAR and in 1936 aerial photography (Figures 3 and 4). At least one section of this tributary is currently impounded by a beaver dam. The free flowing sections have consolidated silt and clay bed and banks.

Jenne Creek was not sampled in this study, but contributes flow and sediment to Kelley Creek. One of the landowners along this tributary described the stream as having a 30 foot deep channel that would be unsafe to investigate. The 1 m resolution elevation shown in Figure 3 confirms this report. Below Foster Road, Jenne Creek's bed is 30 feet below the top of the bank. Figure 8 shows the channel in a similar condition in 1935, although the depth at that time is unknown. As its flow approaches Kelley Creek, Jenne Creek's channel crosses a terrace likely formed as the catastrophic Missoula Floods flowed through the Johnson Creek drainage-way (O'Connor 2008).

Figure 8. 1935 aerial of Jenne Creek and Kelley Creek confluence with Johnson Creek.

From about 1300 m (4200 ft) above its confluence with Johnson Creek, Kelley Creek follows a fault, flowing through a steeply walled (80% to 100% slope) canyon (Madin 1994). At the surface along this section are both areas of exposed basalt bedrock and coarse alluvium. In this section, the channel slope averages 1.6%. A mixed deciduous and coniferous forest covers most of this section of stream channel.

Poorly drained silt loam soils dominate the Kelley Creek drainage basin (Figure 6). Silt loam soil units making up 96% of the catchment area are underlain by a hardpan or fragipan with low permeability and poor drainage. These poorly drained soils become quickly saturated during the wet season. The Soil Conservation Service's soil reports for Multnomah and Clackamas Counties describe approximately 4% of the soils in the catchment as being well drained or moderately well drained (Green 1983; Gerig 1985). The well drained soils lie on uplands and steep escarpments.

Humans have directly and indirectly modified the stream channel in ways that affect sediment transport and storage. Dams, temporary impoundment structures and improperly aligned road crossing culverts throughout watershed impound water and obstruct sediment, increasing storage of fines that might otherwise be carried away in suspension and coarser materials that would be transported as bed load. Jenne Creek, for example, flows through a 375 foot section of pipe and appears in the profile shown in Figure 13 (d). The channel here was filled to allow for land development. The slope of the channel decreases as it approaches this pipe, indicating sediment accumulation above the pipe. A similar process of sediment storage occurs at road crossings along the main Kelley Creek channel at 4100 m (13,000 ft) from its confluence and on Mitchell Creek 2700 m (8800 ft) from its Kelley Creek confluence. The numerous ponds and dams along Kelley and Mitchell Creek impound sediments on the valley floor as shown in Figures 13 and 22. Since beaver populations decreased between 1800 and 1850, the man-made ponds may have replaced historical beaver ponds, resulting in little change in storage in the Kelley Creek channel.

Placement of fill adjacent to the stream increases sediment inputs. A property owner on the lower 600 m (2000 ft) of Mitchell Creek described placing fill dirt along the channel in order to extend the "usable" part of his property. In this same area, another landowner stores fill adjacent to channel. The magnitude and impact of anthropogenic earth movement along the stream channel is unknown. While this earth movement may increase sediment yield from the watershed, it may also contribute to a short term increase in storage within the channel. Channel erosion has also increased as people modify the hydrologic network and concentrate flows in ditches. At least one such ditch is causing head cutting along Mitchell Creek near the 2700 m road crossing.

While some human activities increase sediment flux to the channel, other activities remove sediment from the channel. One landowner along the valley floor section of Kelley Creek described dredging six feet of sediment from a recreational pond on his property following the storms of 1996. Channel hardening can eliminate bed and bank erosion in the lower section, reducing the sediment load. Between Johnson Creek and SE Foster Rd, Kelley Creek was lined by the Works Project Administration in the 1930s with riprap and concrete.

The Johnson Creek Watershed Council and the City of Portland have led efforts to reverse the impacts to Kelley and Johnson Creeks (City of Portland Oregon 2001; Storer 2003). Completed projects include removing riprap, dams and ponds, reconfiguring channel, and replacing culverts. Most of these efforts remove or redistribute sediment storage in Kelley Creek. In removing culverts or other impoundments, previously immobile sediment sometimes becomes mobile. One example of such increased sediment mobility occurred at the Southeast Foster Road crossing, 400 m (1320 ft) from the confluence. The culvert here was replaced with an open-bottomed arch in 2003 (Kesterson 2008). The elevation of the gravel stream bed inside this culvert has dropped approximately 0.5 m by summer of 2008.

In 1998, 1500 acres of Kelley Creek’s Pleasant Valley was incorporated in the urban growth boundary (Savage and Young 2006). As of 2006, the entire Kelley Creek watershed lies within the urban growth boundary (Metro 2006). This change led to a new planning district which covered most of the watershed

(Figure 7). Under the new land use plan, a 50 m wide strip of forest will be left on either side of major stream channels, but the valley floor will be developed.

Field Surveys

Observations and channel geometry sampling on the ground helped to identify major processes moving and storing mass on the landscape. Detailed field investigations at specific sites were stratified by subarea. Areas for study focus included Kelley Creek headwaters, Mitchell Creek, Clatsop Creek and Northern Tributary 2. Because most of the property in this drainage is privately owned, property access constrained sampling locations. Metro, the greater Portland regional government, owns properties in two of the subareas of interest, on Scouter Mountain in the upper end of Mitchell Creek and along Rodlun Road on the upper reaches of Kelley Creek. Still, a few other public properties exist near the confluence. One of these properties, owned by the City of Portland, has recently been modified through a restoration project. Another property includes part of the canyon along the lower channel and along Clatsop Creek. Many landowners cooperated in this research effort and granted permission to access the stream channel on their property. In total, sixteen points along the stream channel were sampled. Figure 9 shows the sample locations and contributing areas for some samples.

At each sample site, qualitative site characteristics were documented. Often, private landowners shared their experiences and observations living along the stream. These discussions provided information about the historical conditions and common ways that the channel has been modified by humans. Many of these modifications were also apparent by visual inspection. Observed channel modifications included a small dam, bank armoring, road crossings, filling and grading adjacent to the channel, and pond excavation and dredging on or adjacent to the channel. Multiple ponds are present on and adjacent to the channel on the valley floor. Ditches along roads have extended and complicated the drainage system and are relatively new sources of sediment to the channel. Other observations made at each site included condition, age and type of riparian vegetation.

Cross section shape

Channel cross section shape was measured perpendicular to the channel at each sample location using a rotating laser level and laser detector attached to a survey rod. A tape was strung across the channel from the left to right bank (facing downstream). Elevations were measured approximately every 0.5 meter or whenever the slope changed. Every attempt was made to locate cross sections along long, straight riffles. The cross sectional transect usually extended a meter or more above the top of the active channel bank. On occasion, these conditions were not met because of limitations of instrument placement, property access or personal safety. In most cases, the measurements capture the width of the floodplain and always the shape of the active channel.

In this study, “bankfull” refers to the point at which the flows reach the floodplain and stage increases little with an increase in discharge. The point of bankfull depth was, in general, the top of the lowest bank. In extraordinarily large channels, changes in bank slope were used as the bankfull mark.

Particle size distributions

Particle size distributions sampled at each cross section followed Wolman's method (1954). The intermediate axes of 100 particles from the surface of the active channel were measured in transects near the cross section. Where the stream bed was composed of silt or sand, particle size distributions were estimated visually.

Characterization of sample subcatchments

ArcMap with the Arc Hydro data model were used to delineate the contributing areas for each of the sample sites. Input data included 9 m elevation grid from USGS seamless data distribution system (2008) and stream line. Arc Hydro generated a polygon for the contributing area of each sample site.

City of Portland provided multispectral aerial images that had been classified into a raster of four land surface types: water, loose soil, impervious surface and vegetation (City of Portland Oregon 2004). The vegetation class did not distinguish between agriculture, forest and landscaping. To distinguish these vegetation types, polygons were drawn around general land use zones visible on the 2005 aerial photograph. A grid cell with vegetation classification within a forest polygon was considered forest, within an agricultural polygon, agricultural vegetation and within a residential, industrial or mixed polygon, miscellaneous vegetation. All non-vegetation surface classes maintained their land surface classification regardless of the land use zone polygon. The miscellaneous vegetation was in areas with mixed land use and mainly would be horticultural landscaping. The sum of each of the three non vegetation and three vegetation classes of cells within the contributing area polygons provided the proportion of land use types above each sample location.

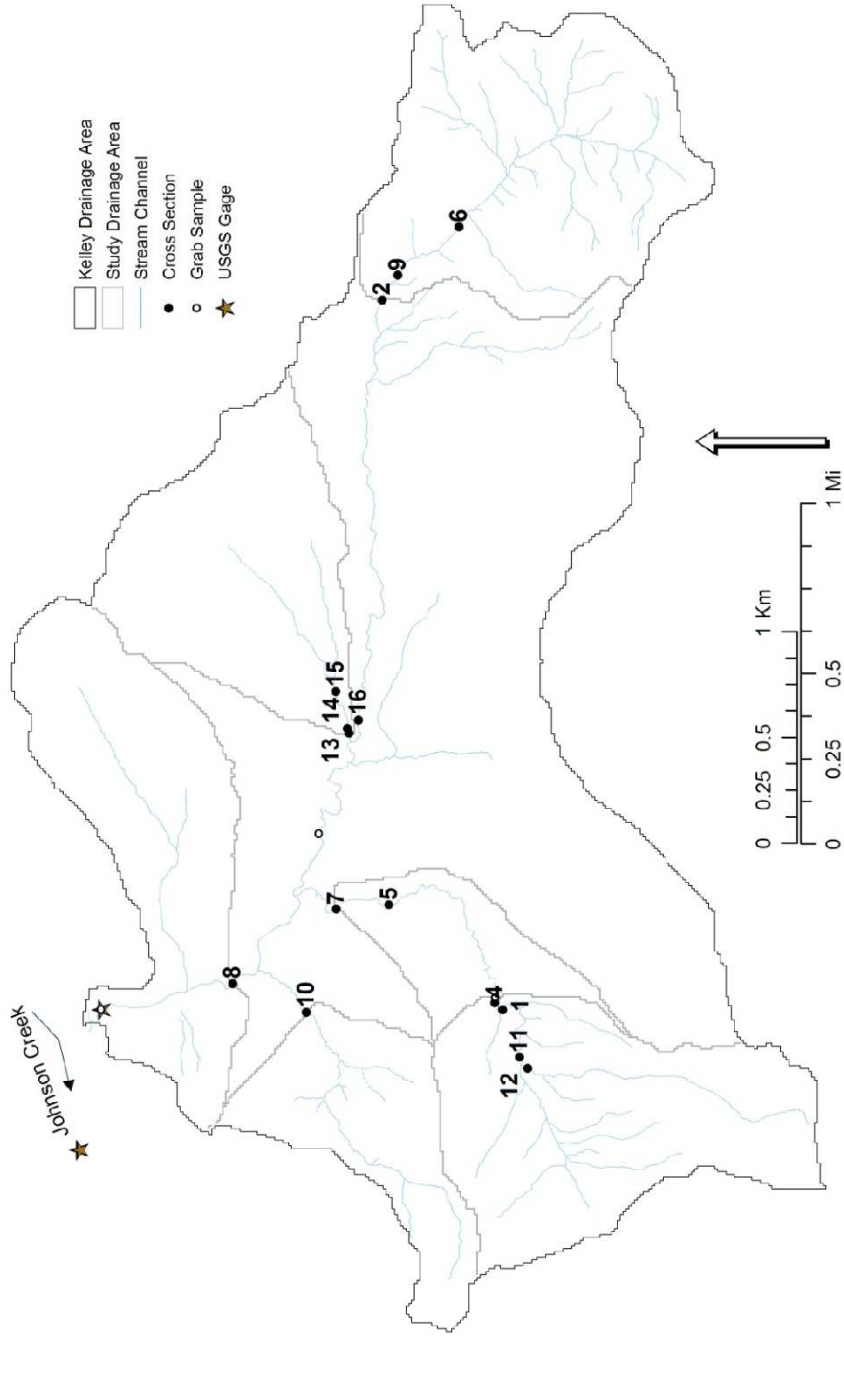
Longitudinal Profile

The longitudinal profile provides information regarding generalized slope throughout major tributaries of the Kelley Creek watershed. Light Detection and Ranging (LiDAR) elevation data with 3 foot resolution was used to generate a stream channel longitudinal profile. Metro, the greater Portland regional government, provided the LiDAR. Deanna Foster with the City of Gresham shared a stream layer based on this same LiDAR data. Lines of major tributaries were adjusted to match the lowest points on the LiDAR. This high resolution elevation data and channel line allowed development of an approximate longitudinal profile for the major tributaries of the Kelley Creek system. This longitudinal profile emphasizes the distinct areas of the watershed based on slope and its associated stream power.

Suspended and Dissolved Solids

Suspended and dissolved sediment rating curves were developed using grab samples collected by the author, the City of Portland and USGS. Grab samples were collected at three locations, shown as open circles on Figure 9; on the main stem of Kelley Creek at 53 m (175 ft) and 343 m (1125 ft) from its confluence with Johnson Creek, and on the Mitchell Creek tributary, 998 m (3275

Figure 9. Sample locations and contributing areas.



ft) from the Kelley and Johnson Creek confluence. The samples were collected during and following spring storms of 2008.

Samples were collected in 250 ml containers that had been washed in an acid bath and soaked in deionized water. In order to integrate inhomogeneous sediment loads throughout the water column, the samples were taken approximately in the thalweg at integrated depths without disturbing the channel bottom. Most sample points were replicated three times, except during highest flows when the water had a visibly high sediment load. Laboratory analysis followed guidelines in *Standard Methods for Evaluating Water and Wastewater,* 2540D (Eaton, Clesceri, Rice, Greenberg and Franson 2005). After the sample volume was measured, the samples were filtered with cleaned, dried and tared Whatman brand glass fiber filters, type GF/F. According to Whatman specifications, these filters retain 98% of particles 0.7 µm. After filtrations, the filters and solids dried in an oven at 105°C for 3-5 days, and then cooled in a desiccator overnight before being weighed again. Total suspended solid concentrations were calculated with equation 1.

$$C_s = \frac{M}{V} \qquad (1)$$

C_s is concentration in mg/L (1 mg/L = 1 g/m^3), M is mass of suspended sediment in sample in milligrams and V is sample volume in liters, before filtration.

The dissolved load in each sample was approximated by measuring conductivity, C, (µS/cm) in the laboratory after filtration and using equation 2 to estimate specific conductance (SC) at a standard temperature of 25°C.

$$SC = \frac{C}{1 + TC(T - 25)} \qquad (2)$$

where TC is a temperature coefficient (0.02) and T is the temperature at which conductivity was measured. The relationship between SC and C_d is approximated with equation 3 (Todd and Mays 2005).

$$C_d(mg/L) = SC\ (\mu S/cm) \cdot \frac{1\ (mg/L)}{1.56\ (\mu S/cm)} \tag{3}$$

Additional samples were collected and analyzed by the City of Portland (the City) in partnership with the USGS from November 2007 to November 2008. These samples were also analyzed according to the *Standard Methods* 2540D (Eaton, Clesceri et al. 2005). No conductivity measurements were made with these samples and dissolved solids were not measured.

The suspended sediment and dissolved solid concentrations from samples collected at the USGS gage on SE 159th Ave, combined with flow discharge values at that location, provide an estimate of annual suspended and dissolved yield from Kelley Creek. Samples from this location, plus two subcatchments locations taken sequentially throughout a single storm event provide an estimate of the relative wash load contributions from each study area.

Land Use Changes and their effects

City of Portland provided multispectral aerial images that had been classified into a raster of four land surface types: water, loose soil, impervious surface and vegetation (City of Portland Oregon 2004). The vegetation class did not distinguish between agriculture, forest and landscaping. To distinguish these vegetation types, polygons were drawn around general land use zones visible on the 2005 aerial photograph. A grid cell with vegetation classification within a forest polygon was considered forest, within an agricultural polygon, agricultural vegetation and within a residential, industrial or mixed polygon, miscellaneous vegetation. All non-vegetation surface classes maintained their land surface classification regardless of the land use zone polygon. The miscellaneous vegetation was in areas with mixed land use and mainly would be horticultural landscaping. The sum of each of the three non vegetation and three vegetation classes of cells within the contributing area polygons provided the proportion of land use types above each sample location.

The trajectory of land use changes occurring over the period of historical record were inferred by comparing aerial photographs over time. The General Land Office maps from the 1850's provide the earliest records of watershed land cover conditions (Cartee 1854; 1855). These maps describe general vegetation type, topography and soils. 1936 aerial photographs provided a basis for historical land use conditions post-European settlement. Interim aerial photographs document timing of forest harvests. Comparing the 1936 and 2005 photo sets, identified major land use trajectories were identified: (1) historically logged and currently forested, (2) historically logged and reforested with increasing residential development, (3) historically agricultural with increasing residential development, and (4) historically agricultural with some forest and becoming increasingly forested and high density residential. Land use was a primary focus, so these distinct land use patterns guided sampling decisions. The cross section samples were stratified by distinct land use trajectory zones.

Discharge

The United States Geological Survey operates a discharge gage near the Kelley Creek confluence, at the lowest suspended sediment grab sample location. This gage has been in operation since 2000, giving eight years of record. The short period of record is one of several sources of error associated with this gage.

Beavers built a dam downstream of the gage, which has impounded water up to the gage during high flows since summer of 2007.

The instantaneous flow measurements for the period of record were plotted as annual flow cumulative duration curves. Proportion of time exceeded for the annual peak flow was calculated using equation 4.

$$P(Q_i) = \frac{i}{n+1} \tag{4}$$

where *P* is the proportion of time flow exceeded Q_i, with rank *i* in *n* number of records for a given year. Flows were ranked highest to lowest from 1 to n. The median annual peak discharge has a two year return interval. The median annual flow duration curve served as the basis for annual sediment transport calculations (Dingman 2002).

For each sample site, the annual peak discharge with two year return interval was estimated based on the proportion of the sample's upstream contributing area compared to the contributing area above the discharge gage.

$$Q_{2s} = \left[\frac{A_s}{A_g}\right] \mathrm{Q}_{2g} \tag{5}$$

where Q_{2s} and Q_{2g} are the discharges (m^3/s) at the sample and gage locations, A_s and A_g are the contributing area (ha) of the sample site and gage site. This method assumes that all areas in the catchment contribute equally to stream flows.

Depth, area of Q_2

The velocity *U* (m/s), area *A* (m^2) and wetted perimeter P_w (m) of a cross section at a given discharge vary depending on channel efficiency. Channel resistance includes friction between the water and solid banks and bed. Channel planform, bedforms and obstructions also cause flow resistance by increasing turbulence (Hey 1979).

To reduce dependence on the planform, bedforms and obstructions, the straightest possible sampling locations were selected, which were ideally away from obstructions but along riffles. Channel resistance was then assumed to depend mainly on skin friction and depth. Areal pebble counts provided a basis for estimating bed roughness. The cross sectional channel geometry was measured directly in a survey and used to calculate hydraulic radius for a given discharge.

Hey's (1979) flow resistance equations (6 and 7) for gravel bed rivers estimates mean velocity at a given depth of the surveyed cross sections.

$$\frac{1}{\sqrt{f}} = 2.03\log\left(\frac{aR_h}{3.5D_{84}}\right) \tag{6}$$

where

$$a = 11.1 \cdot \left(\frac{R_h}{h_{\max}}\right)^{-0.314} \tag{7}$$

and h_{max} is the maximum depth (m) from the bed to the water surface and i% of the particles have median diameter smaller than D_i (m). R_h (m) is the geometric parameter hydraulic radius, calculated with equation 8.

$$R_h = \frac{A}{P_w} \tag{8}$$

where P_w is simply the length (m) of submerged bed and banks, measured perpendicular to flow. Hey's (1979) equation is based on the Darcy-Weisbach friction factor, f, which is dimensionless.

$$f = \frac{8gR_hS}{U^2} \tag{9}$$

Substituting for f as defined in equation 9 into equation 6 gives

$$U = 5.75\sqrt{gR_hS}\log\left(\frac{aR_h}{3.5D_{84}}\right) \tag{10}$$

Volumetric discharge rates (m^3/s) are simply the product of the mean velocity calculated with equation 10 and cross sectional area of flow. Depths (m) and the associated shear stresses were calculated iteratively using Solver in Microsoft Excel and solving for *A* that gives the target Q.

Shear stress of Q_i at sample sites

In order for particles in the bed to move, the forces exerted by the flow must equal or exceed those required to move a given particle. Estimates of critical shear stress, the force required to move a given particle, are based on Shields' parameter, θ (Shields 1936), where

$$\theta = \frac{\tau_o}{(\rho_s - \rho)gD} \tag{11}$$

and τ_o is the boundary or skin friction shear stress (N/m^2) at the given discharge, ρ_s and ρ are the densities (kg/m^3) of sediment and water, respectively, g is acceleration due to gravity (m/s^2) and D is the sediment diameter (m). The stability threshold for Shield's equation, θ_c occurs when τ_o equals τ_c. The value of θ_c varies as a function of critical boundary Reynolds number, R_{e*} (Shields 1936; Buffington and Montgomery 1997; Kaufmann, Faustini, Larsen and Shirazi 2008).

$$R_{e*} = \frac{U_{*c}k_s}{v} \tag{12}$$

where U_{*c} is the shear velocity at initial motion (m/s), defined as

$$U_{*c} = \sqrt{\frac{\tau_c}{\rho}} \tag{13}$$

and k_s is a length scale (m) and assumed equal to D_{50} and *v* is kinematic viscosity of water (m^2/s).

Table 1. Equations used for estimating θ_c and the sediment diameters and Reynolds numbers of the data on which the equations are based (Buffington and Montgomery 1997).

Equation	*D_{50} (m)*	*R_{e*}*	*Equation #*
$\theta_c = 0.035\left(\frac{D_i}{D_{50}}\right)^{-0.94}$	0.054	6744	(14)
$\theta_c = 0.054\left(\frac{D_i}{D_{50}}\right)^{-0.67}$	0.058	8643	(15)
$\theta_c = 0.086\left(\frac{D_i}{D_{50}}\right)^{-0.90}$	0.021	2445	(16)

Equation (14) from Parker and Klingeman (1982).

Equation (15) from Ashworth and Ferguson (1989).

Equation (16) from Wathen, Ferguson, Hoey and Werritty (1995).

D_i and D_{50} are sediment diameter which i% and 50% are smaller than.

To use Shields' parameter to estimate the shear stress or flow depth at incipient motion, θ_c must be parameterized in relation to bed material and channel properties. The author is aware of no sediment budget studies that match Kelley Creek in its set of conditions, R_{e*}, sediment size distributions and flows. Three separate equations give approximations to provide a range of possible critical shear stress values for sampled sites in Kelley Creek, and are described in Table 1. Critical shear stress is found by substituting θ with θ_c from equations 14, 15 and 16 into equation 11 and solving for $\tau_o=\tau_c$.

Skin friction shear stress is the product of density of water ρ (kg/m^3), depth or hydraulic radius R_h (m), and energy slope S (Lorang and Hauer 2003).

$$\tau_o = \rho g R_h S \tag{17}$$

Although incipient motion is actually a stochastic event, bed motion is assumed to occur when τ_o exceeds τ_c.

Relative Bed Stability

Flow competence refers to a given flow's ability to move grains on the stream bed (Kondolf and Piegay 2003; Lorang and Hauer 2003). Bedload transport rates are sensitive to the frequency of competent flows, those that have the power to initiate bed material motion. This assumption is the basis of the relative bed stability (RBS) concept. In general, RBS compares stream power to the particle sizes that make up the stream bed (Lorang and Hauer 2003). A relatively unstable stream bed moves frequently because the stream power frequently exceeds that required to initiate motion. Conversely, when the flow required to move the average bed particle is rarely exceeded, that stream bed is relatively stable. Applying a relative stability index to the Kelley Creek system can highlight areas that are more or less sensitive to changes in flow regime that could result from urban development. Putting together the depth at given discharges, skin friction shear stress and flow duration curves, threshold discharges and their frequency are estimated.

Kaufmann, Faustini, Larsen and Shirazi (2008) used a RBS index ratio of particle diameter at the sample site to particle diameter moved by bankfull flow. At most of the sample sites in the present study, the bankfull discharge recurrence intervals vary significantly from one to another due to channel incision. Instead of using the bankfull flow as the reference flow condition, the relative bed stability index here uses the discharge with a two year recurrence interval. The RBS is calculated as

$$RBS = \frac{\tau_{Q2}}{\tau_c} \tag{18}$$

where τ_{Q2} is the shear stress of the discharge with a two year return period and τ_c is the critical shear stress. RBS values approaching one indicate channel stability whereas values increasing in value decrease stability.

Annual sediment load from bed material

Sediment transport capacity is the amount of sediment transported by a stream, given flow magnitudes and durations (Montgomery and Buffington 1997; Montgomery and MacDonald 2002). Bed load transport rates (volume per time) for given flows can be estimated with the Meyer-Peter and Muller equation (MPM), in the form cited by Kondolf and Piegay (2003),

$$q_b^* = \frac{q_b}{\left[\left(\frac{\rho_s - \rho}{\rho}\right) g D_m^3\right]^{1/2}} \qquad (19)$$

and

$$q_b^* = 8(\theta - 0.047)^{3/2} \qquad (20)$$

where q_b is the sediment discharge rate (volume per time per unit bed width, $m^3 \cdot s^{-1} \cdot m^{-1}$) and D_m is the arithmetic mean sediment diameter (m). When equations 9 (for f), 11 (for θ), 17 (for τ_o), 19, and 20 are combined, the sediment discharge is

$$q_b = 8\left[\left(\frac{\rho R_h S}{(\rho_s - \rho) D_m}\right) - 0.047\right]^{3/2} \cdot \left[\left(\frac{\rho_s - \rho}{\rho}\right) g D_m^3\right]^{1/2} \qquad (21)$$

This commonly used form of MPM omits the bed form correction of the original MPM equation. Implicitly, this equation assumes that for a plane bed, the bed form correction $K_b/K_s = 1$.

For comparing the volumetric bedload transport rates to measured rates presented in literature, volumes were converted to estimated mass in metric tons. Equation (24) converts the volumetric ($m^3 \cdot km^{-2} \cdot yr^{-1}$) bedload yield to mass

($Mg \cdot km^{-2} \cdot yr^{-1}$). This calculation is based on the assumption that the bedload is fine gravel with porosity (ϕ) of 0.34 and density of 2650 kg/m^3.

$$q_b(Mg) = q_b(m^3) \cdot (1 - \varphi) \cdot \ \rho_s \left(\frac{kg}{m^3}\right) \cdot \frac{1}{1000} \left(\frac{Mg}{kg}\right) \qquad (22)$$

Future hydrologic scenarios

At each sample location, sediment discharge rates estimated by MPM were coupled with the median annual flow duration curve to estimate annual sediment yield under existing conditions. Sediment discharge rates were also estimated for alternative hydrologic scenarios that could result from more intensive development in the Kelley Creek basin.

Three hypothetical hydrologic scenarios were developed for this study, each based on a different assumption about future conditions and stormwater management. All scenarios increased the total annual runoff from Kelley Creek by 100 mm, assuming reduced evapotranspiration with reduction in vegetation cover. Studies have shown increases between 20 mm and 300 mm for removing 50% of the vegetation within a watershed (Dunne and Leopold 1978). The actual runoff increase depends on the climate and the amount and type of vegetation replaced by impervious surfaces. Timing and runoff efficiency determine how the increased runoff changes the shape of the individual storm hydrograph including its peak and peak duration. Scenario 1, an unmitigated scenario, doubles the median annual peak discharge and increases flow magnitudes exceeded 2.5% of the time under predevelopment conditions. Scenario 2 assumes that stormwater management efforts would maintain the existing median annual peak discharge for longer duration during storms, increasing the duration of this discharge to 1% of the time from its original duration of 0.01%. Like scenario 1, under scenario 2, discharge magnitudes increased for flows which were exceeded 2.5% of the time in the existing flow duration curve. Scenario 3 increases the frequency of discharges which were exceeded in the period of record between 0.54% and 50% of the time. The flows under scenario 3 represent an increased response to small storms and storms occurring following dry periods. Under all three scenarios, summer low flows remain the same as in existing conditions. Since the low summer flows generally do not transport sediment, changing summer low flows would have little impact on sediment yield.

Uncertainty of bedload transport rates was quantified using a Monte Carlo simulation in a Microsoft Excel spreadsheet (Green 2009). The spreadsheet requires input of the range of stochastic parameters including Manning's n, θ_c and grain size. Simulations are run 1000 times based on the expected values and ranges of the input parameters. The Monte Carlo simulation provided a standard deviation to determine a 90% confidence interval for the calculations made with Meyer-Peter and Muller's equations (19) and (20) integrated over the flow duration curves.

RESULTS

Hydrologic Patterns

Discharge at the Kelley Creek USGS gage at SE 159th Avenue ranges between 0.0005 m^3/s to 7.0 m^3/s (2.1 mm/hr) for the period of record 2001 to 2007 (Figure 10). Median Annual peak discharge over the period of record was 6.1 m^3/s (1.8 mm/hr) while 99% of duration of the median annual curve does not exceed flows of 3.1 m^3/s (0.93 mm/hr).

Figure 10. Flow duration curve for water years 2001 through 2007, from measurements at USGS gage at SE 159th bridge.

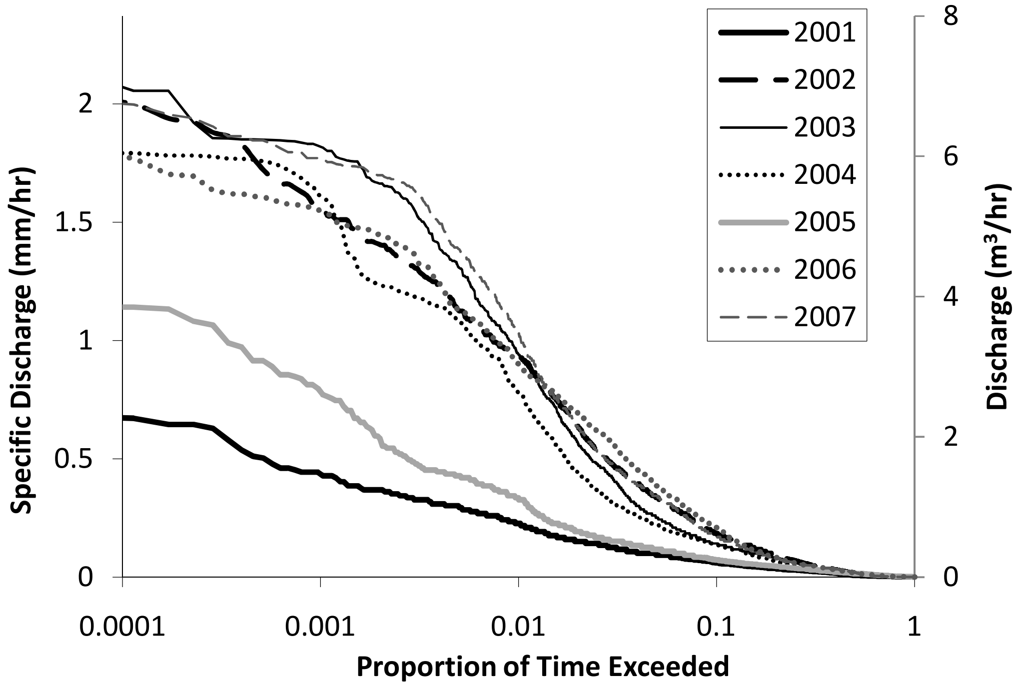
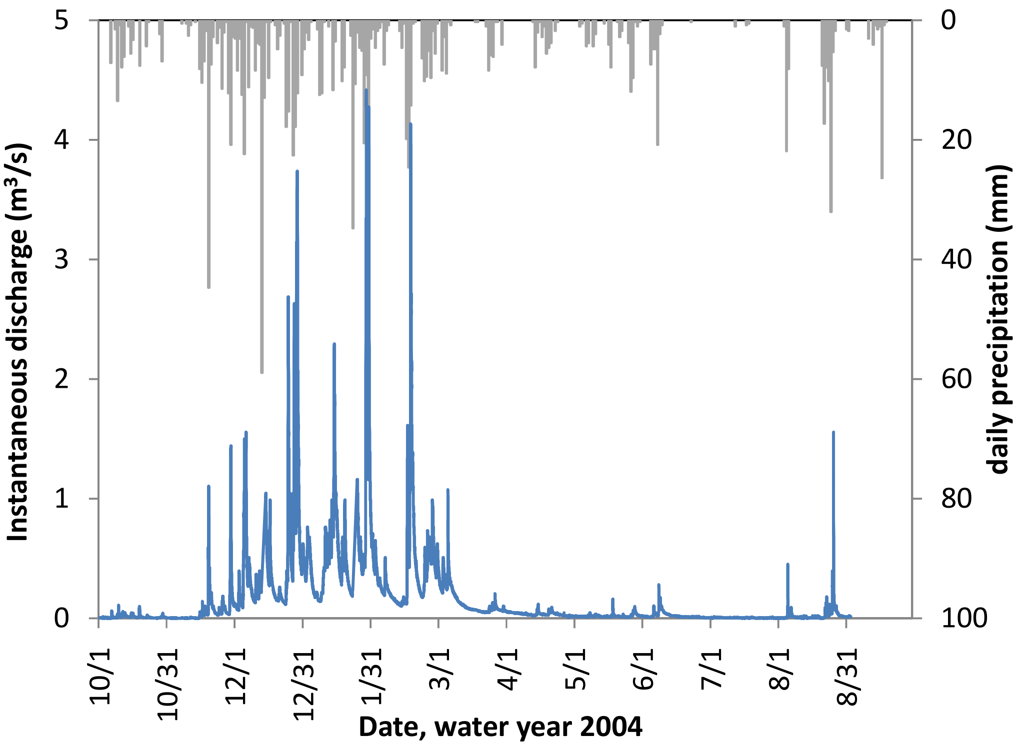


Figure 11. Hydrograph of Kelley Creek for water year 2004.



Kelley Creek's flows reflect the typical wet winters and dry summers of Northwest Oregon (Figure 11). Once the watershed reaches wet conditions in December, Kelley Creek responds quickly to storms through March. Discharges respond little to moderate summer storms with dry antecedent conditions. During the fall wetting up period, some of the most intense storms occur while discharges remain moderate. Extreme stream discharges occur following winter or spring storms.

Channel and Site Characteristics

Table 2. Channel shape, channel slope, mean basin slope and sediment diameters at sample sites on Kelley Creek, listed by tributary, with largest contributing area first.

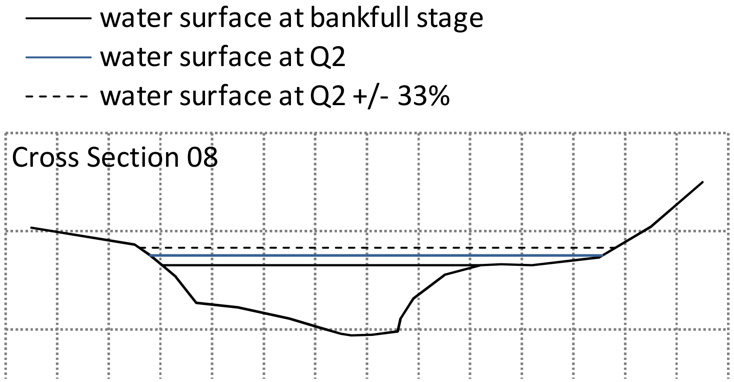
Shape (Scale: 1 rectangle = 1 m x 1 m)	**Sample elevation (ft)**	**Channel slope (%)**	**Mean Basin Slope (%)**	**Basin area (Ha)**	**$D_{16}/D_{50}/D_{84}$ (mm)**
Kelley Creek main stem					
	285	1.4%	16%	1083	24/72/150

Table 2. (Continued)

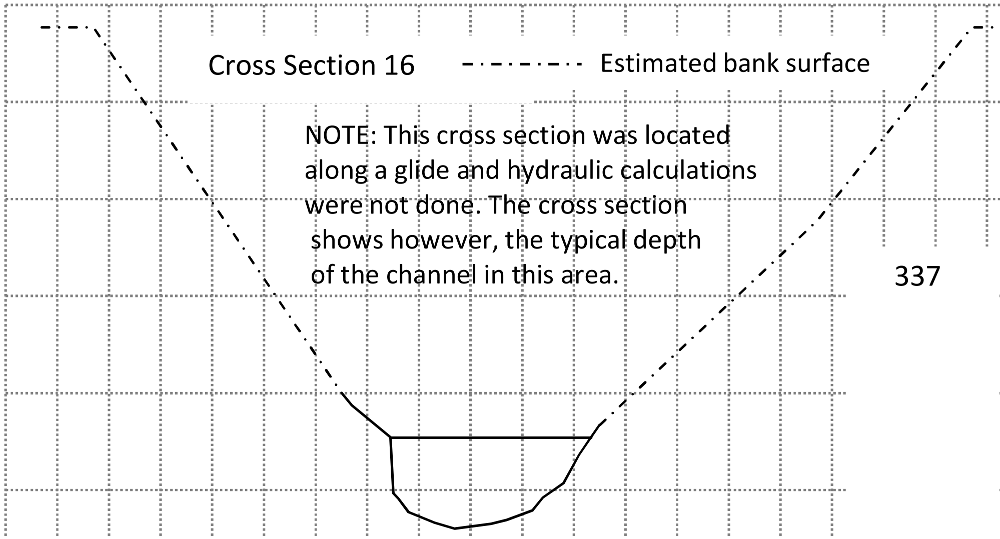
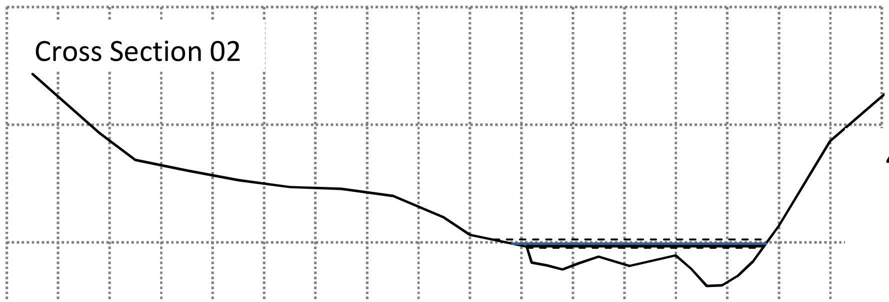
Shape (Scale: 1 rectangle = 1 m x 1 m)	Sample elevation (ft)	Channel slope (%)	Mean Basin Slope (%)	Basin area (Ha)	$D_{16}/D_{50}/D_{84}$ (mm)
	337	0.5%[b]	25%	298	0.1/1/2[a]
	462	3.4%	29%	174	18/53/110

Table 2. (Continued)

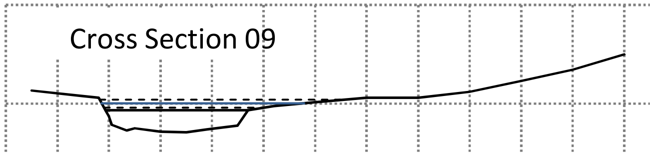
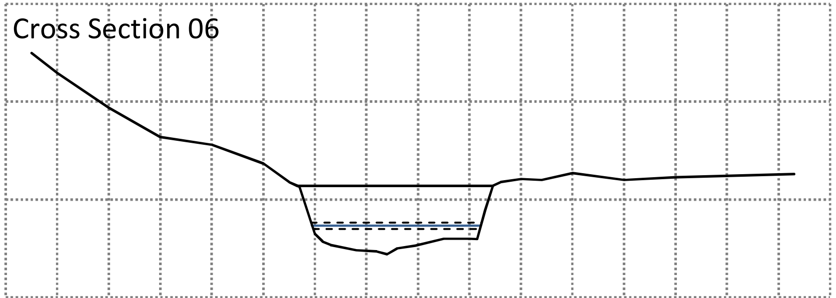
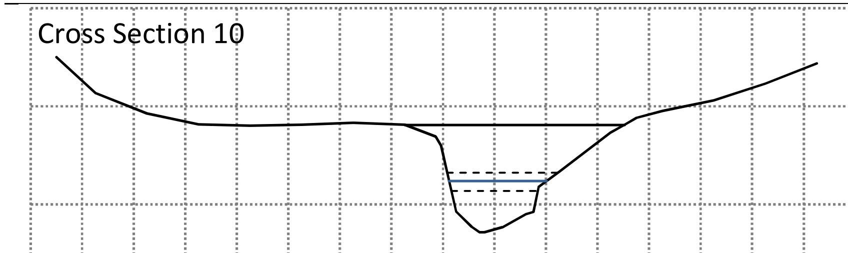
Shape (Scale: 1 rectangle = 1 m x 1 m)	Sample elevation (ft)	Channel slope (%)	Mean Basin Slope (%)	Basin area (Ha)	$D_{16}/D_{50}/D_{84}$ (mm)
	483	2.8%	29%	166	17/50/121
	542	3.8%	27%	149	16/40/111
Clatsop Creek					
	333	0.2%	18%	79	Silt, mud-stone and cohesive clay

Table 2. (Continued)

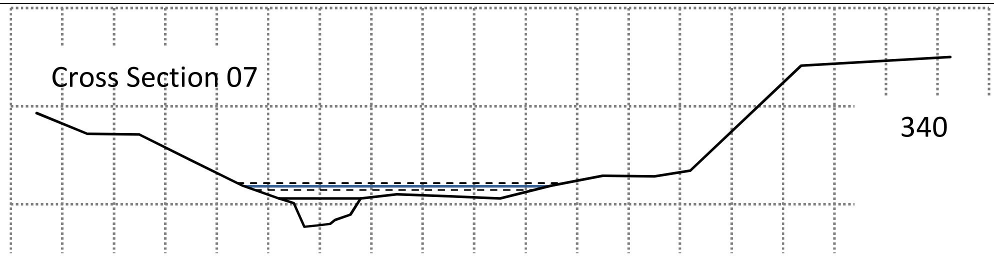
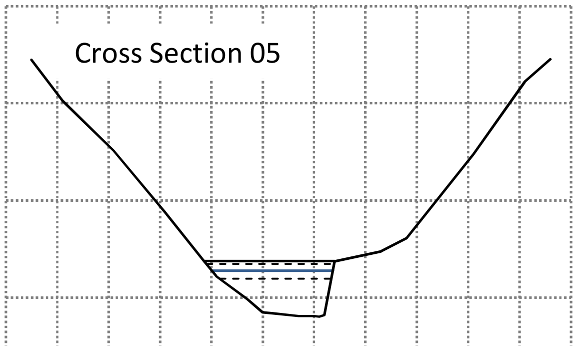
Shape (Scale: 1 rectangle = 1 m x 1 m)	Sample elevation (ft)	Channel slope (%)	Mean Basin Slope (%)	Basin area (Ha)	$D_{16}/D_{50}/D_{84}$ (mm)
Mitchell Creek					
	340	0.9%	16%	202	1/6/14
	350	0.7%	17%	192	9/23/33

Table 2. (Continued)

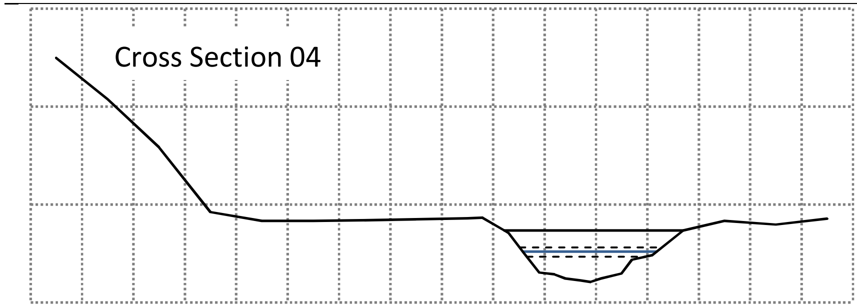
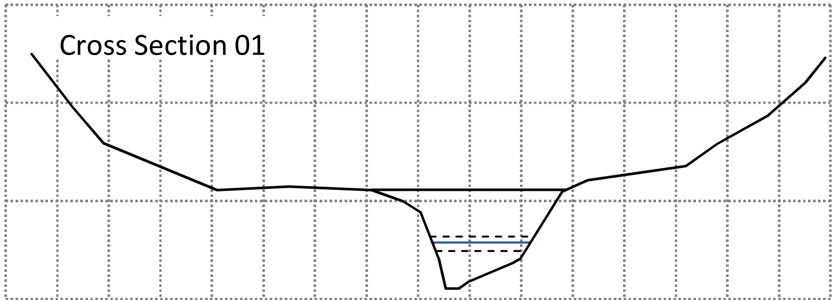
Shape **(Scale: 1 rectangle = 1 m x 1 m)**	**Sample elevation (ft)**	**Channel slope (%)**	**Mean Basin Slope (%)**	**Basin area (Ha)**	**$D_{16}/D_{50}/D_{84}$ (mm)**
Mitchell Creek (Continued)					
	383	0.2% [b]	19%	155	0.1/1/2[a]
	384	0.66%	19%	153	1/4/8

Table 2. (Continued)

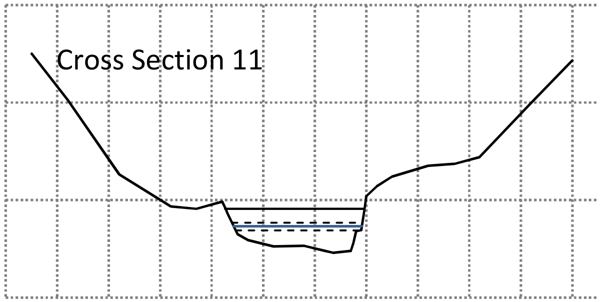
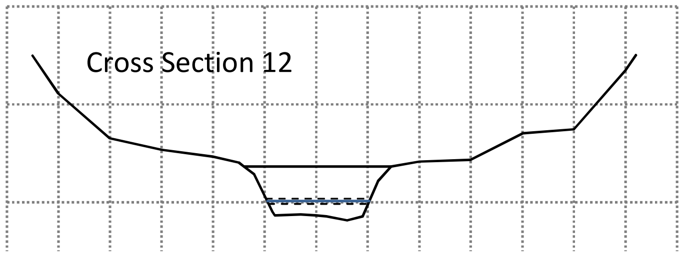
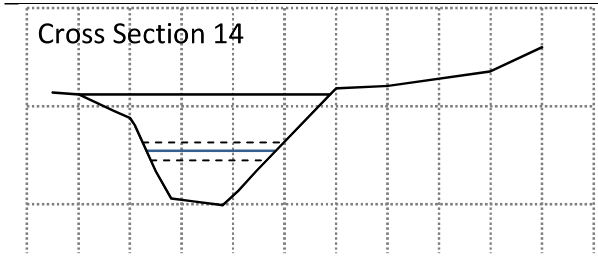
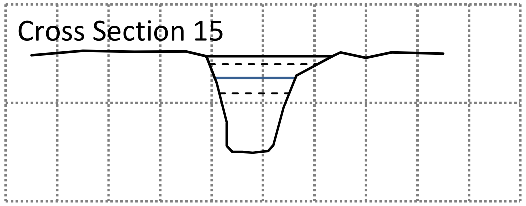
Shape (Scale: 1 rectangle = 1 m x 1 m)	**Sample elevation (ft)**	**Channel slope (%)**	**Mean Basin Slope (%)**	**Basin area (Ha)**	**$D_{16}/D_{50}/D_{84}$ (mm)**
Mitchell Creek (Continued)					
	398	1.6%	19%	121	8/20/32
	404	2.0%[c]	20%	49	8/18/62

Table 2. (Continued)

Shape (Scale: 1 rectangle = 1 m x 1 m)	Sample elevation (ft)	Channel slope (%)	Mean Basin Slope (%)	Basin area (Ha)	$D_{16}/D_{50}/D_{84}$ (mm)
Northern Tributary 2					
	336	0.1%	7%	126	0.1/1/2[a]
	346	0.04%	7%	119	Cohesive siltstone

a. size distribution of sediment estimated visually
Slope measured with laser level and surveying rod and tape, unless otherwise noted next to value, as described below:
b. estimated from LiDAR longitudinal profile
c. measured with clinometer

Table 2 summarizes the results of channel geometry and areal sediment sample size fractions, as surveyed during field investigations, and basin slope as determined with a 9 m digital elevation model and sample elevation as derived from LiDAR data in GIS. Site descriptions in Table 3 provide contextual observations made during site visits.

Table 3. Sample site descriptions.

Site	Riparian	Local conditions
Kelley Creek Main		
08	Mixed forest	• Bedrock in channel below the sample
16	Grass fields, blackberry	• 42 m below culvert • 50 m below beaver dam and extensive pond complex • Fill on surface above top of bank? • Landowner “cleans” channel?
02	Left bank mixed forest approximately 70 years old. On right bank, younger Douglas fir (<20 cm diameter). Blackberry along bank.	• 90 m below culvert. • Part of channel is bedrock.
09	Mixed forest	• 75 m above culvert. • Road parallels channel. Road prism slope starts at 20 m from top of bank
06	Mixed forest 80 years old.	• 70 m below culvert • Bedrock sections of channel above and below sample site • Tire embedded in bank at cross section.
Clatsop Creek		
10	Narrow strip mixed forest. Beyond that on left bank housing development and on right bank grassy field.	• 140 m above culvert • Cohesive clays along bed intermittent with silts.

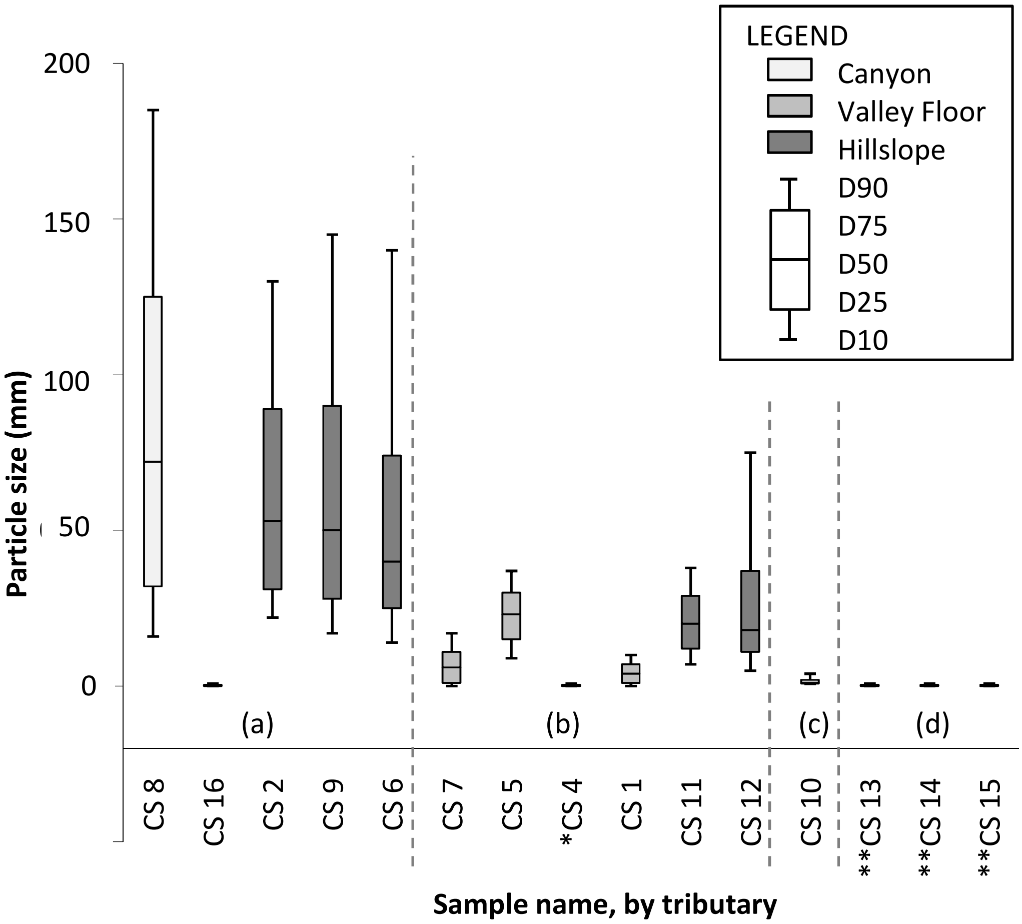
Table 3. (Continued)

Site	Riparian	Local conditions
Mitchell Creek		
07	Grass and exposed dirt at top of banks. Below sample are thick blackberries and large alder patch.	• Pile of fill dirt stored within 25 m of channel. Above site a steel plate used to impound a pond.
05	Lawn and gravel shop yard. A few big leaf maples along stream channel.	• 28 m downstream from culvert • Rip-rap, railroad ties, concrete placed at top of bank for 100 m below culvert • Fill placed in channel to extend area on top of bank. Dry ravel and bank slumping observed in filled area. • At bottom of 100 m section, a large concrete block (ecology block). Immediately below block is a pond where fine sediment has accumulate up to an estimated 0.5 m deep.
04	Mixed forest logged in 1950s.	• On sediment deposit behind a culvert 20.5 m away • 41 m below a concrete dam. • During storm of 2009, about 6” of fine sediment accumulated on the floodplain here.
01	Mixed Forest logged in 1950s.	• 115 m above culvert and 53 m above concrete dam.
11	Mixed Forest logged in 1930s.	• The only place natural large wood seen in channel.
12	Mixed Forest logged in 1930s.	• Heavy foot traffic in area and most of soil bare along bank.

Table 3. (Continued)

Site	Riparian	Local conditions
North Tributary 2		
13	Grass fields, blackberry and a few alder along channel	• Beaver activity immediately upstream of sample. • Did not use sample for hydraulic calculations due to deep placid water at time of sampling.
14	Grass fields, blackberry and a few alder along channel	• Beaver dam 30 m above sample • Debris with hydraulic jump 13 m below sample
15	Fir grove with heavy blackberry understory	• Bed and banks cohesive clay, siltstone.

Figure 12. Size distributions of areal sediment samples in (a) main stem of Kelley Creek, (b) Mitchell Creek (c) Clatsop Creek and (d) northern tributary 2.



* Cross section 4 is located on a deposit above a culvert.
** Cross sections 13, 14 and 15 are located on the valley floor. The sediment sizes for these cross sections are visual estimates.

As the graphic results of bed grain sizes in Figure 12 show, zones within the watershed have distinct associated sediment sizes. On the valley floor, where the channel is low gradient and fine silts were deposited by the Missoula Floods, grains have a D_{50} smaller than 5 mm. On the hillslopes and in the lower canyon, the D_{50} is larger than 10 mm. Cross section 5 is on the valley floor, but located 28 m downstream of a culvert and in a stream reach where the landowner placed fill in the floodplain and hardened the banks.

Figure 13. Longitudinal profiles with corresponding road crossings, ponds and sample sites. (a) Mitchell Creek (b) Kelley Creek main stem (c) Clatsop Creek and (d) Jenne and North Tributary 2.

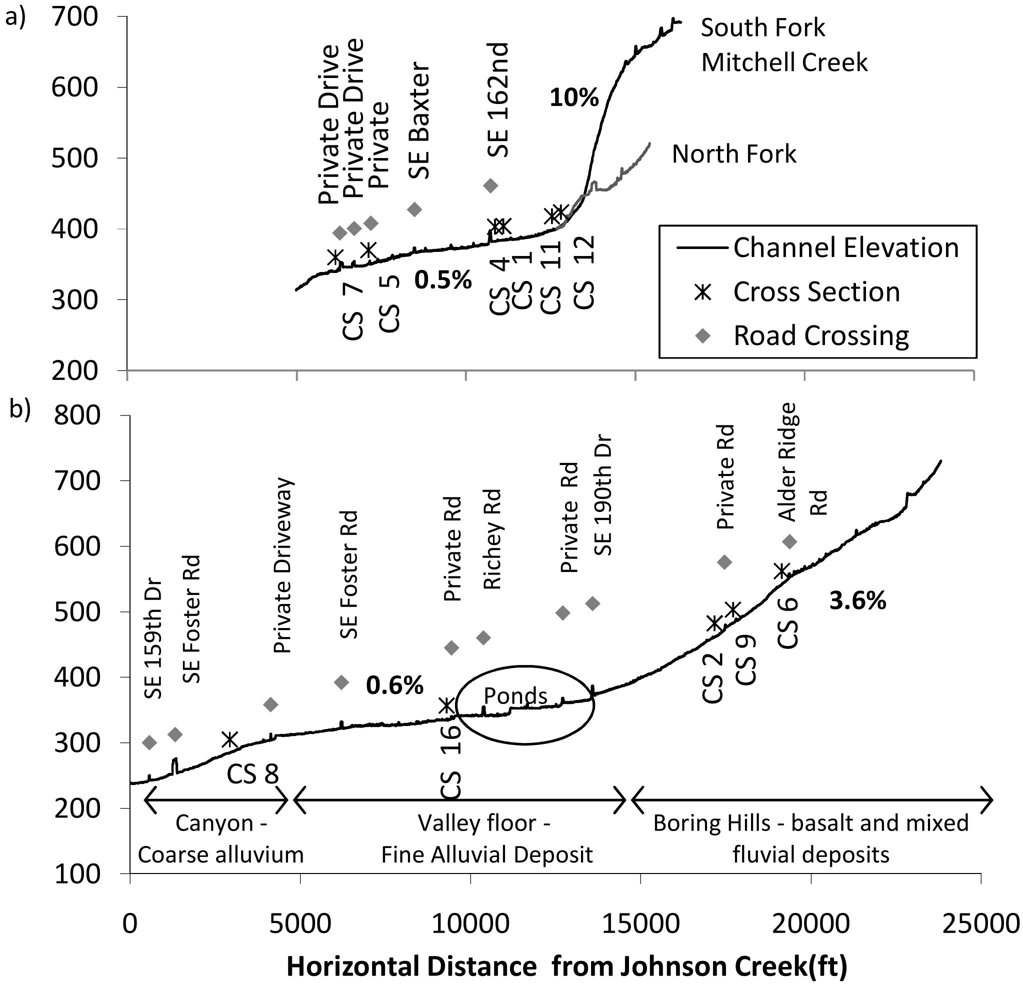
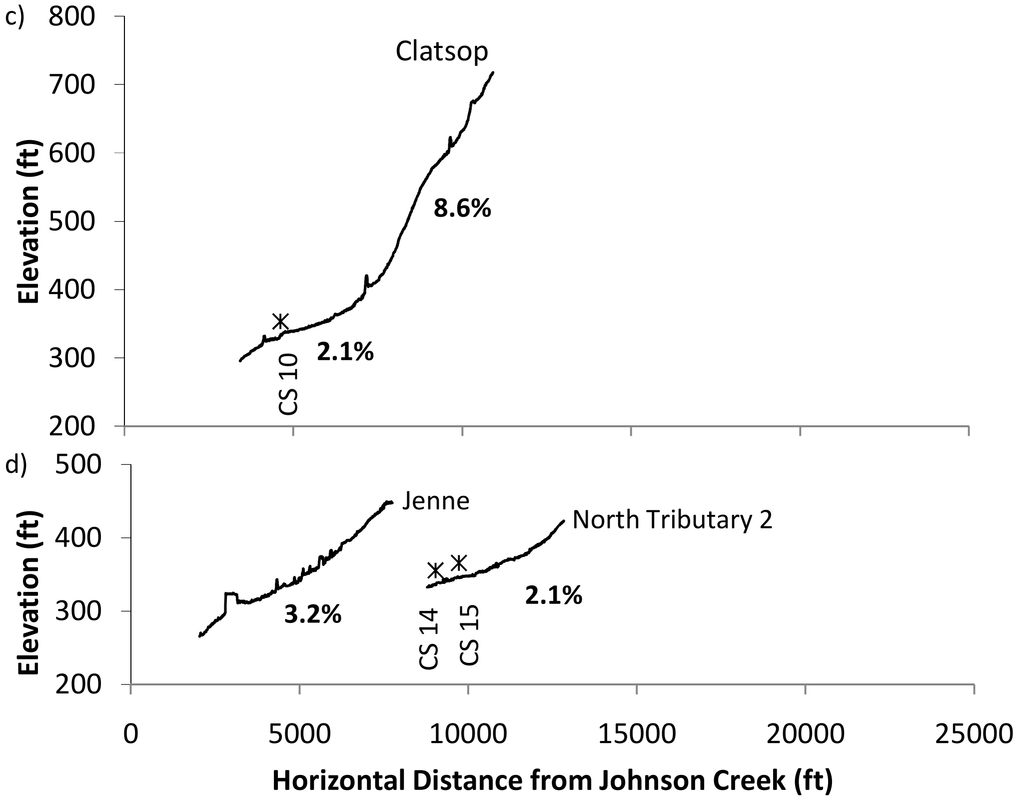


Figure 13. (Continued)



Channel slope relates to geologic zones and controls sediment transport and storage. The profiles of Kelley Creek and its tributaries derived from 1 m resolution LiDAR elevation data (Figure 13) reveal a low gradient mid-channel zone with steeper zones on either end. These low gradient middle sections correlate spatially to fine-textured Missoula Flood deposits whereas steeper sections in the headwaters and canyon are underlain by basalt bedrock. Mitchell Creek has the greatest slope contrast and most abrupt transition between its headwaters and valley sections. Clatsop is generally steepest while Jenne Creek and the North Tributary 2 are both lower gradient tributaries. The elevation profile also reveals sediment deposits upstream of piped sections.

In the lower reaches, below Clatsop Creek and above Foster Road, the grade increases and alluvial deposits are composed of the coarsest material in the watershed. Cross section 8 is located in this section, and drains all tributaries, except Jenne Creek. Sediment at this sample location has the largest D_{50} of all samples in the watershed, despite being below all other cross section samples.

Figure 14. Suspended sediment concentrations as they relate to discharge, including conductivity and dissolved load. Samples were collected at SE 159th near the confluence with Johnson Creek, the same location as the USGS discharge gage. (a) Trend line excluding anamolous points, with a best fit line described by the equation $C_s = 0.00774Q^2 + 0.0633Q - 0.0114$ and $R^2 = 0.89$, where C_s is suspended sediment concentration in kg/m^3 and Q is discharge in m^3/s. (b) Best fit trend line including outlier points at high flows, described by $C_s = 0.0374\ Q^{0.679}$ and $R^2 = 0.89$. (c) Trend line for dissolved sediment concentration as a function of discharge, based on specific conductance measurements. $C_{ds} = 0.0531Q^{-0.144}$, where C_{ds} is concentration of dissolved solids in kg/m^3. This relationship is based on conductivity measurements made in the discharge range of 0.08 m^3/s and 1.8 m^3/s.

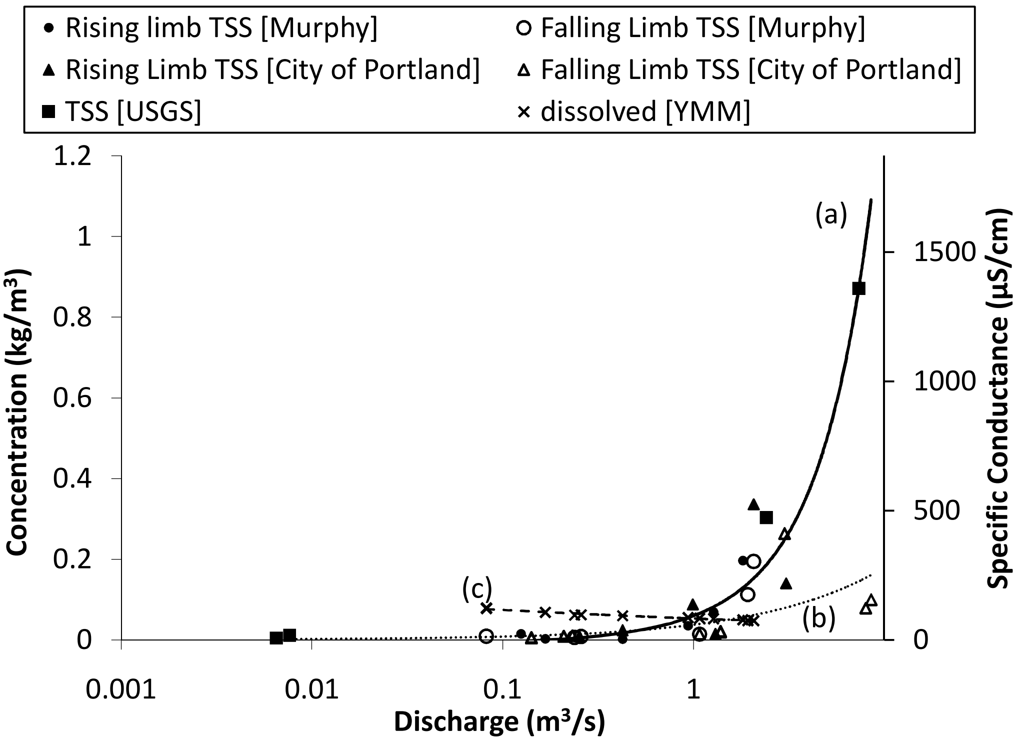
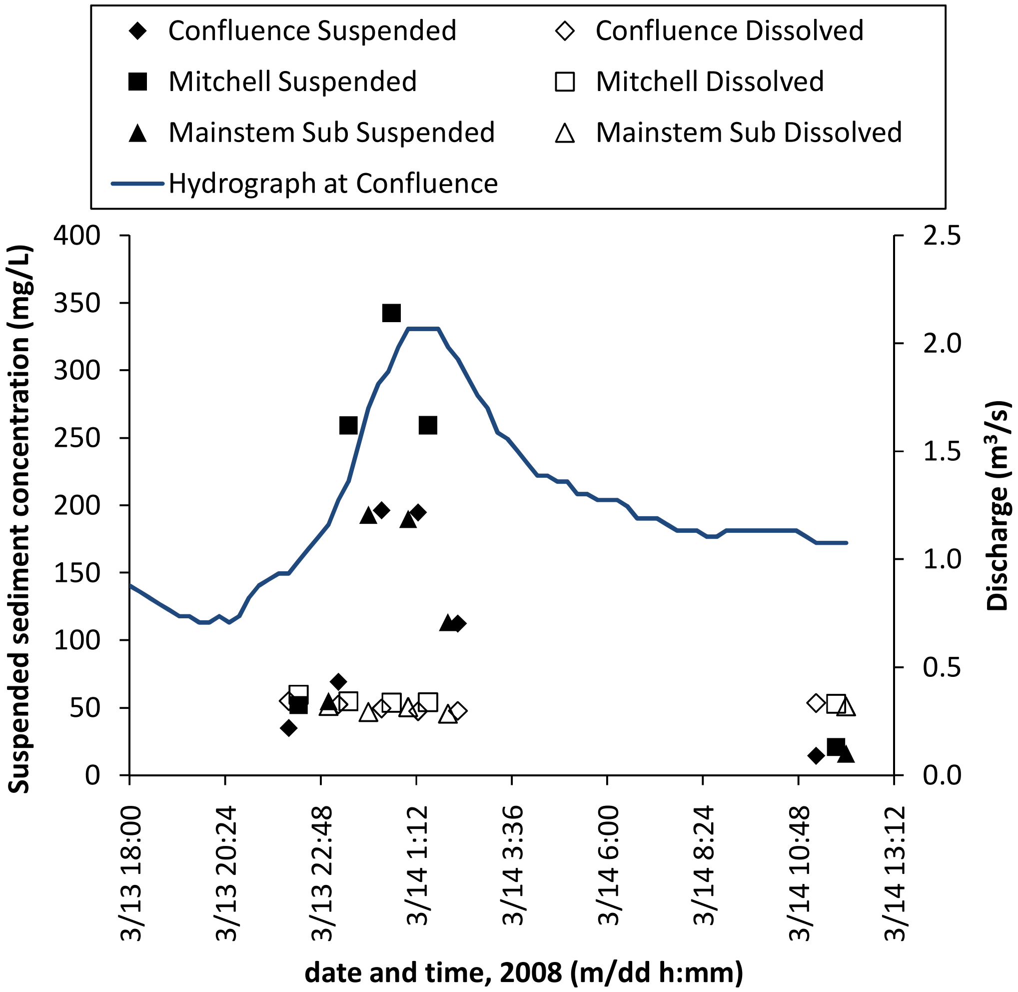


Figure 15. Suspended sediment concentrations at three sites during a single storm event. Confluence site is at the USGS gage. Mainstem Sub is in the middle of the valley floor on Kelley Creek. The Mitchell samples were taken below cross section #1, above the valley floor.



Subcatchments vary in their contributions to the suspended sediment load during a given storm event, as shown on Figure 15. Mitchell contributes a peak suspended sediment concentration of 340 mg/L during the sample storm approximately one hour before peak flows at the gage. Maximum concentrations in Kelley Creek near the mouth reach 195 mg/L and are tracked closely by the concentrations at the sub-watershed sampling station on the main stem of Kelley Creek.

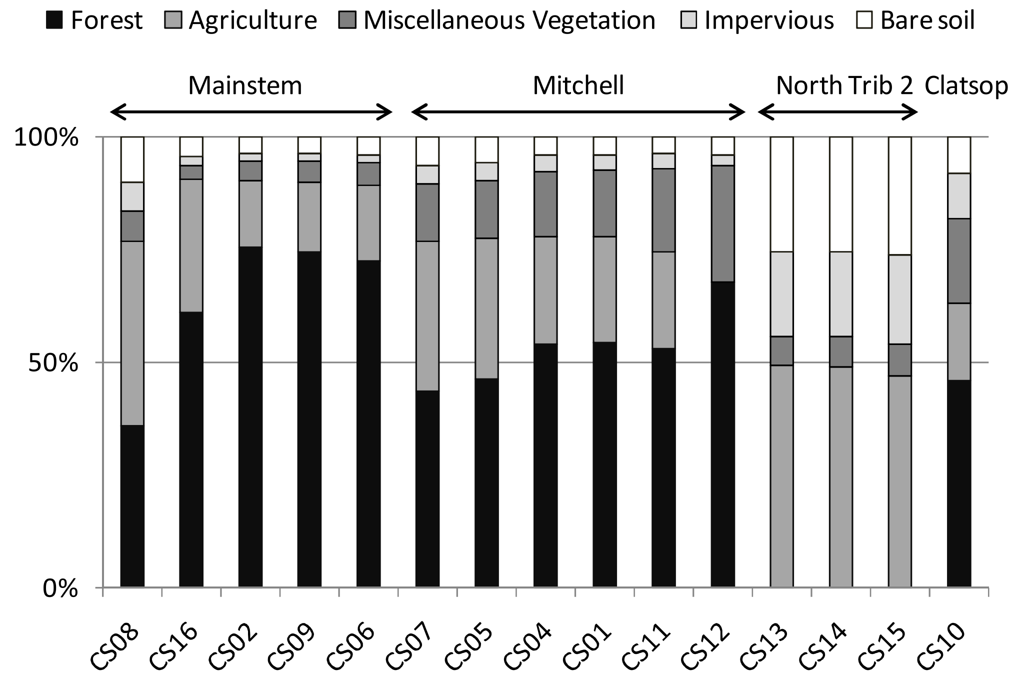
Land Use

Table 4. Land use changes in areal coverage from 1935 to 2005 for areas within the Kelley Creek basin.

Area	Forest	Year Harvested	Agriculture	Residential Development
Mitchell Creek	No Change	1935 Upper half 1955 Lower half	Decreased	Increased
Kelley Creek headwaters	No Change	1935	No Change	No Change
Clatsop Creek	Increased		Decreased	Increased
North Trib 2	None		Decreased, changed to nursery	Increased

In the Kelley Creek catchment land in agricultural use decreased while residential development increased between 1936 and 2005 (Table 4). Kelley Creek headwaters have changed the least but have undergone timber harvest. Almost the entire forested area of Mitchell Creek has been logged in the last century. Clatsop Creek and North Tributary 2 have changed the most, becoming more developed and less agricultural.

Figure 16. 2002 land cover type of drainages upstream of cross section samples. From left to right, the sample locations are increasingly distant from the confluence.



Drainage areas of the four tributaries contrast in land cover types as shown in Figure 16. The headwaters of Kelley Creek remain predominantly forested. Mixed forest, agriculture and miscellaneous vegetation characterize both Mitchell Creek and Clatsop Creek. Northern Tributary 2 is mainly agricultural vegetation and bare soil.

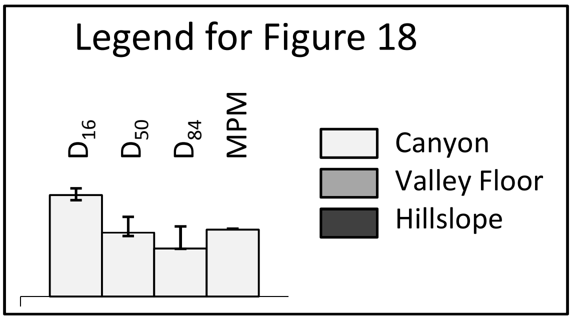
Figure 17. The channel on the valley floor and its inset floodplain. (a)1935 aerial photo. (b) 2008 LiDAR hillshade showing same extent as 1935 aerial. Due to heavy blackberry vines and other vegetation, it is impossible to see the channel in recent aerials photographs.

a) N → b)

The aerial photo from 1935 and LiDAR from 2008, shown in Figure 17, both provide images of the stream planform. An inset floodplain and associated in-channel storage is evident during both years. General channel path and channel features from 1936 remain in 2008.

Stream Channel Sensitivity

Figure 18. $Q_2/Q_{\tau c}$ (above) and τ_{Q2}/τ_c (below) at sample cross sections. Arranged by tributary (a) main stem of Kelley Creek and (b) Mitchell Creek and calculated for the 16th, 50th and 84th percentile clast sizes using Ashworth and Ferguson (1989). $Q_2/Q_{\tau c}$ and RBS for the MPM bedload equation (θ_c = 0.047) are shown on the right side of each cluster. Positive error bars MPM show the confidence intervals calculated with the Monte Carlo simulation. The bedload equations estimate less stability in comparison to that for the D_{50} calculated with Ashworth and Ferguson (1989).



* Sediment size distributions estimated visually at these sample sites. Specific conditions at cross sections are:
CS04 – located on fine silt deposit above culvert.
CS10 – primarily cohesive clay and siltstone with ribbons of silt deposited along channel.
CS14 – Downstream of beaver dam and above small debris dam that impounds water to varying degrees depending on stage.
CS15 – Channel bed and banks hardpan and clays with little loose material on bed.

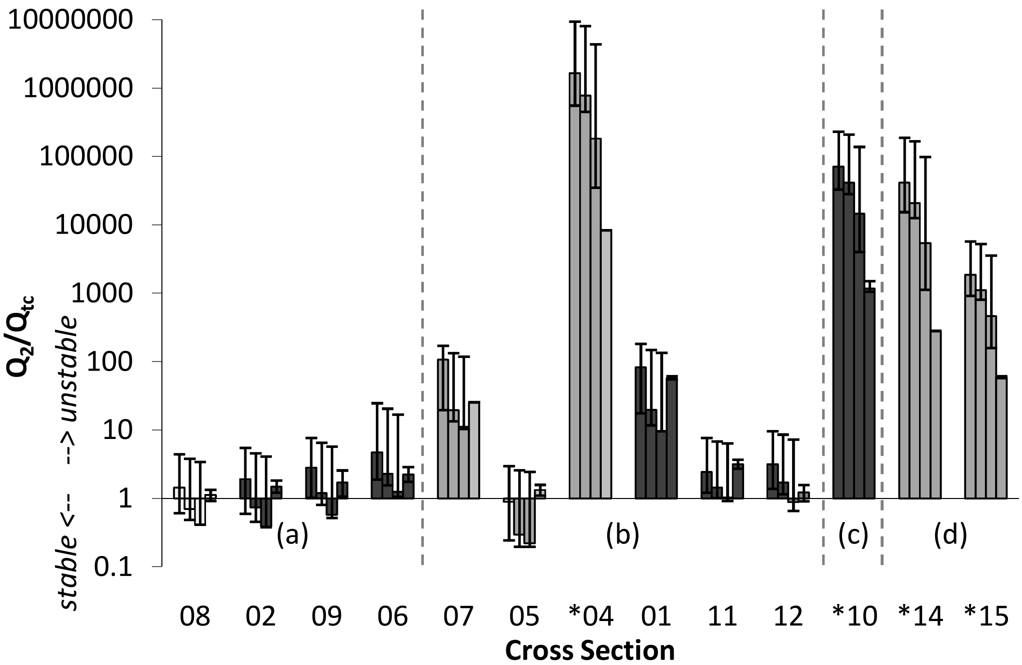
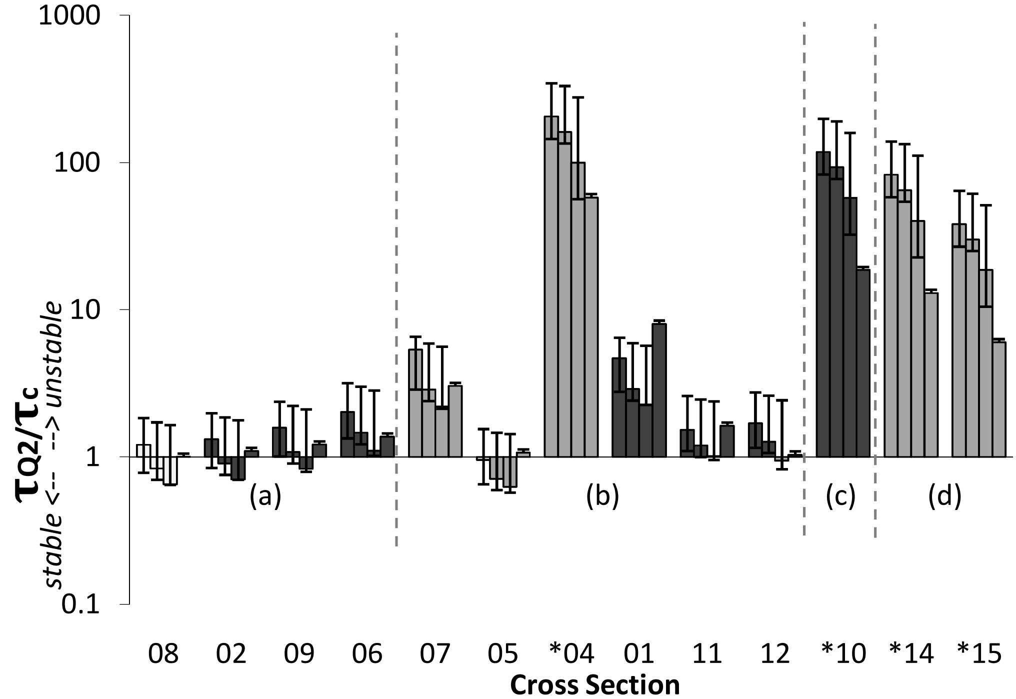


Figure 18. (continued)



The balance of shear stress and particle size is shown in Figure 18. Relative bed stability values at each of the sample sites fall into two categories; RBS value close to 1 or RBS over 2. At samples 02, 05, 06, 08, 09, 11, and 12 the particle sizes and estimated median annual peak shear stress are in balance. Locations where particle sizes are less than shear stresses are located on the valley floor or Clatsop Creek. At many of these sites, local conditions are in play or bed materials are cohesive, which is not accounted for in the model.

Figure 19. Specific discharge at incipient motion threshold. Solid line is the 2-year peak discharge. Note that the lower error bar limit is calculated with Parker and Klingeman's (1982) equation, the upper limit with Wathen et al (1995) and intermediate with Ashworth and Ferguson (1989). The MPM series (on the far right of each cluster) shows the thresholds implicit in the Meyer-Peter and Müller (1948) equations and the Wong and Parker's (2006) modifications.

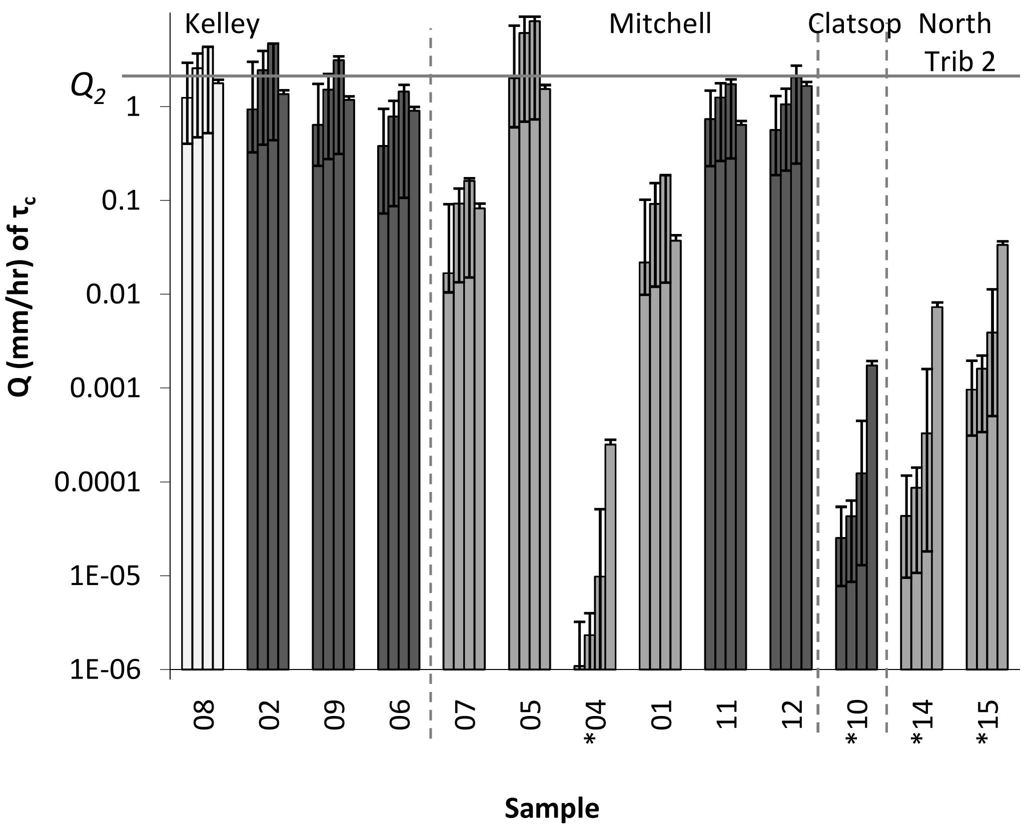


Figure 19 illustrates the estimated discharge at incipient motion for the analyzed sample sites. A discharge at incipient motion is expected to be close Q_2 for those sites with RBS ≈ 1, shown in Figure 18. These estimated motion thresholds are consistent with the results of relative bed stability indices.

Figure 20. Ratio of cross sectional area at Q_2 to cross sectional area (m^2) at bankfull (A_{Q2}/A_{QBF}) flow regressed against a) particle diameter, b) percent impervious, c) residuals of A_{Q2}/A_{QBF} versus percent impervious regression, d) residuals of percent impervious regression versus residuals of D_{50} regression and e) A_{Q2}/A_{QBF} versus RBS.

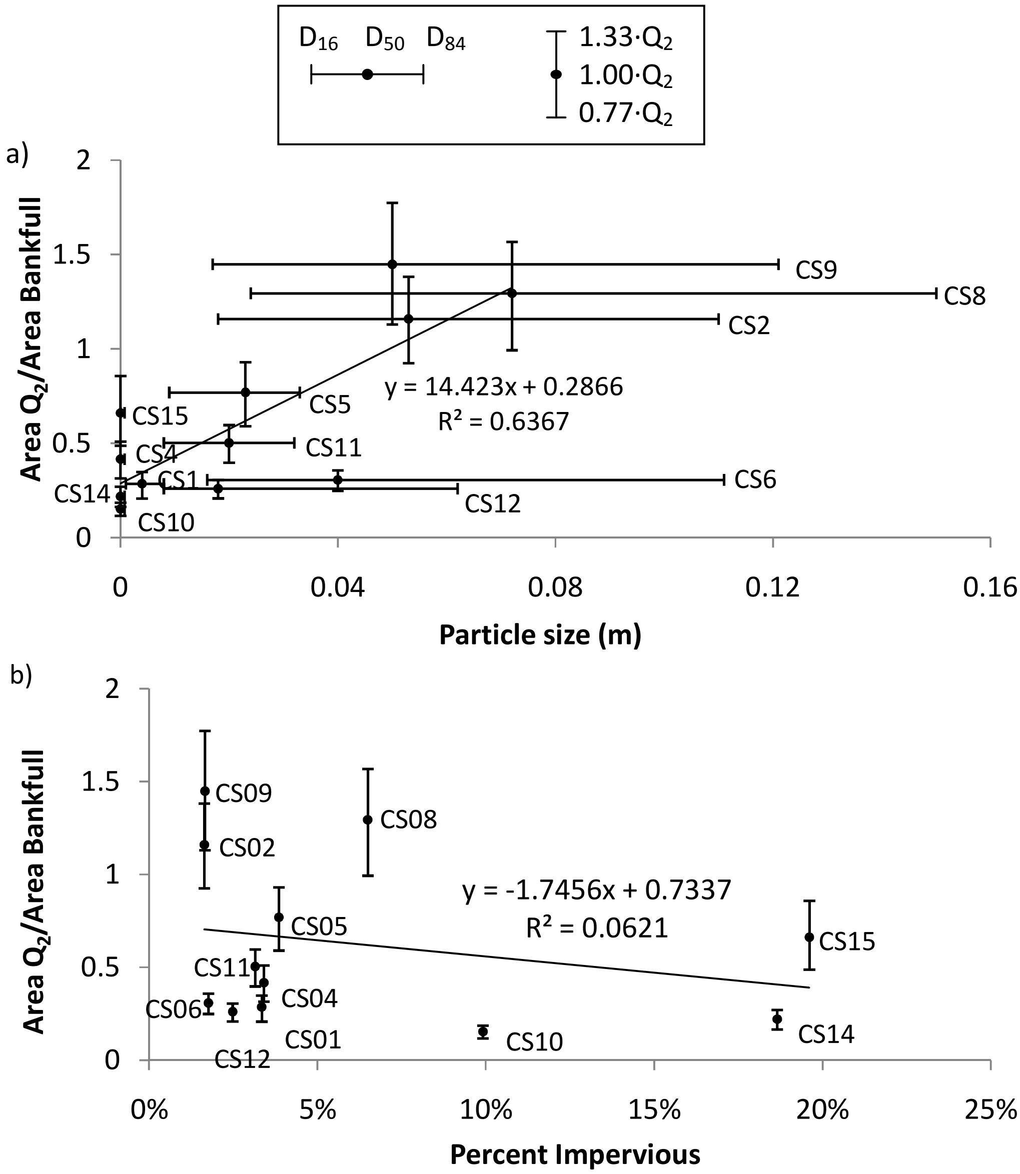
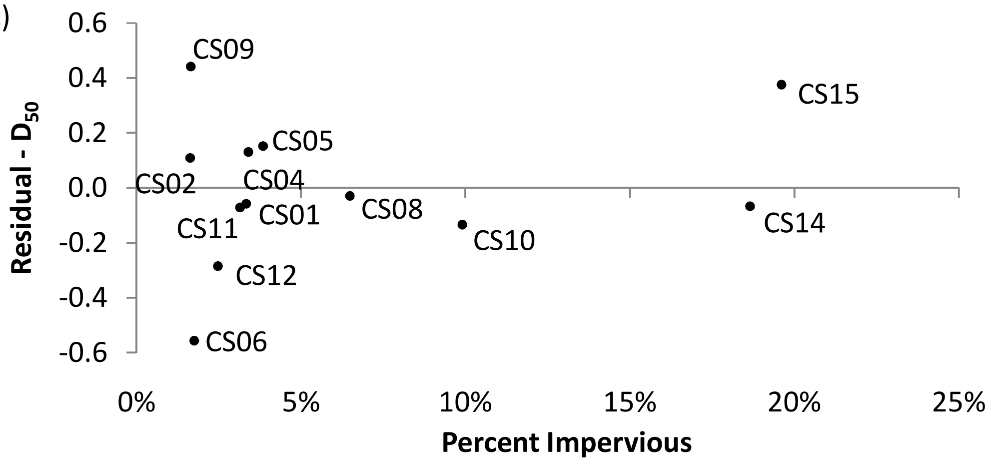


Figure 20. (Continued)

c)



d)

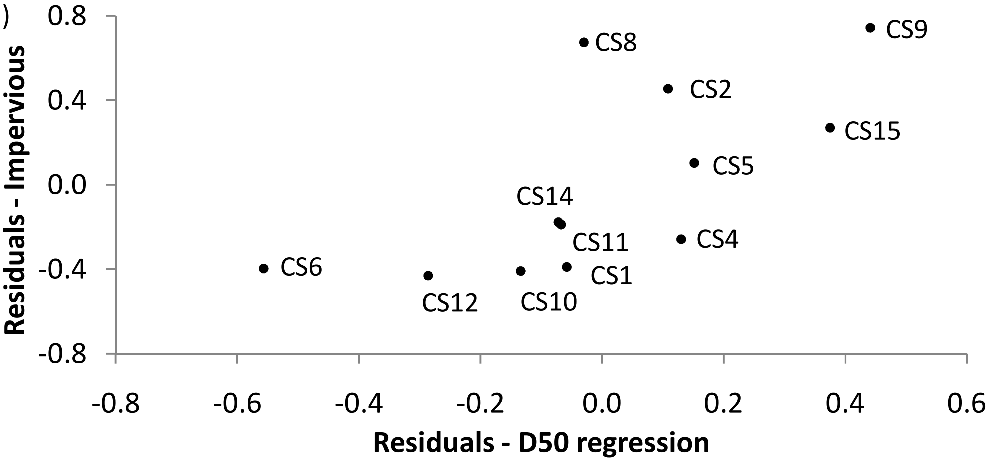
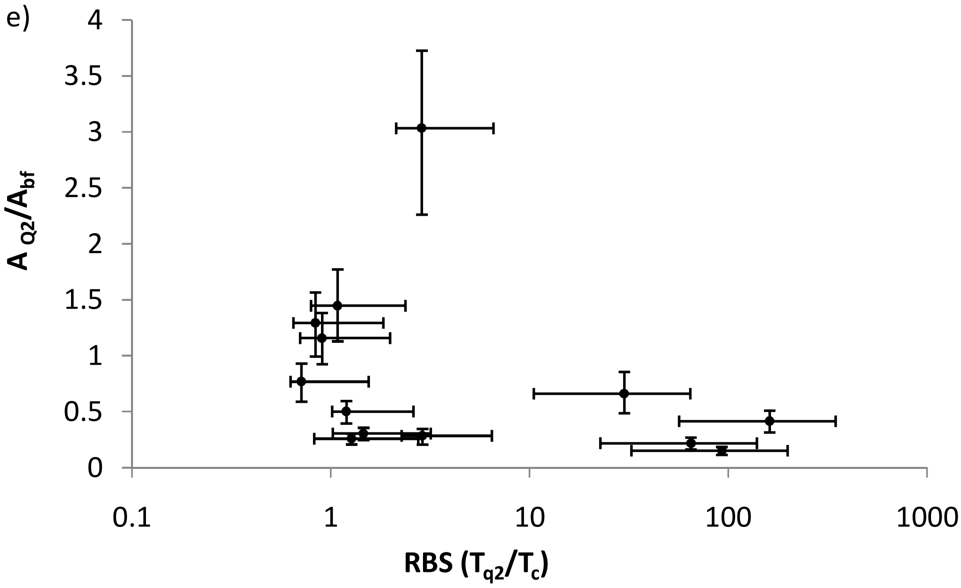


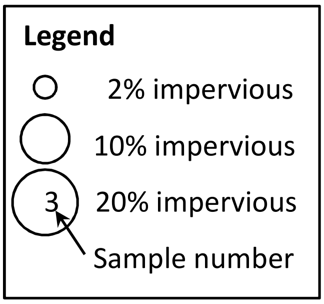
Figure 20. (Continued)

e)



Particle diameter, alterations in the hydrograph caused by impervious surfaces, or other factors could drive cross section area (Figure 20). The regression of A_{Q2}/A_{BF} versus particle size indicates that particle size influences the bankfull cross section area. A_{Q2}/A_{BF} would be expected to equal unity with a particle size of 0.05 m. A_{Q2}/A_{BF} is weakly related to catchment impervious area. The measured results of A_{Q2}/A_{BF} vary more for fine sediments. Residuals of particle size and percent impervious area regressions correlate, suggesting that other factors control A_{Q2}/A_{BF} at certain sites. Figure 20, part e shows a bimodal relationship of A_{Q2}/A_{BF} to relative bed stability: Those sites with RBS near unity vary widely in A_{Q2}/A_{BF}, while at sites with a high RBS index, A_{Q2} is less than A_{BF}.

Figure 21. Relationship between cross sectional area (A_{BF}), catchment drainage area (A_s), and urban development for (a) valley floor samples and (b) hillslope samples. Dunne and Leopold's (1978) estimated that urbanized cross sections fall above the line $A_{BF} = 24.5A_s^{0.66}$ while rural streams fall below the line, shown with their data reproduced in (c). In the maritime Pacific Northwest, Castro and Jackson (2001) found the relationship between cross sectional and drainage area is better described as $A_{BF} = 14.26A_s^{0.739}$, shown here as the bold dashed line.



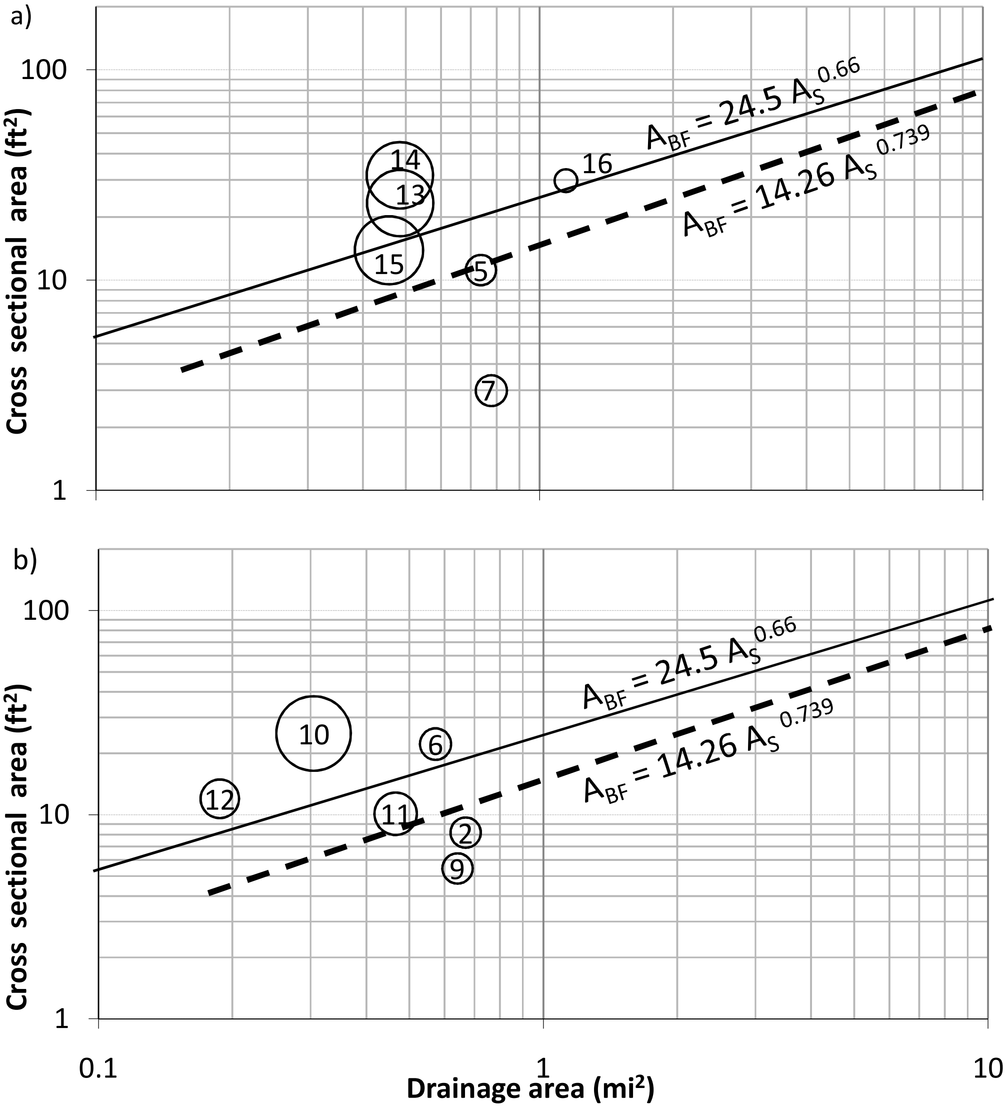
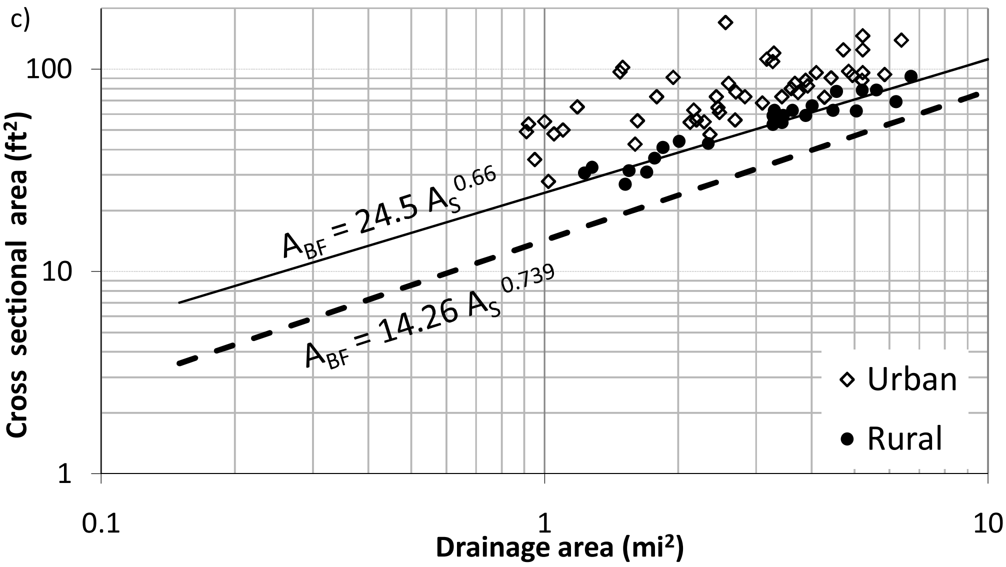


Figure 21. (Continued)



Results plotted in Figure 21 demonstrate that cross sectional area relates to both drainage area and impervious area. For both the headwater catchments and valley floor catchments, the cross sectional areas increase with impervious area, but there are exceptions and no apparent threshold as suggested by Dunne and Leopold (Dunne and Leopold 1978). Most of the cross sections sampled in Kelley Creek lie above Castro and Jackson's (2001) regional regression of cross sectional area and drainage area, suggesting the cross sectional channel area is enlarged relative to other stream channels in the region.

Figure 22. Kelley Creek map showing locations of ponds and results of Meyer-Peter and Müller total sediment load calculations for cross sections. Triangles are cross sections with silt and cohesive beds that were not included in the calculations.

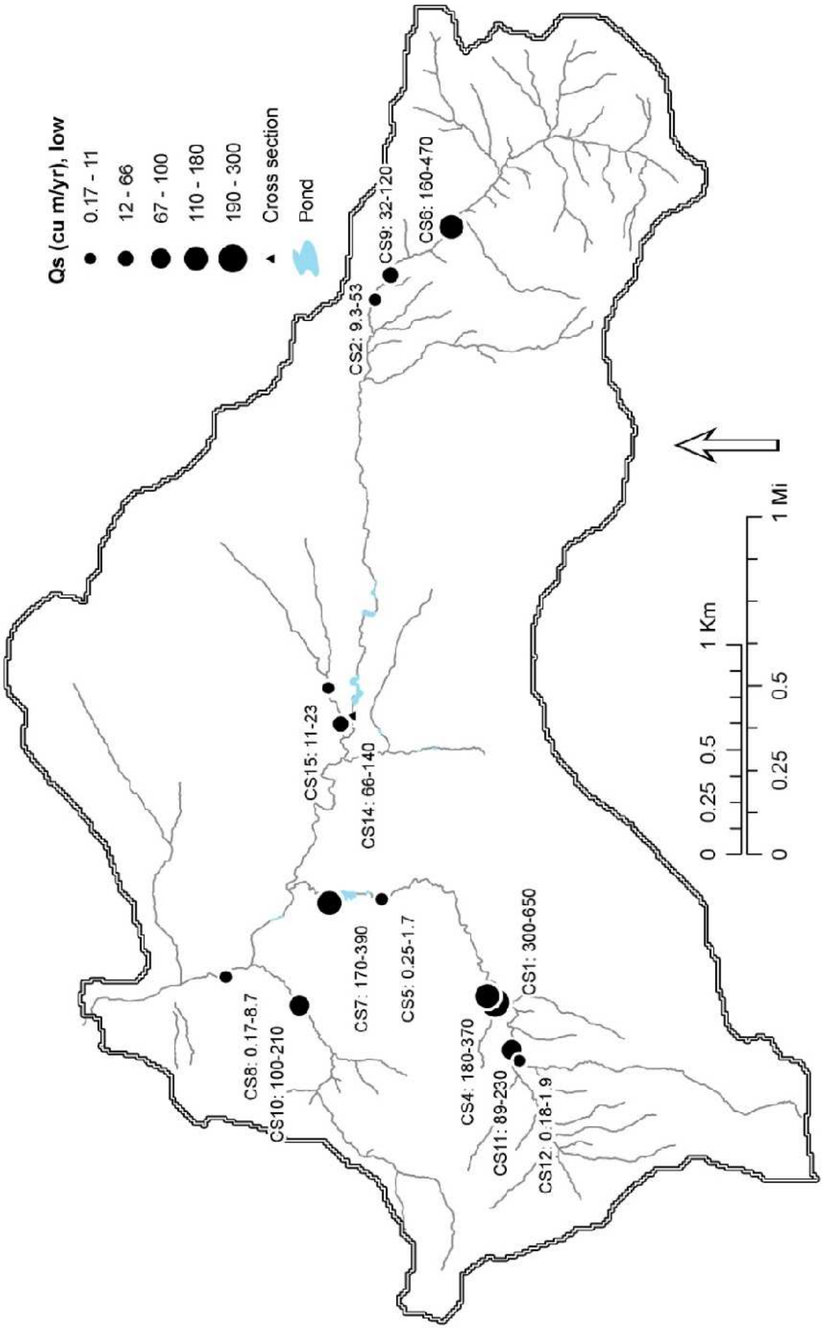
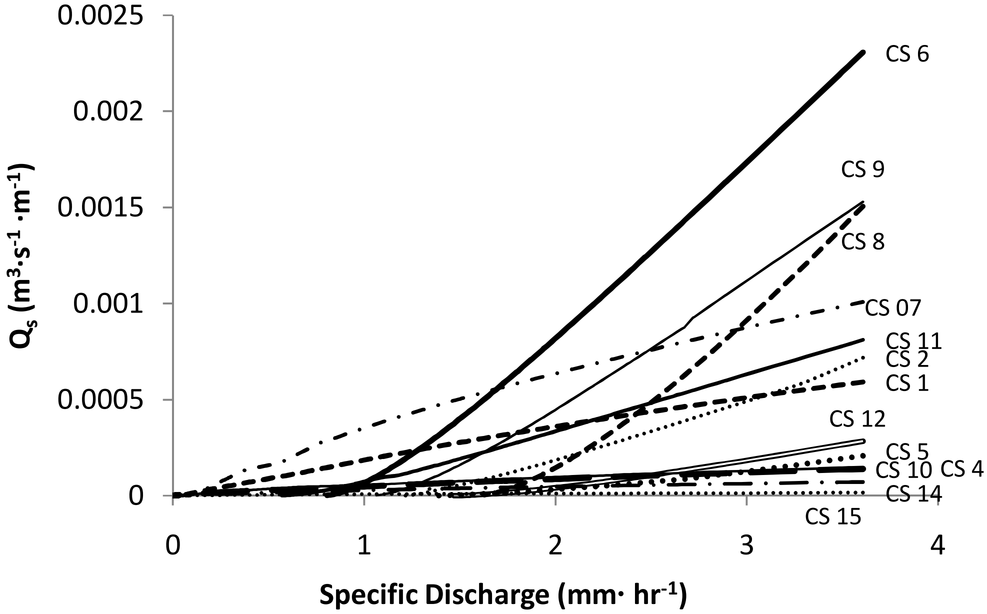


Figure 22 shows the spatial patterns of sediment transport rates predicted by the Meyer-Peter and Muller equations under current conditions. The highest sediment transport rates occur at cross sections 1, 6, 10 and 7. On the main stem of Kelley Creek, transport rates increase with distance from the confluence while on Mitchell Creek the upstream cross sections have the lowest annual bedload. In general, Mitchell Creek has a higher transport potential compared to Kelley Creek. The ponds are located in the middle of the watershed and below hillslope sediment sources.

Lower predicted transport rates do not correlate to locations with lower RBS values. At two out of the six Mitchell Creek samples, cross sections 05 and 12, estimated bedload transport rates less than 5 $m^3 \cdot km^{-2} \cdot yr^{-1}$ are one to two orders of magnitude lower than rates at other sites along Mitchell Creek. A culvert located 28 m upstream from cross section 05 most likely influences hydraulics and coarsens sediment size distributions at the sample. The channel width at cross section 12 is approximately 80% of the width at nearby downstream cross section 11. Cross section 12 drains only 40% of the area contributing to cross section 11, because a second tributary enters between the two sample sites. With a wide cross section and coarse sediment, discharges at cross section 12 lack the competence to move sediments at the same rate as cross sections 11 and others on Mitchell Creek.

Figure 23. Rating curves for modeled rates of bedload versus discharge at sample sites.



Annual bedload is the sum of the products of bedload transport rates, their duration and channel width. The curves with steepest slopes in Figure 23 indicate cross sections where bedload increases most with discharge.

Figure 24. Flow duration curves for existing conditions and future scenarios.

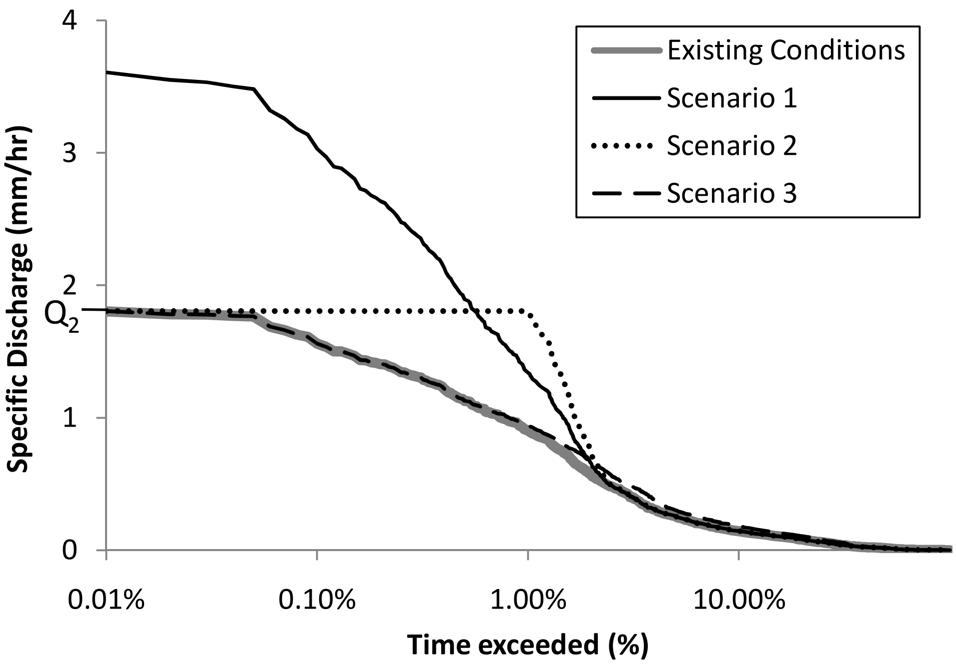


Table 5. Description of hydrologic scenarios. Median annual rainfall over the stream flow period of record at the Pleasant Valley School is 1120 mm.

Scenario description	*Peak Q (mm/hr)*	*Duration $Q \geq Q_2$ (hrs)*	*Range Q increased (%)*	*Total depth Q (mm)*
Existing	1.8	0.9	NA	550
1 - Unmitigated: increase peak magnitude	3.6	49	0.01% - 2.5%	650
2 - Storm detention: increase peak Q duration by 3.6 days.	1.8	86	0.02% - 2.5%	650
3 - Fall storm response: Increase discharge magnitudes for intermediate fall storms	1.8	0.9	0.54% - 50%	650

Figure 25. Sediment yield (in Mg·km^{-2}·yr^{-1}) of three alternative future scenarios and existing conditions for (a) Kelley, Clatsop and North Tributary 2, (b) Mitchell Creek and (c) suspended and dissolved load at the Kelley Creek USGS gage. In a and b, upper limits are the 90% confidence intervals calculated with Monte Carlo simulation. In (c), errors bars reflect the 90% confidence interval for the regressions of results presented in Figure 14.

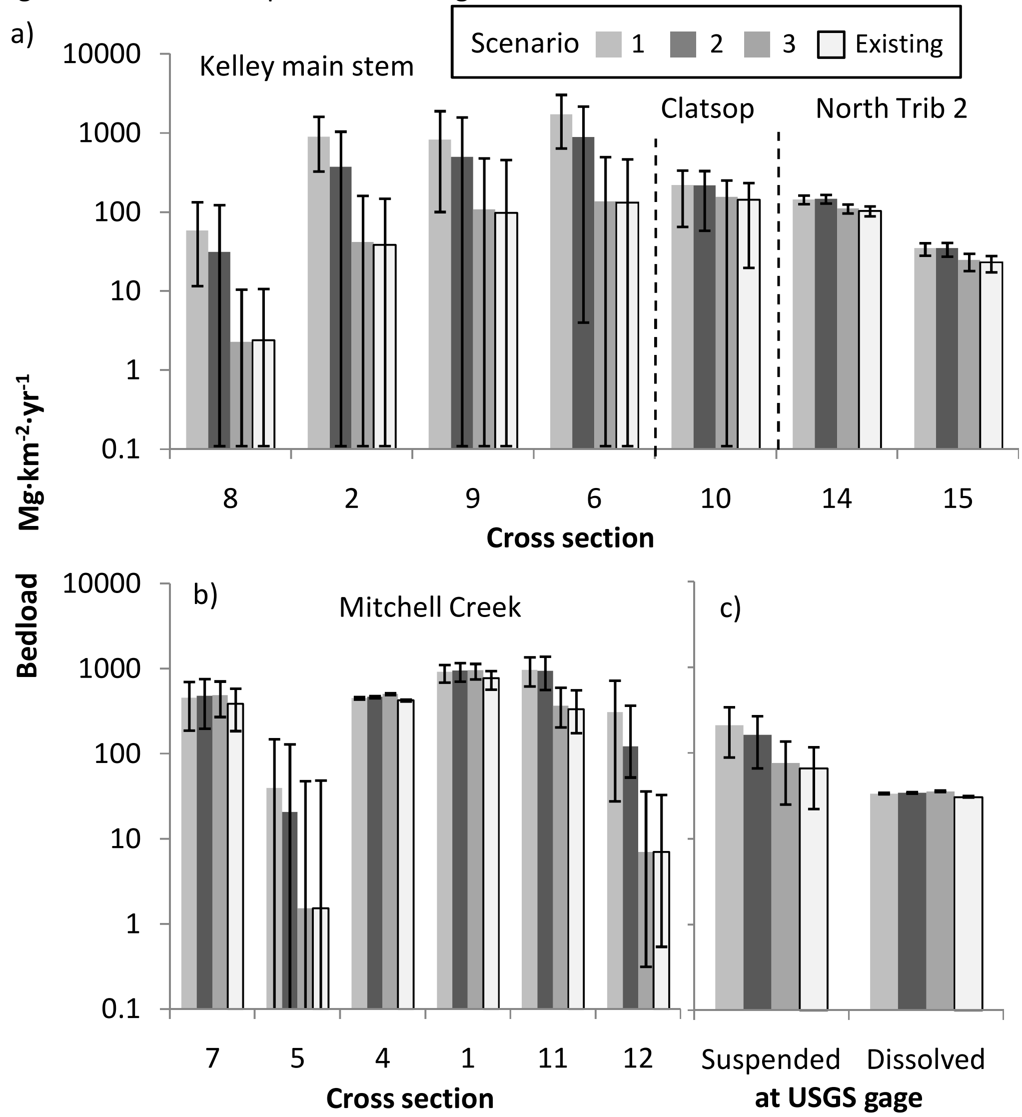


Figure 25 shows results of calculated sediment transport rates under current and future scenarios, described by Figure 24 and Table 5. Under current conditions, bedload transport rates at Kelley Creek sample sites range between

1.4 to 770 $Mg \cdot km^{-2} \cdot yr^{-1}$ (0.8 and 500 $m^3 \cdot km^{-2} \cdot yr^{-1}$), based on simulations using the Meyer-Peter and Muller bedload transport equation (Figure 25 and Table 6). In addition to bedload, 22 to 116 $Mg \cdot km^{-2} \cdot yr^{-1}$ (16 to 82 $m^3 \cdot km^{-2} \cdot yr^{-1}$) of suspended solid material and 30 to 32 $Mg \cdot km^{-2} \cdot yr^{-1}$ (17 to 18 $m^3 \cdot km^{-2} \cdot yr^{-1}$) dissolved solids move out of the watershed at its mouth. Both the annual suspended sediment yield and dissolved load at the mouth contribute greater volumes than the bedload (0.02-0.8 $m^3 \cdot km^{-2} \cdot yr^{-1}$ bedload at cross section 08). The uncertainty in bedload transport rates, in some cases (cross sections 8, 2, 9, 6, and 5) is as large as the predicted value. Because of the wide range of uncertainty, differences in annual transport rates at most of the cross sections are insignificant. However, cross sections 1, 4, 7, 10, 11 with fine sediment (D_{50} < 5 mm) have significantly higher annual bedload transport capacities than cross sections 8, 5 and 12, with coarse sediments.

Sensitivity to hydrologic changes correlates to particle size. Suspended and dissolved load at the gage and those sample sites with fine sediment (10, 14, 15, 7, 4, and 1) are least sensitive to changes in the hydrograph based on results estimated with Meyer-Peter and Muller. At these cross sections, 90% confidence intervals for projected transport rates for the existing and future scenarios overlap. At coarse-bedded cross sections (D_{50} > 10 mm) 8, 2, 6, 11, and 12, scenario 1 (increasing peak magnitude by a factor of 2) significantly increases annual bedload transport capacity. Scenario 2 (increasing duration of Q_2) significantly increases bedload transport capacity only at cross sections 11 and 12, where the projected annual transport capacity is almost identical to that under scenario 1. No cross sections increase annual bedload transport capacity under scenario 3 (increasing magnitude of frequent storms).

Suspended sediment at the gage slightly increases with the future scenarios, but these increases are not significant.

Table 6. Annual suspended sediment yields for existing hydrologic conditions and future scenarios.

Scenario	**Annual Mass (10^3 kg)**	**Volume (m^3) Estimate (90% CI)**	**Depth (mm)**
Existing	800 (270-1400)	560 (190 -990)	0.017 - 0.046
1	2600 (1100-4100)	1800 (750 – 2900)	0.030 - 0.15
2	2000 (800-3300)	1400 (560 – 2300)	0.028 – 0.12
3	930 (300-1700)	650 (210-1200)	0.02 – 0.054

Table 6 summarizes the results of sample mass, regression and integration over the median annual flow duration curve. Concentrations of dissolved solids vary less with discharge and therefore total annual sediment yield for dissolved solids is less sensitive to variation in flow durations compared to suspended sediments, as illustrated in part c of Figure 25.

DISCUSSION

Sediment dynamics within Kelley Creek occur in the context of long-term (on the order of tens of thousands of years), basin-wide geomorphic processes. Throughout most of the basin, Missoula Flood deposits produce conditions of sediment abundance. In the headwaters and near the confluence with Johnson Creek, steeper slopes underlain by Boring basalt create conditions of high transport capacity limited by the elevation of the underlying bedrock. In sediment management, managers must take into account that geomorphology and sediment dynamics occur on the local scale, but depend on these larger, longer-term processes.

Limitations of data and results

This study was limited by a short discharge record, lacking extreme flows that may be responsible for major changes in channels of Kelley Creek. In particular, the flows for the period of record are biased toward dry. The record includes 2 of the driest years on record (2001 and 2005), but lacks wet years that occurred in 1996 and 1997. On the other hand, the 8-yr record does contain annual flows that are responsible for much of the sediment transport (Wolman and Miller 1960; Wolman and Gerson 1978). The USGS gage provides estimates of discharge patterns, but this data is limited in several ways. Being only operated since 2000, the hydrological record lacks statistical robustness, records of multiple extreme events and records of long-term fluctuations such as the Pacific decadal oscillation, which found influences discharge patterns in the Portland area (2007). Karl Lee (2007), USGS Oregon Water Science Center Hydrologist cautions that backwater effects influence this gage during high flows, and there is only one year (2006) with good high flow data. High flows are measured with both a Doppler probe and a rating curve with stage meter. The hydrologist selects the best values from these measurements, which become increasingly imprecise with discharge magnitude. Missing data for this gage comprises less than 5% of the record for each year, but includes several missing storm events. This missing data was estimated from the data at a nearby operating gage.

There is uncertainty in how the hydrology in the Kelley Creek watershed will respond to increased impervious area as development proceeds under recent urban boundary expansions, because the geomorphology of Kelley Creek is unusual, and projected increases in peak discharges are much smaller than those found in other urbanizing watersheds. Unique soil conditions in the basin add uncertainty to hydrologic response following development. Throughout most of the basin, silt loam soils overlay hardpan layers, causing runoff patterns which already resemble those from land with high proportions of impervious surfaces. As a result of this hardpan layer and seasonally saturated soils, peak discharges might not increase very much with increased urbanization. The City of Portland modeled 10-year and 2-year storm event flows for Kelley Creek under future developed conditions with and without stormwater infiltration and detention facilities (Savage and Young 2006). Using the model HEC-HMS, they estimated a 15.8% increase in peak discharge and an 18.9 acre feet volume increase (approximately 2 mm depth) for the 2-year storm. Compared to other research in urban hydrology which found 2 – 14 fold increases in discharge following urbanization (Burges, Wigmosta et al. 1998; Roesner, Bledsoe and Brashear 2001), a 15.8% increase for the 2-year storm seemed low, so in this study, it is assumed that the peak 2-year storm magnitude could hypothetically double following development. The Portland model would have been more relevant to this study had it included hydrological impacts to more frequent events which may have competence to move sediment. The future hydrologic scenarios presented in the present study were developed based on changes measured in other studies of urban hydrology and are generalizations only. These results test sensitivity to land use changes and varying approaches to stormwater management, but are limited by our understanding of how this watershed will change hydrologically following urbanization.

Any estimates of sediment transport rates based on sediment transport and flow resistance equations should be considered with great caution. In this study, the equations were selected based on available parameters and similarity of conditions to the original equation development, following review of the equations' prediction performance for small streams and conditions under which the equations were derived (Reid and Dunne 1996; Buffington and Montgomery 1997). Appropriate sediment transport equations have been derived from data collected in similar conditions to those of the intended application, but most equations were derived from flume studies with uniformly sized sediment. The Meyer Peter and Müller bedload equation was developed with data from flumes with mixed grains ranging in size from 0.4 to 29 mm (Reid and Dunne 1996). The Meyer-Peter and Müller equation requires hydrodynamically rough conditions, with Reynolds number greater than 100, which in the cases of cross sections 4, 10, 14 and 15 were not met. Use of readily obtainable parameters limited equation selection. Stage-discharge rating curves and detailed sediment size distribution data were not obtained for this study, which increase the accuracy of calculated results but also increase the required time and resource investment.

Current conditions

The sediment yields estimated in Kelley Creek fall within the published range for Western Oregon, Western Washington, British Columbia and the

Columbia Basin. However, there are few, if any, other published sediment yield estimates from basins mantled with Missoula Flood deposits. Yields at the mouth of Kelley Creek range from 22 – 116 $Mg \cdot km^{-2} \cdot yr^{-1}$ of suspended solids and 30 – 31 $Mg \cdot km^{-2} \cdot yr^{-1}$ of dissolved solids. At cross section 8, the closest sample to the confluence, flows potentially transport 0.02 – 1.4 $Mg \cdot km^{-2} \cdot yr^{-1}$ as bedload. In warm climates (10° – 25° C), average annual yield of suspended sediment to the world's oceans, without human influence ranges from 137 to 247 $Mg \cdot km^{-2} \cdot yr^{-1}$, while with modern impoundments and changes to land use, annual yields range from 143 to 197 $Mg \cdot km^{-2} \cdot yr^{-1}$ (Syvitski, Vorosmarty, Kettner and Green 2005). Sediment fluxes from small catchments vary widely, even within a given climate and geographic area. Catchments draining into the Columbia basin and northern Pacific Ocean with an area less than 100 mi^2 produce an average of 140 $Mg \cdot km^{-2} \cdot yr^{-1}$, with a low of 10.5 and a high of 385 $Mg \cdot km^{-2} \cdot yr^{-1}$ (Dunne and Leopold 1978). Issaquah Creek, a stream east of Puget Sound, yielded 28 $Mg \cdot km^{-2} \cdot yr^{-1}$ in fine material and 16 $Mg \cdot km^{-2} \cdot yr^{-1}$ in coarse material (Nelson and Booth 2002). Studies of Willamette Valley tributaries focus on Coast and Cascade Range catchments with mean slopes over 20%, much higher than the mean slope of Kelley Creek (16%). These study sites also differ from Kelley Creek in terms of geomorphic history. Coast and Cascade Range slopes are derived from uplifted Tertiary marine sediments (Coast Range) and Tertiary volcanics (western Cascade Range) weathered in situ, rather than Missoula Flood deposits. In the Oregon Coast Range, Sutherlin Creek has a mean slope of 20%, sandy clay and silt loam soils and timber production and agricultural land use. Its annual suspended sediment yield is 174 $Mg \cdot km^{-2} \cdot yr^{-1}$ (Larson and Sidle 1980). By contrast, in the H. J. Andrews Experimental Forest of the Oregon Cascades, with clay loam soils, watersheds with slopes 28 – 31% yielded 2.66 to 11.1 $Mg \cdot km^{-2} \cdot yr^{-1}$ (Larson and Sidle 1980).

Sediment transport rates are source-limited in locations where the bed is coarse (Montgomery and Buffington 1997) due to localized intensified scour or lack of Missoula Flood deposits. Sediment transport rates in the reaches in the canyon below the valley floor (where the Missoula Floods deposited a gravel and boulder bar), and in the headwaters of Kelley Creek, (which were above elevations inundated by Missoula Floods) have coarse sediments and intermittently exposed bedrock with relative bed stability values near one. A few locations, cross section 8 in the canyon and cross section 5 on Mitchell Creek, have exceptionally low sediment transport capacities compared to the other sites; less than 2 $Mg{\cdot}km^{-2}{\cdot}yr^{-1}$ (1 $m^3{\cdot}km^{-2}{\cdot}yr^{-1}$). Cross section 5 is located 20 m below a road crossing while cross section 8 lies below several ponds on the valley floor. Samples in the Kelley Creek and Mitchell Creek headwaters with coarse sediments (D_{50} > 18 mm) and slopes between 2% and 3% were estimated to have intermediate bedload transport capacity between 7 to 600 $Mg{\cdot}km^{-2}{\cdot}yr^{-1}$ (4 and 400 $m^3{\cdot}km^{-2}{\cdot}yr^{-1}$). Coarse sediment and exposed bedrock resemble conditions common below dams, where channels are sediment starved (Kondolf 1997). In Kelley Creek, most of the bedrock is observed below small dams and ponds or improperly aligned and sized road crossings, which trap sediment on the upstream side and scour the channel downstream. These locations are supply limited because of the physical obstructions blocking upstream sources or because channel slopes are so steep that flows have capacity exceeding supplies.

Sediment transport in Kelley Creek is adjusting to up to 10-m deep, silt-textured deposits left by Missoula catastrophic Floods as recently as 10,000 years ago. In the last 200 years, sediment transport rates in the channel have likely increased due to beaver extirpation and destruction of their associated dams. Beavers are present along the stream channel and although beavers were likely obliterated by intensive fur trapping between 1800 and 1850 (Naiman, Johnston and Kelley 1988), beaver dams historically must have provided sediment storage on the valley floor. Counterbalancing increased channel erosion following beaver extirpation, surface erosion and sediment production to the stream channel have accelerated due to a mid-19th century wildfire, agricultural cultivation, forest harvest, and road construction. Despite the loss of beavers, sediment transport rates are transport-limited where the stream channel crosses the low gradient valley floor and inputs from the upstream hillslopes, together with the historical catastrophic Flood deposits on the valley floor provide large sources of gravel alluvium and silt to the valley floor reaches. Further limiting sediment transport in the middle section of Kelley Creek, artificial impoundments slow or prevent transport of material out of Kelley Creek, much in the same way that beaver dams would have in the past, but on a smaller scale. Between these ponds, flows in the low gradient (<1%) channels have low transport capacity. Despite perhaps 200 years of presumably increased hillslope surface and channel erosion rates, the valley floor continues to adjust to the catastrophic flood deposits because they are so deep. Removing man-made impoundments and thus eliminating in-channel storage, which moderates this adjustment rate, could increase sediment yields and lead to channel incision as found above abandoned beaver dams in Yellowstone National Park (Wolf, Cooper and Hobbs 2007; Persico and Meyer 2009).

Impacts of development

The present results indicate that slight increases in frequency of discharges occurring several times per year will have little impact on erosion rates, while increasing peak flow magnitude generally leads to the greatest sediment transport rates. The initial expectation in the present study was that extending the duration of pre-development peak flows would increase total duration of competent flows and lead to sediment yields that exceed those projected to occur with a shorter duration, increased magnitude peak flow. The results presented here suggest that the scenario with increased peak flow magnitude tends to lead to the highest bedload transport rates. The City of Portland's Stormwater Management Manual (2008) aims to address problems associated with urban runoff, including increased stream channel erosion and increased flood frequency. The standards put forth in Portland's manual address these problems by maintaining 2-year, 5-year and 10-year peak flows at their predevelopment levels. Because total event runoff volumes from developed land tend to be higher than from undeveloped land, stormwater management which maintains predevelopment peak flows necessitates extending the duration of those flows to allow this additional volume to run off. Previous studies (Booth 1990; Booth and Jackson 1997; Roesner, Bledsoe et al. 2001) have found that this approach of maintaining 2-year, 5-year and 10-year storms does little to mitigate increased erosion resulting from increasing duration of high frequency, erosive flows. Likely in response to findings that increasing the duration of Q_2 increases channel erosion, specific standards for development in the Kelley Creek watershed call for limiting the post-development Q_2 to 0.5 times the pre-development magnitude (Savage and Young 2006). Results of modeled sediment transport rates generally contradicted our expectation for increasing duration or magnitude of 2-year flows: at most sample sites, maintaining a longer duration of Q_2 slightly reduced total annual bedload yields compared to doubling the Q_2 intensity. As expected, increasing the duration of flows below 0.6 times predevelopment Q_2 results in only a nominal increase in sediment transport rates, suggesting that the standard limiting post-development Q_2 to 0.5 pre-development Q_2 is appropriate for this watershed.

Susceptibility of a site to erosion under present conditions did not indicate that erosion rates at that site were sensitive to hydrological changes. Sites with fine materials (D_{50} < 10 mm) tended to have high transport rates under current conditions but the results of this study indicated that changes in hydrology would only slightly increase bedload yields at these sites. Almost all discharges have the competence to move sediment at these sites, but transport rates calculated with Meyer-Peter and Müller equations increase only slightly as discharge increases. As shown in Figure 23, the slope of the curve relating sediment discharge to water discharge varies with sample site. Cross sections 1, 4, 7, 10, 14, and 15 all have fine sediments, lower slopes in Figure 23 and little increase in bedload yield estimates with increased magnitude or duration of Q_2. Insensitivity of sediment transport rates to increased discharge at cross sections with fine sediment could be an artifact of the equations used to estimated sediment transport rates. These competence-based equations might capture the threshold at which motion likely begins, but differences between actual and calculated sediment transport rates increase with discharge. Results obtained with these equations should be considered together with other observations that can validate the guidance they offer.

Future anticipated exurban development in Kelley Creek, including increasing in impervious surfaces from current 6% to approximately 19% in the future (Savage 2006) will not only change hydrological patterns and influence channel erosion, but they also will alter surface erosion processes and their rates. Surface erosion processes observed in the field included grading and filling and excavating to make improvised roads. Near some of these places, fine textured sediment had accumulated in the channel. These activities and their associated surface erosion would most likely decrease following construction of buildings, roads, and pavement.

Regulating the discharge patterns in Kelley Creek will do little to reduce channel erosion where modifications to the stream channel alter hydraulics, causing local scour and deposition. These modifications include small dams, road crossings, straightened channels and filled floodplains, which confines the channel. Nearly every sample location is influenced by alterations to the channel made by landowners or land managers. These local impacts could be addressed through restoration, public outreach, riparian conservation and road crossing reconstruction. Managing stream channel erosion in an urban context requires dual consideration of altered hydrology and localized structural impacts.

The end of the era of agriculture and forest harvest comes in the Kelley Creek watershed provides an opportunity to protect the stream channel and the organisms that inhabit it from potential damage caused by urbanization. Distinguish between geologic processes and anthropogenic impacts, which will allow us to target our efforts appropriately and determine the most effective approaches. Sediment transport and channel erosion rates are driven by topographic slope, available supply and stream power. The Missoula Floods deposited fine-textured sediment on Kelley Creek's valley floor. The stream channel will continue to adjust to this sediment influx at rates limited by its slope and discharge. Future human development will likely disturb the hydrologic patterns in Kelley Creek. The results of this study suggest that stream reaches with steeper slopes and coarser sediments are more sensitive to these hydrological changes than reaches with more moderate slopes and finer sediments. Direct modifications to the stream channel can dramatically alter channel hydraulics and cause erosion or deposition where it did not previously occur. Protecting the channel from increased erosion rates following development will require both managing the hydrograph and minimizing direct stream channel alterations. Kelley Creek's local scale response to changes imposed by dense human populations will be ultimately driven by long term geomorphic processes occurring basin-wide which have provided a unique set of sediment conditions.

Recommendations for further investigation

Several methods could be used to quantify sediment transport rates in the Kelley Creek watershed and improve prediction of channel erosion rates in response to hydrologic changes. Long-term, net transport rates could be measured at road crossings and ponds on the stream channel with known history of impoundment. Measurements of transport rates during moderate flows could be done with pit samplers and would help to calibrate equations (Wilcock 2001). Such calibration would provide guidance regarding the best equations to use for various sample sites. The resulting sediment transport rating curve would have reduced uncertainty, providing insight into the significance of results.

CONCLUSION

The Kelley Creek watershed, a 12 km^2 watershed on the urbanizing fringe of Portland presents unique challenges in managing anthropogenic stream channel erosion. This system is still adjusting to influx of up to 10 m of silt-sized sediment deposited during multiple Missoula Flood episodes during the late Pleistocene. After a fire burned the forest in this watershed in the mid 19^{th} century, European settlers began to clear and cultivate the land, and construct roads and houses. Activities of the European settlers altered channel by eliminating beavers which maintained dams, building permanent dams and artificial ponds, and hardening the channel. Human influence on geomorphological processes is also evident in road crossings, floodplain fill, bank armoring, soil cultivation and earth movement. The hydrologic network has been extended via ditches along roads. Preventing regeneration of forests and constructing impervious surfaces has likely led to changes in the hydrologic flow patterns. The sediment transport regime in Kelley Creek is adjusting to the influx of catastrophic flood deposits on the basin scale, while the 200 year history of settlement is influencing local scale erosion and deposition rates. Given the large supply of fine sediment, the legacy of agricultural and forestry land use, and rapid urbanization in the watershed, managers are justifiably concerned to identify strategies that prevent future increases in stream channel erosion and ultimately protect aquatic habitat.

Kelley Creek has recently been incorporated into Portland's urban growth boundary, and in the near future will become increasingly urbanized. Urbanization both reduces vegetation and increases impervious surfaces, leading to increased total runoff, reduced time to peak and increased peak flows. In attempts to mitigate the increased flooding and channel degradation caused by these hydrological changes, managers have built storage and infiltration facilities, which can attenuate peak flows, but also increase the duration of peak flows. It has been suggested (Booth and Jackson 1997; Roesner, Bledsoe et al. 2001) that increasing the duration of current 2-year peak discharges (i.e., the amount of time in each water year that flows exceed the 2-yr peak) would increase annual erosion rates.

Sediment transport equations were used to test which effect – increased peak heights, or increased peak duration - would affect sediment transport more. Model results suggest that in the Kelley Creek watershed, the unmitigated doubling of peak discharges increases erosion slightly more than extending the duration of the 2-year peak. However, Monte Carlo simulation indicates that increases in erosion rates for extending the duration of the 2-year peak are only significant at 2 out of 13 cross sections. The scenario that increases magnitudes of intermediate storm flows provides the most benefit in terms of minimizing development-induced erosion. In the Kelley Creek watershed, sediment transport patterns fall into one of two categories: transport or supply limited. Bedload transport capacity increases sharply with doubled 2-yr peak discharges in supply limited sites, which have coarse sediments (D_{50} > 10 mm). Increases in bedload transport rates at these sites will likely be limited by supply from upstream and the hillslope. In contrast, bedload transport rates increase only slightly with doubled 2-year peak discharge magnitudes or longer peak duration in transport limited sites, which have abundant supplies of fine materials in a low-gradient channel. This counterintuitive finding is apparently due to the fact that sediment transport equations predict transport rates more accurately near incipient motion thresholds, with accuracy decreasing as discharges increase above threshold levels. Furthermore, factors such as cohesion and impoundment are not accounted for in transport equations, but influence transport of fine materials in these low gradient reaches. Further study could include calibration of the equations to validate the apparent differences in sensitivity to hydrograph changes.

Local sediment transport rates and their response to increased development depend on long-term geomorphic processes occurring at the basin scale. These geomorphic processes drive stream channel geometry and characteristics of sediment supplies. Kelley Creek is adjusting in recent inputs of alluvial fine sediments, which left its valley floor with low gradient. This large supply of fine sediment and associated adjustment process pose challenges in distinguishing how humans' presence on the landscape influences stream channel erosion.

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APPENDICES

Appendix A. Symbols

Symbol	Description	Units
A	cross sectional area	(m^2)
A_{BF}	cross sectional area at bankfull stage	(m^2)
A_g	contributing area of catchment to gage site	(ha or km^2)
A_s	contributing area of catchment to sample site	(ha or km^2)
C_s	concentration of suspended sediment	(mg/L)
C_d	concentration of dissolved sediment	(mg/L)
D_i	diameter of sediment particles, which i% are smaller than	(m)
D_m	arithmetic mean diameter of the sediment	(m)
f	Darcy-Weisbach bed friction factor	dimensionless
g	acceleration of gravity	(m/s^2)
$h_{\max}$	maximum depth	(m)
M	mass of sample	(g)
n	number of records	
p_i	fraction, by weight, of the bed sediment of mean size, D_i	(%)
P_w	Wetted perimeter	(m)
Q_2	discharge with 2-year recurrence interval	(m^3/s)
Q_{2s}	discharges at the sample site with 2-year recurrence interval	(m^3/s)
Q_{2g}	discharge at gage location with 2-year recurrence interval	(m^3/s)
Q	water discharge	(m^3/s)
Q_i	flow with i^{th} rank in annual discharge values, by magnitude	
$Q_{\tau c}$	critical discharge for initiating motion of sediment	(mm/hr)
q_b*	Dimensionless bedload flux	dimensionless
q_b	Bedload discharge	($m^3\ s^{-1}\ m^{-1}$)
RBS	Relative bed stability index	
R_h	Hydraulic Radius	(m)
R_{e*}	Critical boundary Reynolds number	
S	stream slope, measured as bed slope	dimensionless
SC	specific conductivity	(µS/cm)
TC	temperature coefficient	
U	mean flow velocity	(m/s)
U_{*c}	shear velocity at initial motion	(m/s)
V	volume of sample	(ml)
v	kinematic viscosity of the water	(m^2/s)
θ_c	dimensionless Shields' parameter, often also referred to as dimensionless critical shear stress, τ*	dimensionless
ρ	fluid density	(kg/m^3)
ρ_s	sediment density	(kg/m^3)
τ_c	critical shear stress	(N/m^2)

Appendix A. Symbols (Continued)

Symbol	Description	Units
τ_o	skin friction shear stress, effective bed shear stress	(N/m^2)
τ_{Q2}	skin friction shear stress for the discharge with a 2-year return interval	(N/m^2)
ϕ	porosity	

Appendix B. Material properties

From Todd and Mays (2005)

Material	Density (kg/m^3)	Porosity
Quartz	2650	
basalt	3011	17
fine gravel		34
silt stone		35
silt		46

Fresh water at 20°C

Density	1000 kg/m^3
Kinematic viscosity	1.02×10^{-6} m^2/s
Acceleration due to gravity	9.81 m/s^2

Appendix C. Unit Conversions

Volume	1 m^3 = 1000 L = 35.315 ft^3
Density/Concentration	1 g/cm^3 = 1000 kg/m^3
	1 mg/L = 0.001 kg/m^3
Time	1 yr = 31557600 s
	1 hr = 3600 s
Length	1 ft = 0.3048 m
	1 in = 0.0254 m
Temperature	°C = (°F-32) (5/9)