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Sediment sources in an urbanizing, mixed land-use watershed

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Abstract

The Issaquah Creek watershed is a rapidly urbanizing watershed of 144 km^2 in western Washington, where sediment aggradation of the main channel and delivery of fine sediment into a large downstream lake have raised increasingly frequent concerns over flooding, loss of fish habitat, and degraded water quality. A watershed-scale sediment budget was evaluated to determine the relative effects of land-use practices, including urbanization, on sediment supply and delivery, and to guide management responses towards the most effective source-reduction strategies. Human activity in the watershed, particularly urban development, has caused an increase of nearly 50% in the annual sediment yield, now estimated to be 44 tonnes km^{-2} yr^{-1}. The main sources of sediment in the watershed are landslides (50%), channel-bank erosion (20%), and road-surface erosion (15%). This assessment characterizes the role of human activity in mixed-use watersheds such as this, and it demonstrates some of the key processes, particularly enhanced stream-channel erosion, by which urban development alters sediment loads.

Keywords: Sediment budget; Urbanization; Washington; Development; Streams

1. Introduction

Non-point source pollution has been recognized as a significant source of surface water quality problems since the early 1980s (Novotny and Olem, 1994). Among the most ubiquitous of these pollutants is sediment eroded from the landscape, either from natural or anthropogenic sources. Construction, agriculture, mining, and timber harvesting accelerate natural erosion rates, increasing the supply of sediment to surface water.

Fine and coarse sediment transported by surface water can result in different types of problems. Fine sediment generally causes water-quality problems, both in-channel and to receiving water bodies. In addition to turbidity concerns, other non-point source pollutants such as nutrients and heavy metals can form complexes with the clay minerals in fine sediment, contributing to lake eutrophication and toxicity to aquatic organisms that live in or feed on bottom sediments (Novotny and Olem, 1994). Fine sediment also can occupy pore spaces in salmon spawning gravel, limiting permeability and reducing oxygen delivery to fish eggs deposited in the gravel (Bjornn and Reiser, 1991). In contrast, increased coarse sediment supply does not raise chemical concerns but can cause channel aggradation, resulting in

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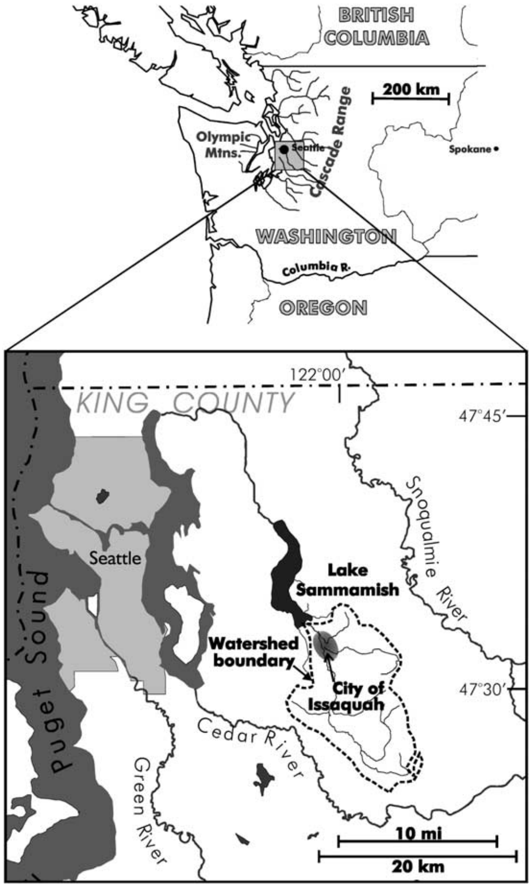

Fig. 1. Location map showing boundary of Issaquah Creek basin.

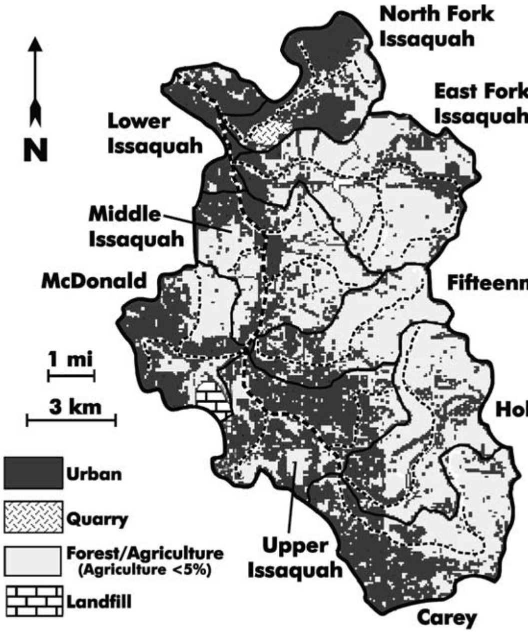

Fig. 2. Basin map showing tributaries and generalized land uses.

reduced flow capacity that can lead to flooding or navigational problems and channel instability.

Urbanization may ultimately result in decreased local surface erosion rates when large areas are covered with impervious surfaces such as roadways, rooftops, and parking lots (Wolman, 1967). However, urbanization can also indirectly increase channel erosion and downstream sedimentation by increasing the frequency and volume of channel-altering storm flows (Leopold, 1968; Hammer, 1972).

The purpose of this study was to develop a sediment budget for an urbanizing watershed by evaluating significant sources, quantities, and delivery of sediment produced from the variety of potential upland and in-stream erosion processes, and in particular to evaluate the ways in which human activity has altered predevelopment processes and rates. The study was conducted in the Issaquah Creek watershed, a 144-km^2 urbanizing watershed located in the Cascade Range foothills and adjacent lowlands about 30 km southeast of Seattle, Washington. The Issaquah Creek watershed is experiencing rapid growth and shares many of the sediment-related water quality concerns being experienced by watersheds at the urban fringe throughout developing regions.

2. Description of the Issaquah Creek watershed

The Issaquah Creek watershed is located in King County, Washington, east of Seattle (Fig. 1). It ranges in elevation from 10 m above sea level at its northern end, at Lake Sammamish, to 915 m above sea level on the summit of West Tiger Mountain, southeast of the City of Issaquah. There are six major tributaries to Issaquah Creek (Fig. 2) and tens of kilometers of first- and second-order channels that feed these main tributaries. Issaquah Creek and its tributaries have vastly different geomorphic characteristics, a consequence of the varied topographic and geologic features of the subcatchments they drain (Booth and Minard 1992; Booth 1995). The headwater streams, Carey and Holder creeks, originate in steep bedrock

Table 1
Summary of land-use and land-cover areas (ha) by sub-basin[a]

Sub-basin	Forest	Urban					Open water	Mining	Agriculture/grass	Landfill	Construction	Roads[b]	Total area (ha)
		Low dev.	Mod. dev.	High dev.	Comm./Ind.	UPD							
North Fork	425	115	256	49	12	181	<1	89	24	0	12	36	1199
Lower Issaquah	168	168	85	15	0	0	<1	0	107	0	10	42	596
Holder	1598	88	6	1	0	0	<1	0	29	0	0	23	1745
Fifteenmile	1050	124	4	1	0	0	0	0	3	0	0	21	1203
East Fork	2027	154	73	5	26	0	4	0	39	0	12	77	2416
Carey	1517	216	12	3	0	0	1	0	182	0	0	46	1979
Upper	1289	425	15	3	0	0	2	0	103	40	0	53	1930
Issaquah	1656	249	29	5	0	0	4	0	68	0	10	63	2085
McDonald	820	267	31	2	0	0	4	0	94	77	0	12	1308
Total area (ha)	10,551	1808	512	85	38	181	15	89	649	117	44	372	14,462
Percent of basin	73.0	12.5	3.5	0.6	0.3	1.2	0.1	0.6	4.5	0.8	0.3	2.6	

[a] Data compiled from GIS land-use/land-cover and geology data layers (King County 1992 and 1995b), and estimated construction rates (King County, 1998).
[b] Includes all gravel and paved roads, except those in storm-sewered developments.

channels draining Tiger and Taylor mountains and drain primarily a forested and agricultural landscape. Fifteenmile Creek drains the steep slopes of Tiger Mountain and is primarily forested. East Fork Issaquah, McDonald, and mainstem Issaquah creeks flow along relatively low-gradient alluvial valley bottoms, receiving runoff from smaller channels draining the adjacent hillslopes with a mix of rural, suburban, and urban land uses.

Land-use in the watershed also varies widely, although 73% is still forested (Fig. 2 and Table 1). The State of Washington Department of Natural Resources (DNR) manages much of the forested property for silviculture, conservation, and recreation. While most of the forested land was harvested in the early part of the century, timber harvesting activities are no longer a dominant activity in the watershed and only 70 ha yr^{-1} (about 0.5%) are harvested by the DNR on Tiger Mountain (Washington DNR, 1986).

Similar to other areas located on the fringe of urban-metropolitan areas, the Issaquah Creek watershed is experiencing rapid urban growth. Urban land uses, including residential and commercial development, occupy approximately 19% of the area. Whereas low-density residential development is scattered throughout the watershed, most of the high-density urban areas are within the City of Issaquah, low in the watershed. Other land uses in the watershed include quarry (1%) and landfill (1%) operations, and small-scale agriculture (4%). Road surfaces occupy approximately 2% of the watershed area. Issaquah is also home to the State's only urban salmon hatchery, operated by the Washington State Department of Fish and Wildlife on the mainstem of Issaquah Creek.

3. Previous studies

The vast majority of sediment budgets reported in the published literature have been conducted in forested drainage watersheds, including several in the Pacific Northwest (Dietrich and Dunne, 1978; Reid, 1981; Madej, 1982; Slaymaker, 1993; Paulson, 1997), and one in a watershed adjacent to Issaquah Creek watershed (King County, 1995a). In mountainous regions of the Pacific Northwest, hillslopes are the dominant erosional features in the landscape, with landslides contributing the majority of sediment to those watersheds (Dietrich and Dunne, 1978; Slaymaker, 1993; Paulson, 1997). In logged watersheds, forest road construction and road-surface erosion also become important sources (Reid, 1981; Madej, 1982).

Fewer studies are available in urban watersheds, and most have focused on particular sediment sources. Wolman and Schick (1967) found that construction activity in once-forested watersheds can increase sediment yield up to several orders of magnitude. Trimble (1997) examined the role of channel-bank erosion in sediment yield from the 228-km^2 San Diego Creek watershed, an urbanizing watershed in southern California. In that study, sediment production from channel enlargement accounted for approximately two-thirds of the measured suspended sediment yield and downstream sediment accumulation.

4. Approach and methods

For this study, sediment-production processes and rates were stratified into the following land-use categories:

- urban areas
- agriculture
- forest/timber harvesting
- construction areas
- landfill
- quarry

At the scale of a 100 + km^2 watershed, direct measurements of sediment loads are infeasible because of variability in both space and time (e.g. Benda and Dunne, 1997). The strategy used here was to apply established procedures for estimating sediment-production rates, using field evidence to calibrate rates and to verify the reasonableness of predicted in-stream sediment loads. Our analysis emphasizes the relative sources of sediment, and in particular the manner(s) in which the influence of urban development is manifest in watershed processes. Fine and coarse sediment production rates were quantified separately, because of their differing expression in the downstream system, and because of differences in the problems and management solutions associated with each. Some sediment-production

Table 2
Methods used to calculate sediment production from various land uses/activities

Land-use category	Sediment production element	Method	Value used	Reference
Urban	Low-density residential	TSS yield coefficient	50 kg ha^{-1} yr^{-1}	Reinelt (1996)
	Moderate-density residential	TSS yield coefficient	322 ha^{-1} yr^{-1}	Horner (1992)
	High-density residential	TSS yield coefficient	350 kg ha^{-1} yr^{-1}	Reinelt (1996)
	Commercial	TSS yield coefficient	805 kg ha^{-1} yr^{-1}	Horner (1992)
	Hatchery	Unit area discharge	Variable	See text
Agriculture	Surface erosion	USLE	Variable	Wischmeier and Smith (1978)
Forest/timber	Landslides	Matrix	Variable	This study
	Soil creep	Creep rate	1 mm yr^{-1} over 0.25 m soil depth	Saunders and Young (1983)
Construction	Surface erosion	TSS yield coefficient	97 tonnes km^{-2} yr^{-1}	Reinelt (1996)
Landfill	Surface erosion	Unit area discharge	Variable	See text
Quarry	Surface erosion	Unit area erosion	162 tonnes km^{-2} yr^{-1}	King County (1995a)
Channel-bank erosion	Enlargement	Regression analysis	Variable	Booth (1990)
Road-surface erosion	Paved roads	TSS yield coefficient	502 kg ha^{-1} yr^{-1}	Mar et al. (1982)
	Gravel roads	TSS yield coefficient	3.4 tonnes km^{-1} yr^{-1}	Reid and Dunne (1984)
	Forest roads	TSS yield coefficient	36 tonnes km^{-1} yr^{-1}	Reid and Dunne (1984)

processes, particularly road-surface erosion and channel-bank erosion, are not unique to a specific land-use and so these elements were evaluated separately.

Land-use and land-cover classifications, sub-watershed areas, road lengths, and channel lengths were determined using geographic information system (GIS) data compiled by King County Department of Natural Resources (DNR) (King County, 1992; King County, 1995b). An annual rate of building construction, and thus of presumed land clearing, was estimated based on data from the King County Annual Growth Report (King County, 1998) and a review of aerial photographs.

Sediment transported into channels from urban land areas, construction sites, the landfill, quarry operations, agricultural areas, and road-surface erosion can reach the channel network only by transport in suspension and so are overwhelmingly fine-grained (defined here to be <2 mm, based on the maximum particle size observed in the Issaquah Creek delta in Lake Sammamish). Mixed sediment, with both 'fine' (<2 mm) and 'coarse' (>2 mm) particle sizes, enter the channel primarily from bank erosion and landslides. Sixteen sediment samples from channel beds, banks, point bars and landslide debris at different geographic locations within the watershed were obtained for analysis of grain-size distribution, using seven different sieves ranging in size from 150 μm (US Standard #100 sieve) to 267 mm (US Standard 1.05-in. sieve). The grain-size data were used to establish relative percentages of fine (<2 mm) and coarse (>2 mm) material delivered to the stream channel from the various sediment-production processes.

4.1. Calculation of sediment production rates

Sediment production from the different land uses in the watershed was estimated using a variety of techniques and references (Table 2). Published yield coefficients for total suspended solids (TSS), nearly all from the Pacific Northwest, were used for many of the urban land uses, including residential and commercial development, construction areas, quarry, and road-surface erosion. These coefficients typically represent the average annual fine sediment delivered by a stormwater conveyance system to an outlet point downstream of the land-use being measured. These outlets almost invariably maintain a direct channel to the natural stream network, and so storage is negligible and delivery approaches 100%. It is difficult to discern the upland processes responsible for sediment production in these types of studies, however, as the values represent cumulative sediment production from all upland activities.

4.1.1. Urban land-cover

TSS pollutant yield coefficients were used for several of the urban sub-categories (Table 2). The TSS pollutant yield coefficients used to estimate sediment production from residential and commercial development include sediment produced from all activities in those developments such as atmospheric deposition, road-surface erosion, and park and playground erosion. In newer subdivisions, stormwater retention/detention facilities may remove some fraction of the sediment that may otherwise be transported to receiving waters. The same pollutant yield coefficients were applied to all residential land, however, because visual inspection and maintenance reports suggest little if any long-term sediment storage is occurring, either in the facilities themselves or in the pipes and ditches that discharge into the stream network.

A number of sediment-producing processes are initiated or modified by urban activity. These include construction site erosion, road-surface erosion, and channel-bank erosion. Although these erosional processes are a direct result of urbanization, they were evaluated separately from the 'urban' land-use category in this sediment budget. Road sanding is largely offset by road and catch-basin maintenance. Approximately 400 tonnes of sediment are removed annually from catch-basin cleaning in the City of Issaquah, a volume roughly equivalent to the amount of sand placed on road surfaces during winter months (B. Heath, personal communication, 1998).

The Issaquah Salmon Hatchery discharges water to Issaquah Creek during its daily operations. Sediment production from the hatchery was estimated through a review of influent and effluent chemical data and historical flow records.

4.1.2. Agriculture

Sediment production from agricultural property

Table 3
Landslide matrix. Values are in tonnes km^{-1} yr^{-1} of sediment delivered to channel in represented slopes and geologic units

Slope (%)	Geology					
	Ice-contact	Bedrock	Glacial till/Bedrock	Advance outwash	Recessional outwash	Fan deposits
<6.5	0	0	0	0	0	0
6.5–13	26	59	8	0	0	0
13–20	0	20	0	47	0	0
20–27	0	145	0	0	0	0
>27	0	145	0	0	0	0

was calculated using the universal soil loss equation (USLE) (Wischmeier and Smith, 1978), which incorporates rainfall, soil erodibility, vegetation, and topography. Data to determine variables in the USLE were obtained from topographic maps (USGS, 1983; 1993a,b; 1995), soil surveys (USDA, 1973), and field observations of vegetative cover. This approach will tend to overestimate the contribution of this source to sediment loads, because typical reported delivery ratios are only about 10–50%.

4.1.3. Forested land-cover

The dominant erosional processes in the forested region of the watershed are soil creep, landslides, and road-surface erosion.

4.1.3.1. Soil creep. A creep rate of 1 mm yr^{-1} over a 0.25-m soil depth was used in this study, based on rates published by Saunders and Young (1983) for similar geologic and climatic conditions (Anderson, 1977). Soil creep was only calculated for those slopes immediately adjacent to the channel network, where an intervening floodplain is absent. Although soil creep occurs on all slopes, it was assumed that the delivery of soil creep from areas not immediately adjacent to channels can be neglected because its delivery rate into channels is inconsequential. Additionally, creep along channels with established floodplains, such as the mainstem of Issaquah Creek, was not included in the calculations because soil creep could not be separated from channel-bank erosion. Soil creep into roadside ditches was also neglected because measured road-surface erosion rate coefficients account for this process.

4.1.3.2. Landslides. Landslides in this watershed are associated almost exclusively with stream channels, and so an inventory of slides was made by evaluating conditions along several representative tributary streams where sediment delivery is nearly equivalent to sediment production. Landslide volumes were estimated from length, depth, and width measurements of observed landslide scars adjacent to the channels. The slides were classified into three age categories, estimated from vegetative growth:

- < 5 yr—characterized by fresh scars and little or no vegetation;
- 5–10 yr—characterized by sparse vegetation consisting of sword ferns, moss, and salmonberries;
- 10–20 yr—characterized by moderately dense vegetation consisting of small alders, salmonberries, and ferns. Little or no bare dirt is present.

Delivery ratios (defined as the amount of sediment delivered by the landslide to adjacent channels) were assigned for three different landslide-size categories, based on field estimates of original landslide volume and amount of sediment delivered to the channel:

Landslide volume (m^3)	Delivery ratio (%)
28	100
28–256	85
>256	65

Landslides were categorized into 5 slope and 6 geologic categories (Table 3). Average landslide volume delivered per length of channel (in each geologic and slope setting) per year was then determined by dividing the estimated volume (delivered to the channel) of each observed landslide by the maximum estimated age, scaled by the length of channel walked in the particular slope and geology

(Booth and Minard, 1992; Booth, 1995, Table 3). For each of the slope and geologic categories adjacent to channels (King County, 1995b), the estimated volume of sediment delivered by landslides to the channel network was multiplied by the lengths of similar channel types in the entire watershed to determine overall sediment input.

Large landslides are rare in the watershed and are readily recognized on aerial photographs, available at scales ranging from 1:4800 to 1:200,000. Only the largest slides documented in the field were visible in the photos, as most of the slopes are densely forested and the photo resolution limits accurate documentation of smaller slides. Two such landslides (volume greater than 1000 m^3) were observed in the field and on aerial photographs adjacent to Holder Creek. They were excluded from the landslide matrix but were included in the overall sediment production estimate. For the purposes of estimating annual sediment contribution from these large landslides, it was assumed that the recurrence interval would be approximately 50 yr, based on the observed vegetation on the two scarps.

Landslides were observed in a variety of field settings, including densely forested conditions and adjacent to clearcut areas. In contrast to reports from other areas of poorly executed logging, there was no obvious correlation between observed landslide frequency and proximity to recent timber harvesting.

4.1.4. Construction

Current construction rates indicate that the watershed is developing at a rate of approximately 44 ha yr^{-1}, about 0.3% of the total watershed area. Of the many pollutant yield coefficients available for bare ground, a value of 97 tonnes km^{-2} yr^{-1} (Reinelt, 1996) was used here, because it was derived from a regional study with similar climate, topography, and construction practices. Because constructed urban drainage systems are ubiquitous in areas of new construction, delivery of the eroded sediment to the stream network was assumed to be total.

4.1.5. Landfill

Surface water from portions of the Cedar Hills Landfill, located in the southern part of the Issaquah Creek watershed, drains into the McDonald Creek sub-watershed. Estimates of annual TSS loading to McDonald Creek from the landfill were calculated using TSS surface water quality data collected at the outfall of the landfill, hydrologic simulation program Fortran (HSPF) modeled discharge data (King County 1990) for McDonald Creek subcatchments to determine a unit-discharge relationship, and stream gage data from the McDonald Creek gage station.

4.1.6. Quarry

An 89-ha gravel quarry is located north of Interstate 90 in the North Fork Issaquah sub-watershed. The gravel quarry has extensive surface water and sediment control measures and recycles most runoff generated on-site. Observations during several storm events in the winter of 1998–1999, however, indicate that the on-site stormwater and sediment control measures are not completely effective, and that this quarry is at least occasionally a source of fine sediment to the channel.

Sediment production from surface mining activities has been reported up to 100,000 tonnes km^{-2}-yr^{-1} (Novotny and Chesters, 1981). King County (1995a) reported annual sediment production from the nearby Sunset Quarry, in the adjacent Tibbetts Creek watershed, to be nearly 500 tonnes, or 1720 tonnes km^{-2} yr^{-1}. This would represent a maximum value for the North Fork Issaquah quarry, which has significantly better water-quality controls. A lower bound of quarry sediment production would depend on the efficiency of the water treatment system and how often overflows into the adjacent channel network occur. Based on observations and agency reports, a delivery ratio one-tenth that of the Sunset Quarry or 178 tonnes km^{-2} yr^{-1}, was assumed.

4.1.7. Channel-bank erosion

Bankfull channel areas can be predicted from regional discharge values, either measured or modeled, and measured channel dimensions (Wharton et al., 1989; Booth, 1990). Modeled 2-yr discharges using HSPF for forested (pre-development) and current (1989) conditions (King County, 1990) were used to calculate changes in stream discharge from past land-use changes in the Issaquah Creek watershed. Bankfull width and depth measurements were made in the field at representative sites along the main channel in each of the major sub-watersheds, using observations of vegetation, floodplain heights, and

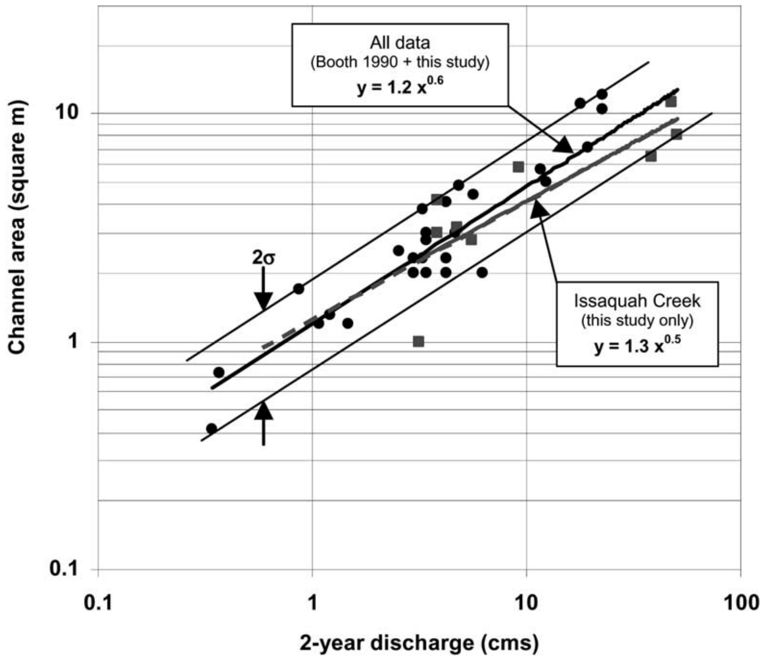

Fig. 3. Regression of measured channel area vs. modeled 2-yr discharge for this study only (in gray) and all data from this study and Booth (1990).

slope breaks (Williams, 1978). Their products were plotted against the modeled 1989 2-yr discharge data (Fig. 3). The resulting regression equation is

$$A = 1.3{Q_2}^{0.5} \quad (1)$$

where A = channel cross-section area (m^2) and Q_2 = two-yr discharge (m^3 sec^{-1}).

The change in channel area from pre-development to current conditions were calculated for the main tributaries using Eq. (1) and the change in modeled 2-yr discharges (current minus forested). Absent more precise information, predicted channel changes were assumed to have occurred uniformly over the 80 yr since development began in the watershed. Because the number of points in the Issaquah Creek data set were insufficient to make a good estimate of uncertainty, the combination of points from this study and Booth (1990), which are statistically indistinguishable, were combined to determine the 2σ boundaries shown in Fig. 3.

Although alluvial channels of any size will enlarge with increased flows, those less than 1.4 km^2 were not modeled by King County (1990). Lacking pre-development flow data, they were not included in this analysis. Approximately 53 km of alluvial tributary channels were thus excluded from this calculation, about 50% of the alluvial channel network (but uniformly the smallest channels in the watershed). The final estimate of watershed-wide sediment delivery from channel expansion is thus a minimum value.

4.1.8. Road-surface erosion

There are approximately 420 km of roads in the watershed, crossing all categories of land-use and land-cover. For the purposes of this study, roads were divided into three categories: ‘paved,’ ‘gravel residential,’ and ‘gravel forested.’ Roads in residential areas that are connected to storm sewer systems were not included in the road-surface erosion calculations, because sediment from these roads would have been included in the sediment yield coefficient for urban residential areas. Gravel roads located within forested areas of the watershed were separated out from residential and other gravel roads, because these roads were built specifically for timber harvesting activities and will generally experience greater truck traffic, which results in higher sediment yields than from

Table 4
Summary of total sediment production from various land-uses/land-covers by sub-basin (coarse sediment in parentheses)

Land-use/land-cover	Sub-basin									Total
	North Fork	Carey	Holder	East Fork	Upper Issaquah	Middle Issaquah	Lower Issaquah	McDonald	Fifteenmile	
Forest										
Landslides	0 (0)	104 (41)	693 (270)	770 (300)	137 (53)	883 (344)	3 (1)	101 (39)	573 (223)	3264 (1271)
Soil creep	5 (2)	13 (5)	46 (18)	29 (11)	18 (7)	36 (14)	1 (0)	17 (7)	25 (10)	190 (74)
Roads	0 (0)	52 (0)	181 (0)	0 (0)	0 (0)	0 (0)	0 (0)	78 (0)	366 (0)	677 (0)
Urban										
Low-density residential	6 (0)	11 (0)	4 (0)	8 (0)	21 (0)	12 (0)	8 (0)	13 (0)	6 (0)	89 (0)
Mod.-density residential	82 (0)	4 (0)	2 (0)	23 (0)	5 (0)	9 (0)	27 (0)	10 (0)	1 (0)	163 (0)
High-density residential	17 (0)	1 (0)	0.4 (0)	2 (0)	1 (0)	2 (0)	5 (0)	1 (0)	0.2 (0)	30 (0)
Commercial/Industrial	10 (0)	0 (0)	0 (0)	21 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	31 (0)
Urban planned development	58 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	58 (0)
Hatchery	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	11 (0)	0 (0)	0 (0)	0 (0)	11 (0)
Mining	178 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	178 (0)
Agriculture/grass	1 (0)	13 (0)	1 (0)	6 (0)	22 (0)	4 (0)	5 (0)	7 (0)	1 (0)	60 (0)
Landfill	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	11 (0)	0 (0)	11 (0)
Construction	11 (0)	0 (0)	0.2 (0)	12 (0)	0 (0)	10 (0)	10 (0)	0 (0)	0 (0)	43 (0)
Roads (not including forest roads)	30 (0)	43 (0)	18 (0)	50 (0)	32 (0)	32 (0)	22 (0)	18 (0)	23 (0)	268 (0)
Channel-bank erosion	75 (56)	208 (156)	37 (28)	126 (95)	225 (169)	329 (247)	228 (171)	44 (33)	27 (20)	1299 (975)
Fine sediment (tonnes yr^{-1})	415	247	667	641	232	723	137	221	769	4052
Coarse sediment (tonnes yr^{-1})	58	202	316	406	229	605	172	79	253	2320
Total sediment (tonnes yr^{-1})	473	449	983	1047	461	1328	309	300	1022	6372

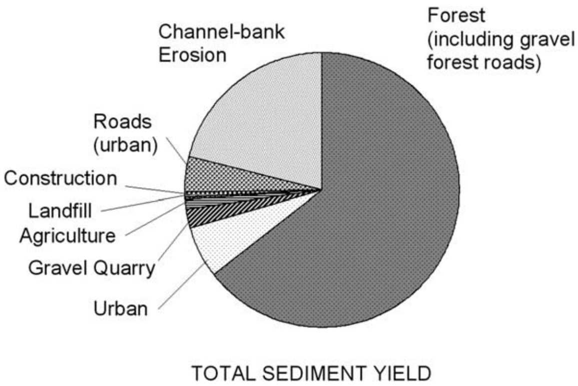

Fig. 4. Relative total sediment production from different land uses.

roads used primarily by passenger vehicles (Reid and Dunne 1984).

4.2. Sediment budget balance

Sediment production is only one part of a full sediment budget. Sediment storage and transport out of the watershed are also components, although we did not directly address either. We observed little evidence of fine-sediment storage and aggradation on the generally confined floodplain of the watershed, and we elected not to undertake a full analysis of fluvial routing of sediment along the channel network. Instead, independent data were collected to validate the estimated sediment-production rates and thus to evaluate indirectly the consequences of these intentional omissions. The methods used in this study included site-specific measurements and subsequent calculations of sediment transport and deposition at selected sites in the mainstem of Issaquah Creek, and an estimate of the rate of Issaquah Creek delta growth into Lake Sammamish.

4.2.1. Sediment transport and deposition

Bedload sediment transport calculations were made for two reaches on lower Issaquah Creek as part of the Issaquah Creek Basin Plan (King County, 1991) and on one reach of Middle Issaquah Creek for this study. Channel width, depth, and water-surface slopes, along with median subsurface particle sizes (D_{50}) and flow-duration data (King County, 1991) were input into Bagnold's (1980) sediment-transport equation to estimate annual sediment transport at the particular cross-sections evaluated. The calculated transport capacity was compared to the estimated upland sediment production in the mainstem of Issaquah Creek. Channel surveys from bridges, spanning as much as 30–50 yr between measurements, were also reviewed to determine general sedimentation trends along the mainstem channel of Issaquah Creek.

4.2.2. Delta growth

The Issaquah Creek delta is the repository for much of the fine sediment transported down Issaquah Creek, and it has been expanding into Lake Sammamish for at least 50 yr. The delta growth rate was evaluated using historical aerial photographs from 1944, 1961, 1965, 1970, 1978, 1985, and 1995. To estimate the volume of annual growth of the delta, the visible portion of the delta was measured and adjusted for slope, measured from the Lake Sammamish bathymetry map (King County, unknown date) and assumed to be constant. The slope of the non-deltaic shoreline was assumed to be the slope of the wedge underlying the delta. The volume of this wedge was subtracted from the calculated delta volume.

5. Results

5.1. Sediment production

The sediment production from upland sources and in-stream erosion in the Issaquah Creek watershed is approximately 6400 tonnes yr^{-1} (Table 4). Since the watershed is 73% forested, forest processes (landslides, soil creep and forest road erosion) understandably contribute the greatest volume of sediment, with the bulk coming from landslides (3264 tonnes). The next most voluminous sediment sources are channel-bank erosion (1299 tonnes), urban land uses (382 tonnes), and urban road-surface erosion (268 tonnes) (Table 4). Normalized by land area, the total watershed yield is 44 tonnes km^{-2} yr^{-1}, compared to an estimated predevelopment rate of 24 tonnes km^{-2} yr^{-1}. The greatest present-day sediment yields per unit area are from the steep forested sub-watersheds (Fifteenmile, Middle Issaquah, and Holder), followed by the most urban sub-watershed

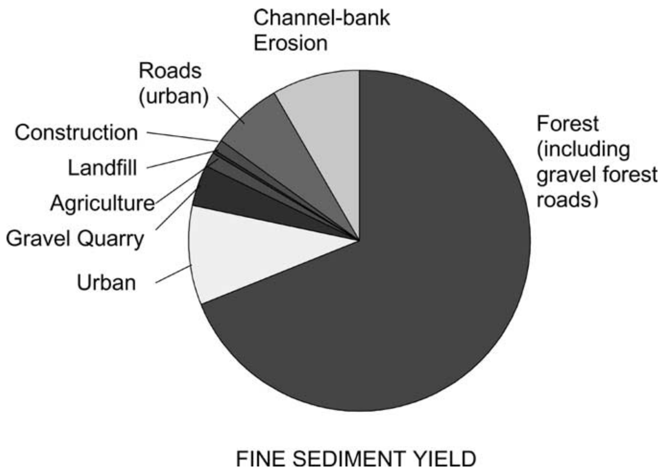

Fig. 5. Sediment yield by land-use.

(Lower Issaquah Creek). Although landslides and forest processes contribute most of the sediment in this budget, construction and other land-clearing activities yield the most sediment on a unit-area basis (Fig. 4). Agricultural sources are relatively low here, despite their (unrealistically) high assumed delivery ratio, because this land-use occurs only on the low-gradient valley bottoms. The predevelopment rate is based on the assumption that forested yield (i.e. landslides and soil creep), less the gravel road contribution, is a good approximation of pre-development conditions.

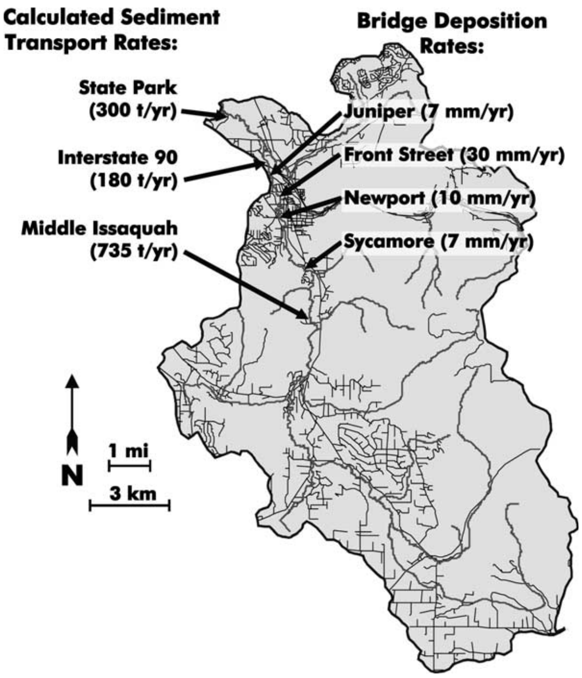

Fig. 6. Relative fine-sediment production from different land uses.

Sources of fine sediment, nearly two-thirds of the sediment production, are dominated by landslides (49%), followed by forested gravel roads (10%) and urban sediment production from residential and commercial areas (9%). Other sources that contribute significant percentages of fine sediment to the budget are channel-bank erosion (8%) and gravel-residential and paved roads (7%) (Fig. 5).

Only three processes evaluated for this sediment budget contribute coarse sediment to the overall budget: landslides, soil creep, and channel-bank erosion. Again, the dominant coarse sediment-producing process is landsliding activity (54%). Channel-bank erosion supplies 43% of the coarse sediment, with the remainder attributed to soil creep.

5.2. Validating the sediment budget

Unit-area rates of sediment yield and delivery, both measured and inferred from the literature values, range tremendously. Any confidence in sediment budget results can come only from independent evidence of the relative and absolute magnitudes of sediment erosion, transport, or accumulation. In this watershed, we have had the benefit of more than half a

Table 5
Estimated rates of sediment transport and predicted channel aggradation

Reach	Sediment input (tonnes yr^{-1})	Average sediment transport (tonnes yr^{-1})	Sediment surplus (tonnes yr^{-1})	Sediment surplus (m^3 yr^{-1})	Length of channel (km)	Width of channel (m)	Channel area (m^2)	Aggradation (mm yr^{-1})
Middle Issaquah	1700	735	965	601	8.5	12	102,000	6
Lower Issaquah	1155	300	855	533	5.1	12	61,200	9

century of observations that serve to validate the sediment budget predictions.

5.2.1. Patterns of fluvial transport and deposition

Calculated bedload transport rates in the lower portion of Issaquah Creek range from approximately 180–320 tonnes yr^{-1} (Fig. 6). Sediment transport in the Middle Issaquah reach, nearly 20 km upstream, is calculated at more than 700 tonnes yr^{-1}, suggesting the likelihood of long-term deposition through the intervening channel segment in the City of Issaquah. The calculated coarse sediment delivery rate exceeds the transport rate in the Middle Issaquah reach, which should, therefore, extend the anticipated zone of long-term deposition even farther upstream. Surplus bedload sediment equates to an aggradation rate of approximately 6 mm yr^{-1} in the Middle Issaquah reach and approximately 9 mm yr^{-1} in the Lower Issaquah reach (Table 5). These calculated aggradation rates compare favorably to measured long-term deposition of 7–30 mm yr^{-1} observed at bridge crossings in the City of Issaquah (Fig. 6 and Table 6).

In contrast to anticipated and observed aggradation, sediment transport rates in the lowermost section of Issaquah Creek suggest the potential for channel degradation. The calculated transport rate at the State Park (320 tonnes yr^{-1}) (King County, 1991) exceeds the calculated rate upstream at I-90 (180 tonnes yr^{-1}). To the 180 tonnes of coarse sediment per year transported into this reach, bank erosion from channel expansion in the lower reach should contribute approximately 110 tonnes yr^{-1} of coarse sediment, leaving a calculated net deficit of only 30 tonnes yr^{-1}. By both calculation and observation, this reach is likely in near-equilibrium.

5.2.2. Delta growth

Over the 51-yr span of available aerial photographs (Table 7 and Fig. 7), the average annual growth rate of the Issaquah Creek delta into Lake Sammamish requires approximately 2640 tonnes yr^{-1}. Almost no coarse sediment reaches the mouth of Issaquah Creek, whereas much (but certainly not all) of the fine sediment will come to rest on the delta. Thus the rate of fine-sediment production from the watershed should be of similar magnitude, but greater than, the rate of delta growth. The data are quite consistent: total fine sediment production for the watershed is estimated to be approximately 3820 tonnes yr^{-1}, about 1.5 times the average annual rate of delta growth.

6. Discussion

6.1. Effects of urban development

The overall estimated current sediment production in the watershed is 44 tonnes km^{-2} yr^{-1}, compared to a pre-development sediment production of 24 tonnes km^{-2} yr^{-1}. Consequently, urbanization has increased watershed-wide sediment production, primarily through channel erosion resulting from increased discharges, and this process now accounts for approximately 20% of the total watershed sediment budget. Other urban elements, including construction, road-surface erosion, and sediment production from residential and commercial areas, contribute an additional 12% to the total sediment production. Construction practices have been documented to be a major sediment contributor in urbanizing watersheds (Wolman and Schick, 1967); however, there is very little land being

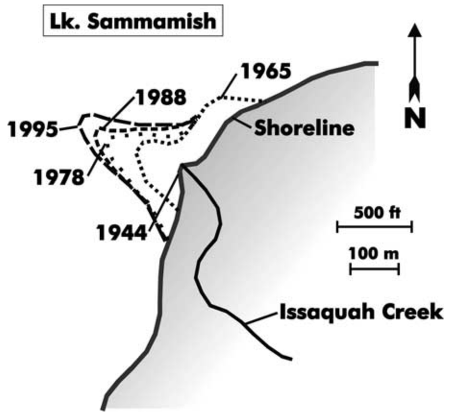

Fig. 7. Location of calculated sediment-transport rates (tonnes yr^{-1}) and sediment deposition at bridge locations (mm yr^{-1}).

developed (0.3% yr^{-1}) relative to the size of the watershed, and so construction contributes relatively little (< 1%) at present.

Although the urban areas of the watershed directly generate relatively little sediment, much of the sediment produced by channel-bank erosion can be attributed to urbanization. The larger channels in the watershed, including the mainstem of Issaquah Creek, are particularly susceptible to channel enlargement from increased discharges, insofar as all are situated in highly erodible valley-bottom deposits. Here and elsewhere, increased discharges resulting from urbanization cause channels to permanently enlarge to accommodate the new flow volumes.

6.2. Sources of error

Practical considerations limit the precision of any sediment budget (Reid and Dunne, 1996). Production rates of the various sources of sediment relied on data from other studies conducted outside of this watershed; not every landslide, stream, and other watershed feature could be field checked during this study. As a consequence, assumptions made in the evaluation of each particular study element have surely introduced inaccuracies.

The results most sensitive to such errors arise from those elements that produce the majority of the sediment: landslides, channel-bank erosion, and road-surface erosion. Landslides were evaluated on just 5% of tributary streams in the watershed, and the information gathered was extrapolated to stream channels that were not field checked. Landslides generally could not be identified on aerial photographs because of low photo resolution and dense vegetative cover. These factors, combined with the inherent difficulty of predicting landslides even with the most detailed survey, result in significant uncertainty in the calculated landslide sediment production rate.

Channel-bank erosion rates cannot be measured directly, and our approach of inferring increased erosion from increased discharge has two significant uncertainties. First, the correlation between the two-yr discharge and channel cross-section area (Fig. 3) is good but not precise—the 2σ uncertainty on this data set is about $\pm 60\%$. In addition, the lack of modeled discharges for the smaller tributaries means that channel-bank erosion can only be calculated for those mainstem tributary channels located in erodible geologic material. This represents only a fraction of the total channel network having potential to enlarge significantly with increased flows, approximately 50% by length but more than 80% by channel cross-sectional area. Thus we anticipate that the channel-bank erosion estimated here is most likely a minimum estimate; the true value could be modestly lower, or it could be as much as perhaps 60–80% higher. In either case our overall conclusion remains unchanged—this source is a very significant component of the total

Table 6
Average annual deposition at City of Issaquah bridges

Bridge location	Stream	Date of surveys	Number of years	Amount of deposition (m)	Average annual deposition (mm)
Front street	East Fork	1970–1997	27	0.82	30
Newport way	Issaquah	1970–1997	27	0.27	10
Sycamore	Issaquah	1968–1997	29	0.21	7
Juniper street	Issaquah	1949–1997	48	0.36	7

Table 7
Estimated rate of Issaquah Creek delta growth

Aerial photo (year)	Scale	Surface area (m^2)	Delta thickness (m)	Total volume (m^3)	Total volume (tonnes)	New volume (tonnes)	Tonnes yr^{-1}
1944	1:20,000	800	1	400	700		
1961	1:4800	4800	3	7700	12,300	11,600	700
1965	1:4800	4800	3	7700	12,300		
1970	1:24,000	6700	3	10,700	17,100	4700	900
1978	1:12,000	11,200	5	26,800	42,800	25,800	3200
1985	1:24,000	11,900	5	30,400	48,600	5800	800
1995	1:12,000	21,000	8	83,800	134,000	85,500	8600
Average over entire period:							2600

yield, and it may account for as much as 1/3 of the total under existing urbanizing conditions.

Road-surface erosion rates published in the literature span a very wide range, especially for gravel-surfaced roads. Depending on the rate chosen, sediment production from road-surface erosion could vary by more than an order of magnitude. Sediment production rates at the low end of the ranges established by Reid (1981) were chosen, based on the relatively low gradient of the gravel-surfaced roads in the watershed and the observations of generally light traffic throughout the duration of this study.

The net consequence of these uncertainties and potential errors is difficult to quantify directly, which is why we have emphasized the independent evidence for validation. Production rates cannot be substantially *less* than calculated here, or else the observed rates of delta growth and channel aggradation simply could not be supported. At worst, rates could be 50–100% greater, particularly from landslides and channel-bank erosion, within the constraints of our observational and sampling strategies—but even under this scenario, the management implications of this study (Section 6.3) would not be compromised by such a range.

6.3. Comparison to other studies

Sediment yields from different areas will vary because of geographic and climatic differences, differing study approaches and methodologies, and differing timescales of investigation. Results from other studies, however, provide a basis from which to evaluate the validity of our key assumed sediment-production processes and the resulting calculated yield of 44 tonnes $km^{-2}\,yr^{-1}$. Published sediment yields for Pacific Northwestlll forested watersheds

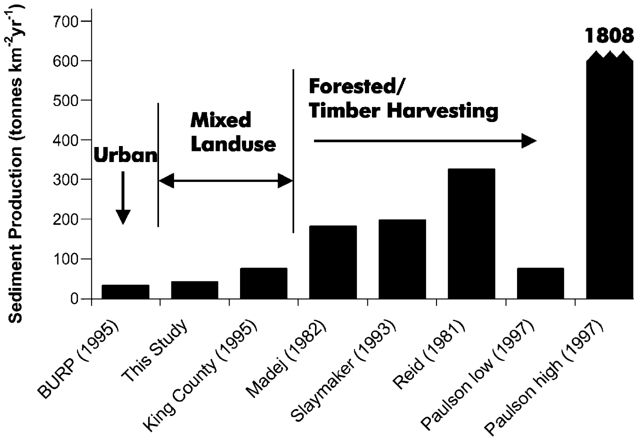

Fig. 8. Issaquah Creek delta growth in Lake Sammamish.

range from 76 to 1808 tonnes km^{-2} yr^{-1}, and for one urban sediment yield study (the 'Bellevue Urban Runoff Project'; City of Bellevue 1995) that range from 10 to 35 tonnes km^{-2} yr^{-1} (Fig. 8). Nelson's (1971) measurements of suspended sediment discharge in tributary streams of the adjacent Snohomish River watershed also provide additional comparisons. In that study, the three mixed-use sub-watersheds closest in size to Issaquah Creek had yields of 23 tonnes km^{-2} yr^{-1} (Patterson Creek, 40 km^2), 54 tonnes km^{-2} yr^{-1} (Woods Creek, 144 km^2), and 68 tonnes km^{-2} yr^{-1} (Raging River, 78 km^2). Nelson also estimated that his measured suspended-sediment yields probably reflected 88–95% of the total sediment yield at most stations.

As with our study, most sediment budgets conducted in forested areas have also found landslides to be the greatest contributor of sediment to overall watershed sediment production (Dietrich and Dunne, 1978; Slaymaker, 1993; Paulson, 1997). Gravel road-surface erosion, however, can also be an important sediment contributor (Reid, 1981; Madej, 1982; Paulson, 1997).

Trimble's (1997) study of the San Diego Creek watershed was the only study reviewed here that quantified channel-bank erosion resulting from urbanization. The San Diego Creek watershed is rapidly urbanizing and was approximately 50% urban at the time of Trimble's study. Other land uses in that watershed were agriculture and undeveloped property. Trimble found that approximately 67% of total sediment production from the San Diego watershed came from channel-bank erosion, consistent with the 20% contribution found in this study for a watershed that is 19% urbanized.

6.4. Management implications

The primary sources of sediment in the Issaquah Creek watershed are

- Landslides
- Channel-bank erosion
- Road-surface erosion

Of these processes, landslides and channel-bank erosion contribute both fine and coarse sediment, whereas roads primarily contribute fine sediment. Fine sediment is generally transported through the system out to Lake Sammamish, where it potentially contributes to long-standing eutrophication problems because of associated phosphorus. Coarse sediment accumulation has been implicated in reduced channel capacity and consequent flooding.

These sediment sources each pose unique problems and opportunities. The landslides here pose a difficult management scenario for watershed managers. The observed landslides are in 'natural' areas and are not obviously the result of human activity. Reducing the frequency of sediment delivery once ground failure had occurred would be costly, probably impractical, and potentially detrimental to sediment-dependent fish habitat farther downstream. In contrast, road-surface erosion in forested areas can be directly attributed to forest practices (Reid and Dunne, 1984). Maintenance of active roads, and closure and revegetation of roads that are no longer used, would likely have a significant impact on road sediment production and at least a modest effect on overall watershed sediment yield.

Probably the greatest opportunity to limit sediment production in the Issaquah Creek watershed, and in other urbanizing basins as well, is by reducing channel-bank erosion resulting from increased storm-water discharges. As urbanization continues, better efforts should be made to minimize increases in discharge to the channel network. Unlike more visible sources of sediment (such as construction runoff), channel enlargement is a process that can occur without notice until property is lost or structures are threatened. Localized channel-bank erosion could be reduced through revegetation efforts; however, erosion resulting from modified bank vegetation was not a significant percentage of the calculated channel-bank erosion here. If surface water discharges continue to increase in the Issaquah Creek watershed, channel enlargement will continue to be a significant source of sediment. Bank hardening and other management strategies may reduce localized erosion, but disproportionate enlargement may occur in other areas of the channel network as a result.

Other opportunities to limit sediment production will always exist for watershed managers in urbanizing areas, including greater control over sediment-laden discharges from construction and quarry properties. Yet where development patterns and rates are similar to those of this mixed-used urbanizing watershed, our results suggest that any resulting benefits may only be significant in the small channels draining those sites, and not to the channel network as a whole.

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