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Floods, channel change, and the hyporheic zone

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Abstract. We investigated the influence of flood-induced channel changes on the hyporheic zone of 4th- and 5th-order reaches of a mountain stream network. Preflood versus postflood comparisons were made in three study reaches from well networks established before and reestablished after a major flood. Flood effects were scale dependent and varied with channel constraint and the dominant channel forming process. Large changes were observed in unconstrained stream reaches where channel incision drove large changes in subsurface flow paths and the extent of the hyporheic zone. However, subreach scale differences were apparent. In the lower portion of the studied reach, channel incision lowered the water table, leading to abandonment of secondary channels, and decreased the extent of the hyporheic zone that previously extended more than 30 m into the floodplain. In contrast, the extent of the hyporheic zone increased at the head of the studied reach where channel incision steepened head gradients through a meander bend. In another unconstrained reach, lateral channel jumps dramatically altered exchange flow paths. However, the extensive hyporheic zone was maintained throughout the reach. Less change was observed in the constrained stream reach where both the depth and area of sediment available to be reworked by the flood were limited by bedrock constraining the width of the valley floor. This flood dramatically changed the hyporheic zone at the three study sites and these physical changes are expected to be biologically important, considering the role of the hyporheic zone in stream ecosystem processes.

1. Introduction

The hyporheic zone is the region in unconfined, near-stream aquifers where stream water is present, including zones where stream water is mixed with groundwater. There is growing recognition of the importance of the hyporheic zone to stream ecosystem functions [*Hynes*, 1983; *Findlay*, 1995; *Brunke and Gonser*, 1997], including stream metabolism [*Grimm and Fisher*, 1984; *Mulholland et al*., 1997], nutrient retention and cycling [*Triska et al*., 1989b; *Vallet et al*., 1996; *Wondzell and Swanson*, 1996b], habitat for aquatic insects [*Stanford and Ward*, 1988; *Williams*, 1984], flood refugia [*Dole-Olivier et al*., 1997] and ecosystem stability [*Grimm et al*., 1991; *Vallet et al*., 1994]. Most hyporheic research has focused on small to intermediate sized mountain streams [*Triska et al*., 1989a, b; *Harvey and Bencala*, 1993; *Valett et al*., 1996; *Wondzell and Swanson*, 1996a, b; *Morrice et al*., 1997]. These studies have treated the physical environment that gives rise to the hyporheic zone as static, except for hydrologic conditions that change in response to catchment wetness or stream discharge [*Meyer et al*., 1988; *Wroblicky et al*., 1998].

The hyporheic zone is created by flows of surface water into the subsurface and eventual return flows to the stream. These flows, called exchange flows, are driven by head gradients created by morphological features of stream channels. Exchange flows typically occur through point bars [*Vervier and Naiman*, 1992], between pools in pool-step sequences [*Harvey and Bencala*, 1993] and between primary and secondary channels where multiple channels are present [*Wondzell and Swanson*, 1996a]. The morphology of stream channels changes through time in response to geomorphic processes. For example, the combination of bank erosion and accretion of sediment on point bars leads to gradual lateral-channel migration of meandering, lowland rivers [*Leopold et al*., 1964]. Channel and valley floor morphologic features of steep, boulder-bedded mountain streams do not change gradually. Rather they are typically stable over long periods, changing abruptly during major floods.

Major floods and flood-related disturbances, such as debris flows, are the primary events shaping channel morphology in many high-gradient, mountain stream networks. Floods with recurrence intervals of 50 to 100 years leave a geomorphic imprint of sediment deposits and large woody debris (LWD) jams that can persist a century or longer in the Pacific Northwest [*Lyons and Beschta*, 1983; *Gottesfeld and Johnson-Gottesfeld*, 1990; *Gregory*, 1991; *Nakamura and Swanson*, 1993, 1994]. Because channel and valley floor morphology control exchange flows, major floods could dramatically change the spatial extent of hyporheic zone and the direction of subsurface flow paths and through these changes alter both the hydrologic residence time of water in the hyporheic zone and the rate of hyporheic exchange flow. Such physical changes are expected to be biologically important, considering the role of the hyporheic zone in stream ecosystem processes.

Our initial work on the hyporheic zone [*Wondzell and Swanson*, 1996a, b] viewed the valley floor and channel morphology as static. This view proved to be shortsighted when a major flood in February 1996 dramatically altered stream channels in

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Table 1. Peak Flows, Unit Area Discharge, and Average Recurrence Interval for Selected Gauged Watersheds at the H. J. Andrews Experimental Forest During the Floods of February 7, 1996, and November 18–19, 1996

					Feb. 7, 1996			Nov. 18–19, 1996		
Watershed	Period of Record	Treatment	Treatment Date	Size, ha	Peak Q, L/s	Unit Area Q, L/s/ha	R.I., years	Peak Q, L/s	Unit Area Q, L/s/ha	R.I., years
WS8	1964–1996	control	···	21.4	275	12.9	12.6	190	8.9	2.5
WS7	1964–1996	90% partial cut	1974	15.4	286	18.6	32.6	136	8.8	4.0
Mack	1980–1996	control	···	581	9,656	16.6	37.3	6,994	12.0	6.8
McRae*	none	~30% clearcut	1950–1970	1400	23,307	16.6	37.3	16,882	12.0	6.8
WS2	1953–1996	control	···	60.3	1,303	21.6	69.9	580	9.6	3.9
WS1	1953–1996	100% clearcut	1962–1966	96.9	2,387	24.9	52.1	1,274	13.3	3.8
Lower Lookout†	1958–1990	~30% clearcut	1950–1970	6242	155,743 to 226,560	25.0 to 35.8	50 to 100	84,384	13.5	6.8

R.I., recurrence interval.

*Peak discharge, unit area discharge, and return frequency calculated from Mack Creek discharge adjusted for difference in catchment area.

†Peak discharge in the February 1996 flood was uncertain due to deposition of as much as 1 m of alluvium in the control section where stream is gauged.

studied stream reaches. Well networks used for these hyporheic studies had been established in the Lookout Creek catchment before the flood of 1996. Reestablishing these well networks provided a unique opportunity to study the effects of geomorphic change on stream-groundwater interactions in a mountain stream network. Specifically, we examined the types and scales of change caused by major floods in (1) subsurface flow paths and (2) the areal extent of the hyporheic zone. To do this, we compared the preflood and postflood channel and valley floor morphology at three study sites. We examined how geomorphic processes reshaped stream channels during this major flood and how these changes influenced the hyporheic zone.

2. Methods

The Lookout Creek catchment (H. J. Andrews Experimental Forest) is located in the western Cascade Mountains of Oregon (44°10′N, 122°15′W). Elevation within the catchment ranges from 425 m at the mouth of Lookout Creek to 1600 m at the highest points along the drainage divide. Average annual precipitation is approximately 2500 mm, falling mainly between November and March [*Bierlmaier and McKee*, 1989]. Peak flood flows in the catchment are generated by rain-on-snow events. Above-normal snow pack combined with a 4-day period of record rainfall in early February 1996 caused major flooding, with peak discharge recorded on February 7, 1996 (Table 1). This flood was either the largest or second largest flood on record for gauged watersheds in the Lookout Creek catchment (Figure 1). Thus estimates of recurrence intervals are uncertain. Estimates for larger watersheds in the region with longer periods of discharge records indicate that flood recurrence intervals ranged between 50 and 100 years [*Hubbard et al.*, 1996].

2.1. Hyporheic Exchange Flows

McRae Creek (Table 2) was the site of an intensive study of hyporheic processes between 1989 and 1994. This site is located along a 4th-order, unconstrained stream reach (Figure 1). Data were collected to study changes in subsurface flow paths in response to changing stream discharge, and stream-groundwater interactions were simulated using a groundwater flow model [*Wondzell and Swanson*, 1996a]. Wells were installed at this site between 1989 and 1992 and reinstalled in the summer of 1996 following the methods described by *Wondzell and Swanson* [1996a].

The lower Lookout Creek site (Table 2) is located along a 5th-order stream reach that is tightly constrained between bedrock walls and a high terrace. Nineteen wells were established on a gravel bar in 1991. Three wells survived the flood intact. The original bench mark elevation used for surveying was reestablished from these wells. Twenty-four new wells were installed on the gravel bar in lower Lookout Creek in the summer of 1997.

A well network was established in middle Lookout Creek (Table 2) during the summer of 1996 to examine hyporheic exchange flows in an unconstrained reach of a large mountain stream. Floods during the winter of 1996–1997 (Table 1) destroyed many wells and changed channel morphology at this site. Destroyed wells were replaced during the summer of 1997.

Water table elevations were recorded from wells at each site and stream water elevations were measured outside of wells located in the wetted channel. Stream water elevations were also recorded when surveying longitudinal stream profiles. Kriging was used to interpolate water table elevations from measurements made from each well and from stream surface elevations measured at survey points in the main and back channels. Contour maps of water table elevations were drawn from the interpolated data using Surfer® (Golden Software, Inc., Golden, Colorado) and overlaid on base maps of each study site.

2.2. Flood-Caused Channel Changes

Repeat mapping of each study site was used to document flood-caused channel changes. A 400-m section of McRae Creek was mapped in 1989. Distances among secondary (open to through flow of stream water) and back channels (fed by upwelling of hyporheic water and groundwater without through flow of stream water); islands; key woody debris; and LWD jams were paced off and hand sketched. The stream reach was remapped after the flood, using low-level aerial photographs taken from a blimp tethered 20 m above the

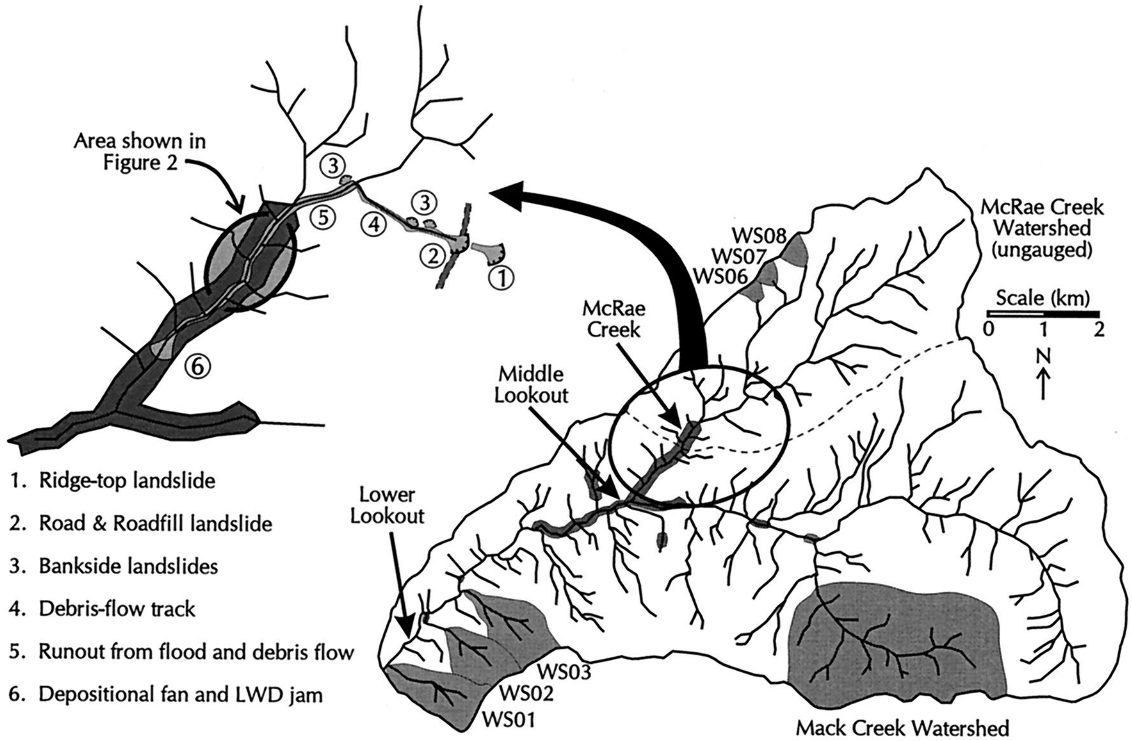

Figure 1. Location of study sites, gauged watersheds (light gray) and unconstrained stream reaches (dark gray) within the Lookout Creek catchment. The ungauged McRae Creek watershed (above the study site) is outlined (dashed line). Inset shows the lower 3 km of McRae Creek.

active channel. Photos were printed at a scale of 1:180 and pasted together to provide a detailed image from which a postflood map of the stream channel was drawn. The preflood map was redrawn to 1:180 scale by overlaying it on the postflood map and using relic features to locate the prior positions of secondary channels and islands. After channels were drawn to scale, the approximate positions and size of key woody debris pieces and LWD jams present before the flood were drawn. A 200-m section of McRae Creek was mapped in 1991 [*Wondzell and Swanson*, 1996a] and remapped in 1996.

Aerial photographs of the valley floor of Lookout Creek were taken in 1989 at a scale of 1:2250. Photographs of the middle Lookout Creek study site were scanned and screen digitized to map the preflood channel. Low-level aerial photographs of middle Lookout Creek were taken in the summers of 1996 and 1997 from a blimp tethered 60 m above the active channel. These photos were printed at a scale of 1:350 and pasted together to provide a detailed image of the 900-m reach from which 1996 and 1997 postflood maps of the stream channel were drawn.

The lower Lookout Creek site is located on a small cobble bar in a narrow, highly constrained stream reach. The site is not visible in aerial photographs. However, channel configurations, the location and extent of cobble bars, and the key woody debris within this reach were mapped in the summer of 1990 [*Nakamura and Swanson*, 1993]. Well locations on the gravel bar were mapped in 1991 following the methods used at McRae Creek [*Wondzell and Swanson*, 1996a], and the site was remapped in 1997.

Channel down cutting and in filling were documented at each study site. Stream longitudinal profiles were surveyed at McRae Creek on three dates. Stream water levels were surveyed in 1990 at 10-m intervals along the left bank. In 1993 the elevation of the streambed was surveyed at 1-m intervals down the center of the wetted channel, and water depth was recorded. The longitudinal profile of the streambed was resurveyed in 1996, following the methods used in 1993, except that survey points were spaced at ~5-m intervals in the upper stream reach. A valley floor cross section at the McRae Creek study site was surveyed in 1989, with points located 1.0 m apart,

Table 2. Reach Attributes for the Three Studied Stream Reaches

Study Site	Area, ha	Length of Study Reach, m	Gradient, m/m	Valley Floor Width, m	Active Channel Width, m	VFWI, m/m	Sediment Size Distribution D_{50}	Sediment Size Distribution D_{84}
McRae	1400	245	0.032	75	13	5.6	70	510
Middle	4996	310	0.018	90	15	6.0	94	229
Lower	6242	91	0.016	22	17	1.3	98	275

VFWI, the valley floor width index, is the ratio of valley floor width to active channel width [*Grant and Swanson*, 1995]. Size distributions of streambed sediment from *Lambert* [1997].

except in the active stream channel, where survey points were 0.5 m apart. The cross section was resurveyed in 1996. The longitudinal profile of the streambed of middle Lookout Creek was surveyed in 1996 and resurveyed in 1997. Stream water elevations were surveyed in 1991 along the bank of the gravel bar in lower Lookout Creek. The longitudinal profile of the streambed of lower Lookout Creek was surveyed at 1-m intervals down the center of the wetted channel, and the water depth was recorded in summer 1997. Monumented cross sections were established in lower Lookout Creek in 1978. Three cross sections bracket the studied gravel bar. Cross sections were surveyed in 1995, the summer before the flood, and resurveyed in the summers of 1996 and 1997.

3. Results

3.1. McRae Creek

McRae Creek was the site of intensive hyporheic studies between 1989 and 1994 [*Wondzell and Swanson*, 1996a, b]. During this time, no changes in the channel morphology or position of large woody debris (LWD) were observed. Further, characteristics of LWD and the distribution of age cohorts of alder established in the late 1960s (Julia Jones, unpublished data, 1996) suggest little channel change had occurred since the winter of 1964–1965, the date of the last major flood.

Large changes in channel morphology and the position of LWD were apparent after a flood in February 1996. A debris flow originated in a tributary channel near the watershed divide, 300 m above the valley floor of mainstem McRae Creek (Figure 1). The debris flow entrained road fill from a road spanning the channel and was augmented by smaller streamside slides along this 0.9-km-long, 1st-order channel, eventually adding ~2000 m^3 of sediment and an unknown quantity of LWD to the mainstem of McRae Creek (M. Wallenstein and F. J. Swanson, unpublished data, 1996). The wood and sediment continued down lower McRae Creek more than 2 km. Further changes in channel morphology and the position of LWD have not occurred since the summer of 1996, although large floods occurred during the winter of 1996–1997 (Table 1).

The lower 2.5 km of McRae Creek flows through a 50- to 100-m-wide floodplain (Figure 1). Prior to the 1996 flood, the active channel was narrow and incised approximately 2 m into the floodplain, except where blocked by LWD jams. A thick wedge of sediment had collected behind two LWD jams approximately 2 km above the mouth of McRae Creek (Figure 2), raising the elevation of the streambed to within <1 m of the floodplain surface. The active channel was braided around many small gravel bars and a higher island upstream of the LWD jams. The flood of 1996 breached the LWD jams (Figure 2) and the channel cut down through the wedge of accumulated sediment (Figure 3). Large logs were deposited in levees along the stream banks. The levees concentrated flood water into a single channel, enhancing scour and down cutting in the primary flood way. Mouths of secondary channels were blocked by LWD because logs were too large to navigate narrow, secondary channels and sharp bends in the primary channel. Thus secondary channels were protected from scour during peak flood flows, so the preflood elevation of the streambed in secondary and back channels did not change. Incision of the primary channel exceeded 2 m in the lower end of this reach (Figure 3) and caused the abandonment of secondary channels. McRae Creek now flows through a deep, narrow, single-thread channel (Figure 2).

Incision of McRae Creek into the floodplain at the lower end of the reach led to a corresponding drop of the water table in near-stream zones. Vertical changes in water table height of ~1 m near the stream bank propagated laterally more than 30 m into the floodplain (Figure 4), rerouting subsurface flow paths. Before the flood a back channel in the lower end of the reach acted as a drain, collecting subsurface flows of groundwater from the floodplain and hyporheic water from McRae Creek (Figure 5). Extensive down welling occurred throughout the lower end of this reach where hyporheic flow paths were oriented 45° away from the stream. The incision of McRae Creek caused the water table to drop so that subsurface flows were no longer intercepted by the back channel after the flood. Rather, groundwater from the floodplain flows under the back channel, through the cobble bar and is discharged to the stream. After the flood, down welling in the lower reach occurred only in limited areas (Figure 5).

At the upper end of the intensively studied reach, lateral channel changes created a sharp bend in the stream (Figure 2). Sediment deposition at the very head of the reach and channel incision downstream steepened head gradients through this meander bend (Figure 5). Consequently, the head of the reach was converted from a zone of groundwater discharge before the flood to a zone of hyporheic exchange flow after the flood.

3.2. Middle Lookout Creek

Aerial photographs dating to 1959 record a history of floods that left a network of secondary and back channels within the floodplain. Before the February 1996 flood a back channel was present in the lower end of the reach (Figure 6). The back channel followed a former mainstem channel of Lookout Creek along a bedrock outcrop at the base of the valley wall. Lookout Creek occupied this channel after a flood in 1964 (1967 aerial photo) and then abandoned it after flooding in 1977 (1979 aerial photo).

Lateral jumps in the location of the active channel exceeded 30 m during the February 1996 flood (Figure 6). The large gravel bar present on the right side of the active channel in 1989 was bisected by a new channel formed in the February 1996 flood. A new back channel on the left side of the active valley floor marks the location of the preflood channel. Sediment deposited by the February flood was reworked by smaller floods during the winter of 1996–1997. Some lateral channel changes are obvious in the lower third of the study site where a high bank of gravel was isolated as a midchannel bar. Changes in streambed elevations were small at this site in the floods of 1996 and mostly limited to localized filling or scouring of pools (Figure 7), with the exception of the mouth of McRae Creek near the head of the study site. Cobbles and boulders from McRae Creek were deposited at the mouth of McRae Creek in the February 1996 flood, raising the streambed elevation. McRae Creek began cutting down through the accumulated sediment during the winter of 1996–1997.

Well networks were not established until the summer of 1996, so changes in hyporheic exchange flow resulting from the February flood are based on channel features visible in aerial photographs taken in 1989. The hyporheic zone probably occupied the entire lateral extent of the active valley floor on both sides of middle Lookout Creek before February 1996 (Figure 6). Surface flow was present along the length of the right back channel after the flood and there was no evidence of

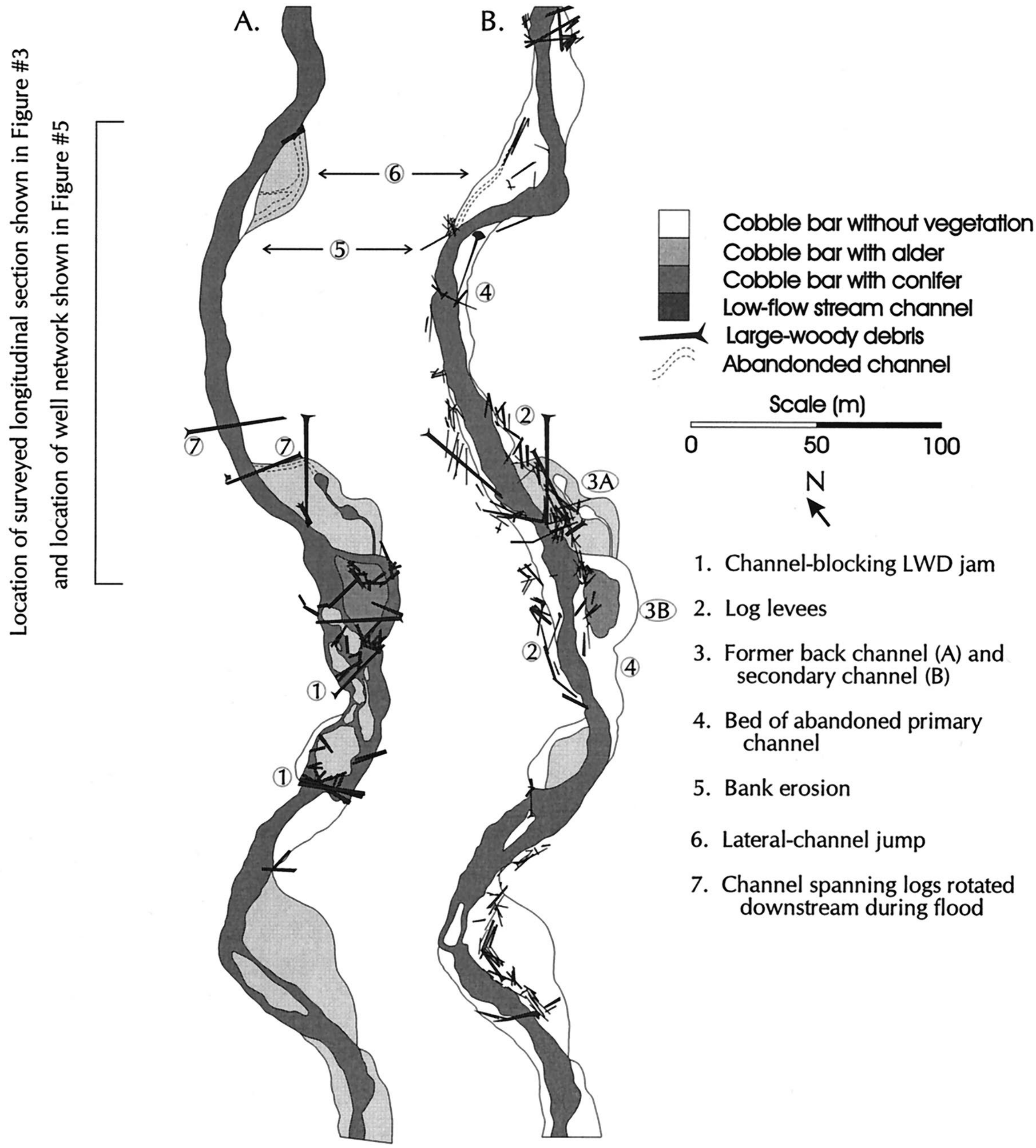

Figure 2. Lower McRae Creek showing the general planform of the active channel, locations of key woody debris, secondary channels, and gravel bars (a) before and (b) after the flood of February 1996.

recent down cutting that would have reactivated this channel following the February 1996 flood. Down cutting of the primary channel must have occurred because several logs cabled to bedrock in a pool at the mouth of the back channel were left hanging from their cables, ~0.5 m above the stream, after the flood. Because the back channel remained wetted even though the primary channel down cut, it is reasonable to assume that the back channel would have collected upwelling hyporheic water before the flood just as it did after the flood. Subsurface flows would have been dominated by 30- to 40-m-long exchange flows between the primary and the right back channel at the lower end of the reach (Figure 6).

Exchange flow paths should have been abruptly altered by lateral jumps in channel location during the February 1996 flood. After the flood, exchange flows were dominated by down welling of stream water along the upper and middle portions of each gravel bar (Figure 8). Steep head gradients were also present at steps (or riffles) in the primary channel and at the junction of McRae and Lookout Creeks. Vertical hydraulic gradients through the streambed exceeded 3.0 in the newly deposited sediment at the mouth of McRae Creek. Exchange flows maintained extensive hyporheic zones beneath both gravel bars. Hyporheic water upwelled into springs at the heads of both back channels and seeped from the riverward bank of each back channel (Figure 8). Strong upwelling was not observed in wells along the mainstream. Instead, return flows of

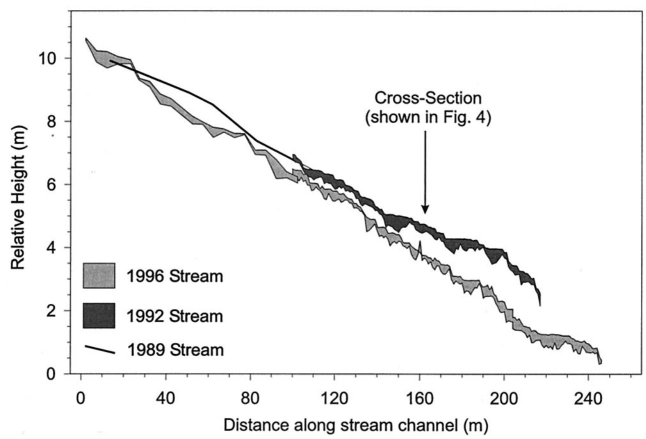

Figure 3. Longitudinal profile of McRae Creek before and after the flood of February 1996. The area between the surface of the stream water and the streambed is shaded. The location of the surveyed cross section (Figure 4) is shown. LWD jams are just downstream of the surveyed stream reach.

hyporheic water flowed out of the stream banks along the lower parts of both gravel bars. Groundwater was not seeping into the right back channel during the summer because the bedrock that lines its bank against the valley wall was dry.

3.3. Lower Lookout Creek

Largest changes in channel morphology occurred at lower Lookout Creek during the February 1996 flood. Observations of the site and remeasurement of channel cross sections showed that little change occurred during floods in the winter of 1996–1997. The gravel-bar surface was scoured by bed load and floating logs during the February 1996 flood. Many wells were snapped off at the ground surface, and 10 to 20 cm of gravel was deposited in some areas (Figure 9). However, the sediment of the gravel bar could not have been deeply scoured and replaced during the flood, otherwise four 3.8-cm-diameter plastic wells and a 1-m-long piece of wood partially buried in the channel would not have remained in place after the flood. Net change in sediment-surface elevations resulting from the February 1996 flood did not exceed 50 cm at cross section 2 (Figure 9). Changes to the planform of the gravel bar in the vicinity of the well network were also small (Figure 10). However, there was great spatial heterogeneity in erosion, transport, and deposition of bed load sediment. Approximately 1 m of gravel was deposited in the stream channel at cross section 3. The net effect was to dramatically extend the headward length of the gravel bar and deflect the stream into the opposite bank (Figure 10).

Prior to the flood, exchange flows at the head of the gravel bar were driven by steep head gradients around a step (or riffle) between two pools. Down welling occurred along the upstream half of the gravel bar, in the area near cross section 2 (Figures 9 and 10). Exchange flow at the tail of the bar resulted from head differences between the primary channel and an off-channel (backwater) embayment. A large pool at cross section 3 was filled with gravel during the February flood (Figure 10). After the flood the stream was shallow and spread across a wide sheet of gravel at the head of the reach before dropping over a steep riffle into a deep pool. There is extensive down welling across the entire sheet of gravel above the riffle, and water flows out of the stream banks below the riffle. Changes in the locations of pools and steps reduced head gradients in the center of the reach, near cross section 2, after the February flood (Figure 9). Changes in subsurface flow paths have increased water table elevations across the width of the gravel bar at cross section 2 (Figure 9). There is a small zone of exchange flow at the tail of the bar where part of the off-channel (backwater) embayment still exists (Figure 10).

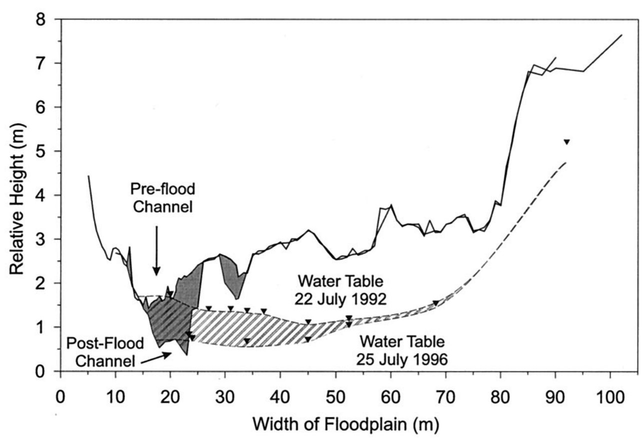

Figure 4. Cross section through the floodplain and channel of McRae Creek before and after the flood of February 1996. Cross-sectional area of sediment lost by erosion (light gray) and the loss in saturated thickness of the aquifer (cross-hatched) are shown. The lower "apex" of solid triangles shows the water table elevation observed in wells near the cross section. Dotted line shows the interpolated water table elevation along this transect. Difference between wells and the dotted line is because wells are not located exactly on the cross section.

4. Discussion

4.1. Channel Change and Type of Geomorphic Processes

Previous research in mass-movement-prone mountain catchments [*Costa*, 1981; *Montgomery and Buffington*, 1997] has shown that geomorphic change in headwater channels tends to be dominated by landslides and debris flows whereas larger streams are dominated by fluvial processes. This distinction between channel forming processes is important because it helps determine the frequency and magnitude of changes to channel and floodplain morphology. In the Lookout Creek catchment, fluvial processes dominate in the 5th-order mainstem of Lookout Creek [*Lambert*, 1997]. Third- and 4th-order streams, such as McRae Creek, are transitional between debris flow–dominated channels of headwater streams and fluvially dominated channels.

Channel changes resulting from mass movement events are different than those resulting from fluvial processes alone [*Costa*, 1981]. Fluvially formed channels in unconstrained stream reaches tend to be wider and shallower, with width-to-depth ratios greater than 12 [*Johnson*, 1970; *Costa and Jarrett*, 1981; *Costa*, 1981]. The cross-sectional profile of the primary channel of McRae Creek resembled a deep U-shaped trough after February 1996. The width:depth ratio of the channel decreased from approximately 12 before the flood to 6 after the flood (Figure 4), suggesting that fluvial processes alone did not form the channel. A track of distinctive riparian disturbance and channel change extended 2 km down McRae Creek,

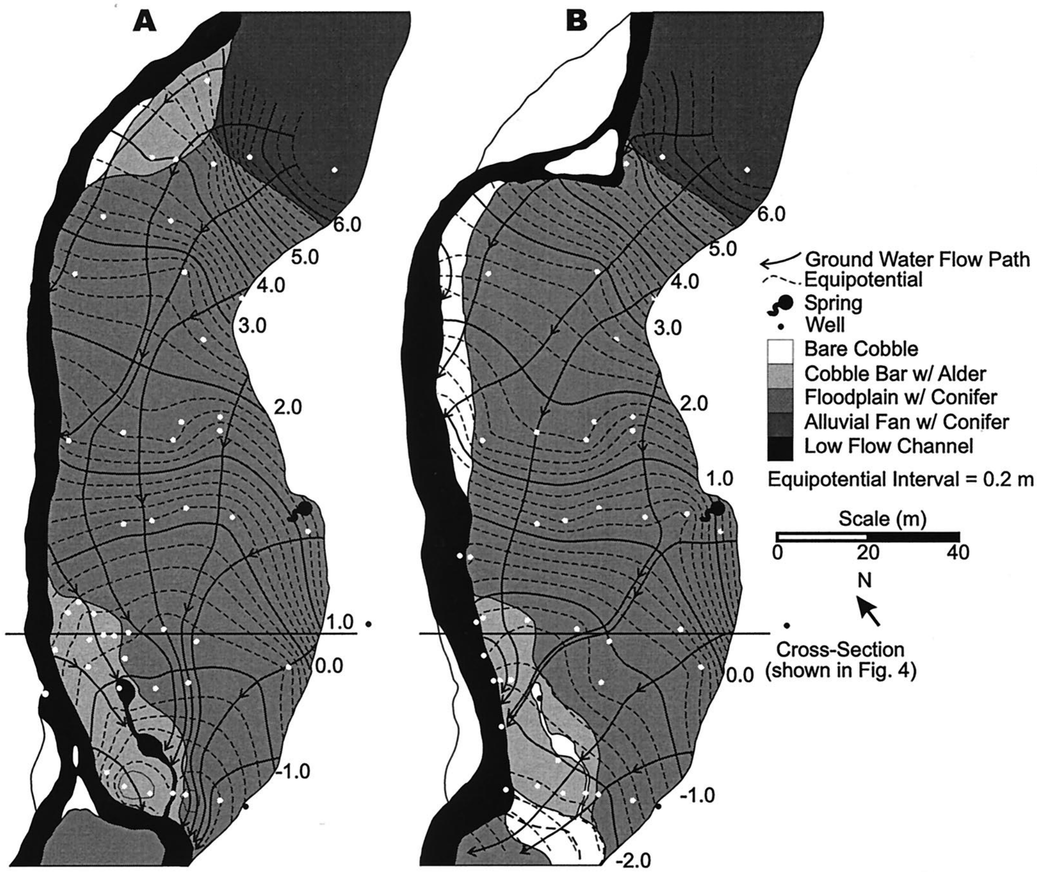

Figure 5. Changes in the water table and subsurface flow net at McRae Creek before (July 22, 1992) and after (July 25, 1996) the February 1996 flood. Equipotentials interpolated from water table elevations observed in the wells shown on each map and from survey points located along the stream channel (not shown). Bold lines with arrows show subsurface flow paths of water. Water table elevations along the surveyed cross section are shown in Figure 4.

from the junction of the tributary channel where the debris flow occurred. Debris flows rarely travel long distances in low-gradient streams, nor were poorly sorted debris-flow deposits present along the banks of McRae Creek. This evidence suggests that channel changes were caused by movement of LWD carried down the channel in a surge of flood water and not by debris flows or fluvial processes alone. *Braudrick et al.* [1997] studied log movement in flume experiments. Transport regimes ranged from uncongested, when logs moved as single pieces, to congested, when logs moved as a single mass occupying more than 33% of the stream channel area.

The descriptions of congested wood transport agree with observations of LWD deposits and channel changes in McRae Creek after the 1996 flood. LWD was deposited on stream banks along McRae Creek and in a LWD jam at the end of the 2-km-long disturbance track. This LWD jam extended across the full width of the valley floor. Sediment accumulated behind the jam formed a thick wedge that extends 50 to 100 m upstream and is dissected by secondary and back channels. A similar event may have led to the development of the braided channels and gravel bar complex associated with LWD jams that were present before February 1996, just downstream of the intensively studied reach (Figure 2). These observations suggest that recent changes to the McRae Creek channel resulted from the congested transport of LWD. Channel changes and the transport of LWD would be expected to be infrequent. This agrees with my observations of the active channel after peak flows of 15.6 m^3/s in 1990 (recurrence interval of 4.9 years) and 16.9 m^3/s in November 1996 (recurrence interval of 6.8 years) in which the channel, bar, and LWD configurations did not change.

Geomorphic changes occur frequently in unconstrained reaches of the 5th-order mainstem of Lookout Creek. Large changes were evident after major floods in 1964 and 1996, but changes also occurred after smaller floods in 1977, 1986, and during the winter of 1996–1997. While channel-forming processes are fluvially dominated, LWD is also an important agent of geomorphic change. However, congested transport of logs was not observed in the 5th-order mainstem of Lookout Creek during the 1996 flood (F. J. Swanson, personal observation, 1996). Rather, the predominant mode of LWD transport was as single pieces. The movement of single logs occurs when water depth exceeds the buoyant depth of the log [*Ishikawa*, 1990; *Braudrick et al.*, 1997]. Batches of LWD added to the mainstem by debris flows in tributary channels disaggregated once they reached Lookout Creek because flood waters were sufficiently deep and wide to float the largest logs.

LWD interacts with flood water and can substantially alter flood-related channel changes. Landslides, debris flows, and peak rates of LWD movement occurred at or prior to the peak

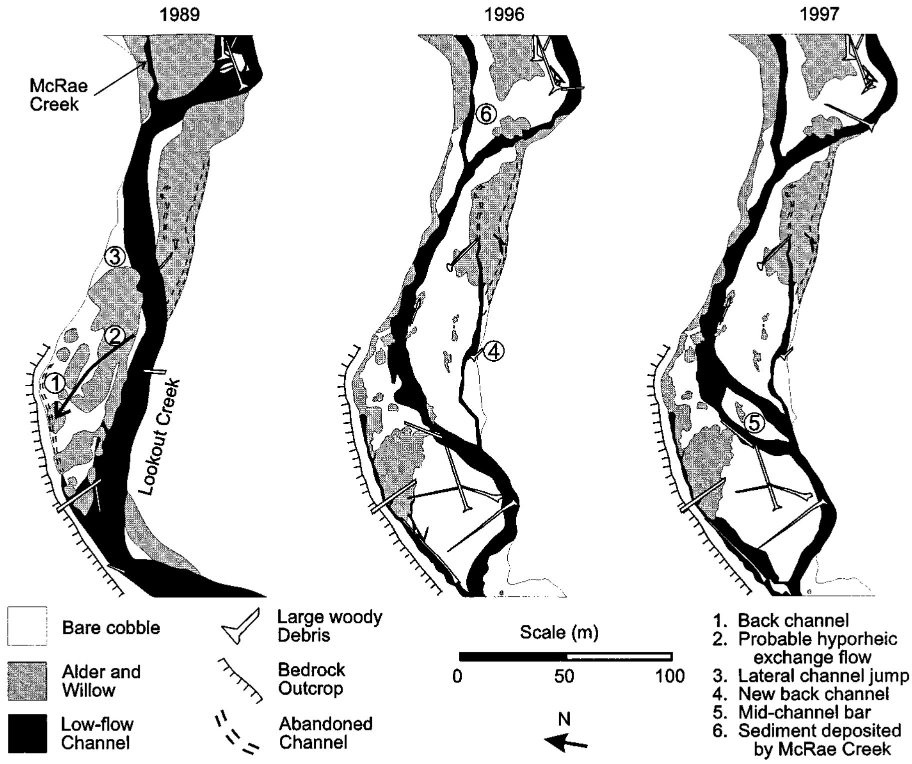

Figure 6. Middle Lookout Creek showing the general planform of the active channel, locations of key woody debris, secondary channels, and gravel bars in the summer of 1989, in the summer of 1996 after the flood of February 1996, and in the summer of 1997 after floods during the winter of 1996–1997.

of the February 1996 flood (F. J. Swanson, personal observation, 1996). Further, LWD added to the channel by tree fall between major floods [*Lienkaemper and Swanson*, 1987] and some wood added to the channel by debris flows early in the storm were not lodged in stable LWD jams and were vulnerable to transport by flood water. Consequently, abundant amounts of LWD were available to affect fluvial processes during peak flood stage. Especially important was the blocking of active channels by LWD which forced lateral-channel jumps in unconstrained stream reaches [*Gottesfeld and Johnson-Gottesfeld*, 1990]. These channel changes differ from gradual, lateral-channel migration in that LWD abruptly diverts flow, causing the stream to reoccupy abandoned channels.

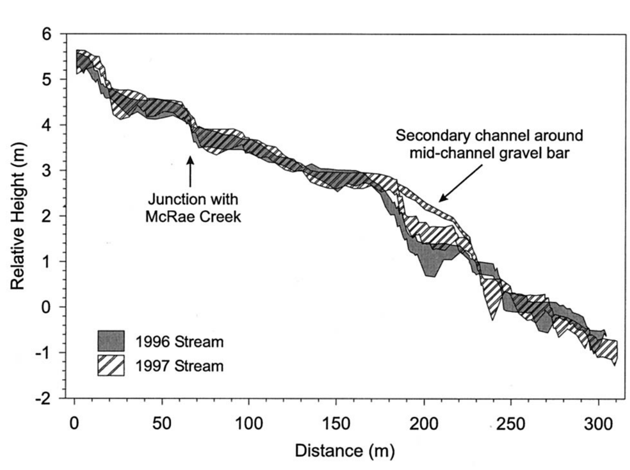

Figure 7. Longitudinal profile of middle Lookout Creek surveyed before and after floods during the winter of 1996–1997. The area between the surface of the stream water and the streambed is shaded.

4.2. Channel Change and Hyporheic Impacts

The magnitude of changes observed in the hyporheic zone in response to changes in channel and floodplain morphology result from (1) the type of the morphologic factor controlling exchange flow and (2) the potential change in head gradients resulting from flood and flood-related changes in channel morphology.

4.2.1. Change in streambed elevation.

4.2.1.1. The channel-unit scale. At the channel-unit scale, floods may scour new pools and may deposit sediment to create new riffles or fill old pools, thus changing both the number and location of pool-step units. Changes at this scale can alter the extent of the hyporheic zone and the locations of down welling and upwelling sites. For example, sediment deposition and pool in filling shifted the large riffle and the primary location of down welling within the constrained reach of lower Lookout Creek (Figure 10). The extent of the hyporheic zone also increased where sediment accumulated at the head of the studied gravel bar. Similar changes at the channel-unit scale were observed in the unconstrained reach of middle Lookout Creek, but had little effect on hyporheic exchange flows. Instead, subsurface flow paths were controlled by reach-scale differences in head between primary and back channels.

The changes observed in the hyporheic zone of McRae Creek at the channel-unit scale are compounded by the larger, reach-scale changes. Focusing only on the channel-unit scale, the fine-scale survey of McRae Creek (Figure 3) showed that

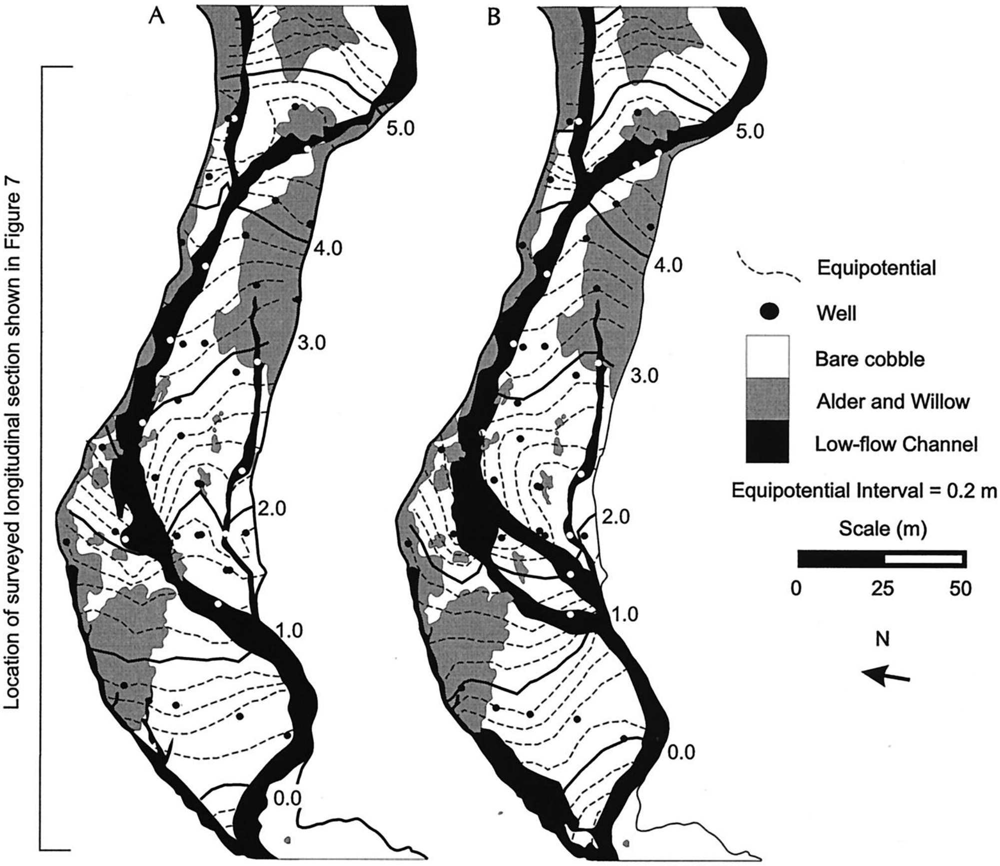

Figure 8. Water table elevation at Middle Lookout Creek (a) before (October 17, 1996) and (b) after (August 20, 1997) floods during the winter of 1996–1997. Equipotentials interpolated from water table elevations observed in the wells shown on each map and from survey points located along the stream channel (not shown). Wells are shown as white dots (dark background) or black dots (white background).

several large pools were lost at the lower end of the study reach where the channel was converted to a continuous riffle. Because pool-step sequences are a major feature forming hyporheic zones, their loss must have helped reduce the extent of the hyporheic zone in lower McRae Creek. Similar changes in channel-unit sequences observed after a debris flow in a nearby stream were accompanied by decreased hydrologic residence times of water [*Lamberti et al.*, 1991]. These results suggest that loss of pool-step sequences after large mass-movement events, such as debris flows or congested wood transport, may result in decreased hyporheic exchange flow.

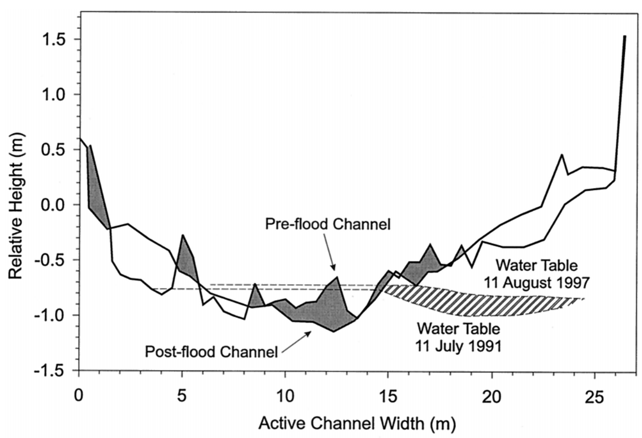

Figure 9. Cross section through the gravel bar and active channel of lower Lookout Creek before and after the flood of February 1996. Cross-sectional area of sediment lost by erosion (light gray) and increased saturated thickness of the aquifer (crosshatched) are shown. Dotted line shows the interpolated water table elevation along this transect.

4.2.1.2. The reach scale. Down cutting (in filling) occurs when scour (deposition) causes a net change in the streambed elevation within a stream reach. Major change can occur in both the vertical and horizontal extent of the hyporheic zone because small changes in stream water elevation can propagate laterally, long distances into the floodplain, changing water table elevations within the aquifer and rerouting subsurface flow paths. Whether down cutting or in filling will increase or decrease the extent of the hyporheic zone depends on the configuration of channels within the reach. At McRae Creek, down cutting caused both increases and decreases in the extent of the hyporheic zone. In one location, down cutting increased head gradients through a meander bend which increased the extent of the hyporheic zone. In another location, LWD jams were breached and the channel cut down as much as 2 m through accumulated sediment. However, deposition of LWD in the mouths of secondary channels prevented down cutting while wood levees accentuated incision of the primary channel. Under these conditions, channel down cutting converted mul-

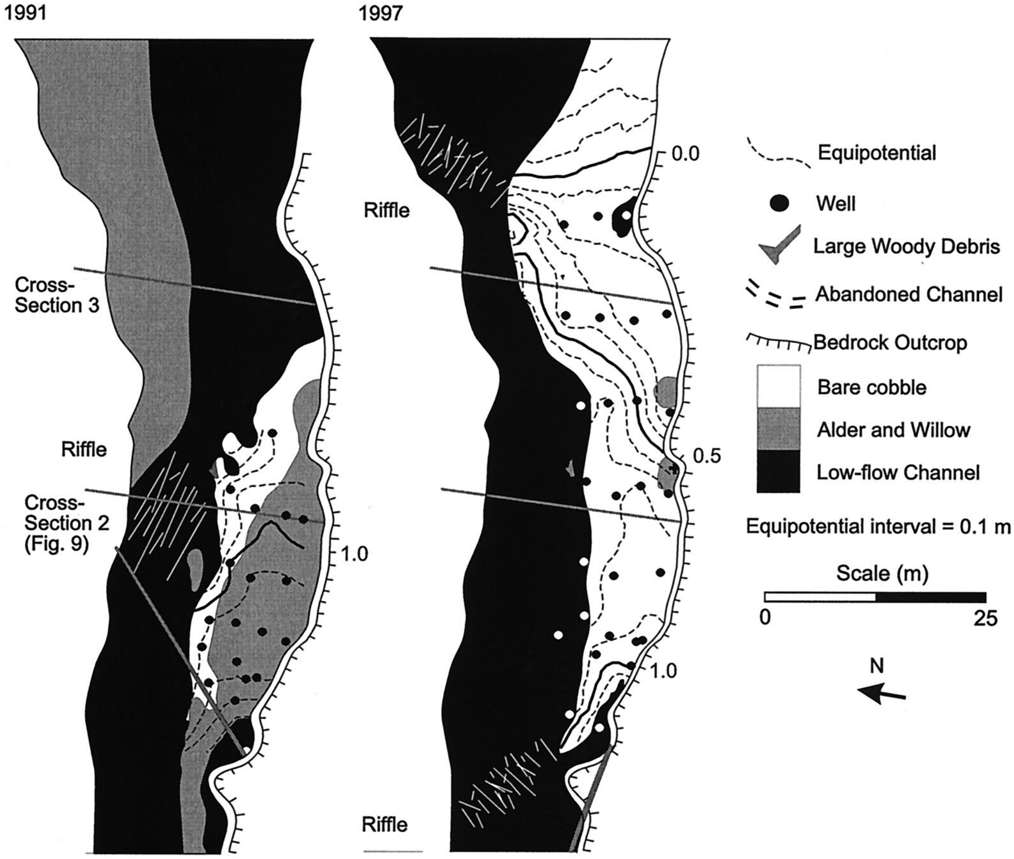

Figure 10. Lower Lookout Creek showing the general planform of the active channel, and the location of riffles, the backwater embayment, and the extent of the gravel bar before (July 11, 1991) and after (August 11, 1997) floods in 1996 and 1997. Equipotentials interpolated from water table elevations observed in the wells shown on each map and from survey points located along the stream channel (not shown). Wells are shown as white dots (dark background) or black dots (white background).

tiple channels into a narrow, deep, single-thread channel. The large differences in the relative elevation of primary and secondary/back channels resulted in the loss of the laterally extensive hyporheic zone. In this case, interactions with secondary channels exacerbated effects of down cutting on hyporheic exchange flows. However, if both primary and secondary channels had incised into sediment stored behind LWD jams in McRae Creek, exchange flows driven by head differences of water flowing through multiple channels would have persisted.

Breaching of LWD jams was the major cause of scour and down cutting observed in this study. However, floods and debris flows can also form channel-spanning LWD jams in unconstrained streams where alluvium accumulates [*Keller and Swanson*, 1979; *Hogan*, 1987]. Debris jams 1 to 2 m in height create wide zones of sediment accumulation that extend tens to hundreds of meters upstream because channels have low gradients. The LWD jam formed in 1996 in lower McRae Creek (Figure 1) holds a thick wedge of coarse alluvium and colluvium deposited in large bars dissected by secondary and back channels. Subsurface flow patterns behind this LWD jam have not been investigated, but it is likely that exchange flows between the multiple channels have led to the formation of an extensive hyporheic zone.

4.2.2. Change in lateral channel position. Lateral-channel jumps are a common result of floods and related fluvial processes in unconstrained reaches of higher-order streams. Channel-spanning LWD jams, such as those described above, are not present in 5th-order streams in the Lookout Creek catchment. Instead, LWD often blocks secondary channels, forcing the stream to reoccupy abandoned channels [*Johnson et al*., 1997]. Flooding has left a network of secondary and back channels within the floodplain that remain connected to the primary channel by surface and subsurface flows of water. Exchange flow of water between these channels leads to the development of extensive hyporheic zones. The major flood of 1996 did not appreciably change the extent of the hyporheic zone at middle Lookout Creek, even though changes in channel configuration were large. Instead, changed channel configurations altered the patterns of subsurface flow paths. This was clearly observed after floods in the winter of 1996–1997 (Figure 8) and we speculate that similar changes resulted from the much larger flood of February 1996.

The distinction between back and secondary channels is stage dependent. As stage height in primary channels increase, water overtops, or flows around, blockages so that through flow of stream water is renewed. The configurations of back channels and the height of blockages determine the frequency of through-flowing stream water. This distinction is important because differences in water levels between primary and either secondary or back channels is a major factor driving hyporheic exchange flow. Head differences are maximized between primary and back channels because the stream water elevation in the primary channel, at the mouth of the back channel, determines the base level for return flows of hyporheic water. Surface flow of stream water through secondary channels maintains a higher stage of water, reducing head gradients between primary and secondary channels. In the extreme case where stream water elevations are identical on both sides of an island, hyporheic exchange flows will be driven only by the longitudinal gradient of the primary stream channel. In this case subsurface flows parallel the stream so that exchange flow occurs only at the head and tail of the island. More commonly, head differences between primary and either secondary or back channels permit lateral hyporheic exchange flows as was observed in middle Lookout Creek. Further, the length of channel along which hyporheic exchange flows occur is also maximized because hyporheic exchange flows tend to traverse gravel bars.

4.3. Major Floods and the Role of the Hyporheic Zone in Stream Ecosystems

A growing body of research attests to the importance of the hyporheic zone in stream ecosystem processes [*Hynes*, 1983; *Stanford and Ward*, 1993; *Findlay*, 1995]. The hyporheic zone provides a unique environment for stream invertebrates [*Williams and Hynes*, 1974; *Williams*, 1984; *Stanford and Ward*, 1988; *Boulton*, 1992] and may be a refuge for benthic organisms during floods [*Palmer et al*., 1992; *Dole-Olivier et al*., 1997]; it is an important location for heterotrophic metabolism within the stream network [*Lush and Hynes*, 1978; *Grimm and Fisher*, 1984; *Mulholland et al*., 1997], it is an important site for biogeochemical transformations of nutrients [*Triska et al*., 1989b; *Duff and Triska*, 1990; *Wondzell and Swanson*, 1996b], and exchange flows of water through the hyporheic zone link aquatic and terrestrial components of riparian ecosystems [*Wondzell and Swanson*, 1996b]. Geomorphic processes, especially floods, change the spatial extent of the hyporheic zone and presumably change the volume and hydrologic residence time of water in the hyporheic zone. Thus floods and flood-induced channel changes have the potential to dramatically change stream ecosystem processes.

Several authors have proposed that the hyporheic zone confers stability to stream ecosystems, thereby speeding ecosystem recovery after floods [*Grimm et al*., 1991; *Valett et al*., 1994]. Especially important are the possible refuge sites deep in the alluvium, the maintenance of biogeochemical processes, and perhaps stores of nutrients that will continue to be regenerated from hyporheic sediments and made available to primary producers colonizing freshly scoured sediment surfaces. However, this view assumes that the hyporheic environment is more resistant to flood disturbance than is the channel or benthic environment. The results from McRae Creek show that large floods (50- to 100-year recurrence interval), combined with congested LWD transport, can rework sediments to sufficient depths so as to disturb much of the hyporheic volume. Repeat surveys have shown population declines for species such as salamanders and sculpins that sought refuge from flood in interstitial spaces of streambed sediments [*Erman et al*., 1988; *Swanson et al*., 1998]. Our observations suggest that scour may limit the extent of refugia within the hyporheic zone. However, this effect would depend on the extent of the hyporheic zone, depth of scour, and species-specific patterns of utilization of the hyporheic zone.

The impact of floods on the hyporheic zone is not limited to physical disturbance of the alluvium because changes in subsurface flow paths may also change the rates or types of biogeochemical transformations. Even apparently small physical changes in the extent of the hyporheic zone have potentially large impacts on stream ecosystem processes. For example, the persistence of the hyporheic zone in near-stream locations of McRae Creek does not mean that the mineralization of dissolved organic nitrogen that previously took place in the extensive hyporheic zone [*Wondzell and Swanson*, 1996b] also persists. This is because the effect of the hyporheic zone on stream nutrient cycles is proportional to the residence time of water in the hyporheic zone [*Findlay*, 1995; *Valett et al*., 1996]. Some biogeochemical processes, especially the breakdown and mineralization of dissolved organic matter, occur slowly. Thus changes in exchange flow paths that shorten hydrologic residence times could significantly alter biogeochemical processes in stream ecosystems.

Exchange flows of water also mediate interactions with terrestrial components of riparian ecosystems. For example, when the water table was high in the gravel bar along lower McRae Creek, nitrate was leached from the rooting zone of streamside alders, a nitrogen-fixing species [*Wondzell and Swanson*, 1996b]. Leaching of nitrogen from streamside alders should have been reduced after the February 1996 flood because the water table can no longer reach the rooting zone during storm events. These losses are not offset by changes at the head of the study reach where new hyporheic flow paths pass beneath old-growth conifer forest. Less nitrogen leaches from coniferous floodplain forests and nitrogen from this source is mostly dissolved organic nitrogen [*Wondzell and Swanson*, 1996b]. The 1996 flood stripped riparian vegetation from many gravel bars along the stream network, especially stands of streamside alders growing on surfaces reworked in the 1964 flood (G. Kennedy and S. M. Wondzell unpublished data, 1997). Therefore streamside vegetation must regrow before the preflood interactions between the aquatic and terrestrial components of riparian ecosystem can recover completely.

Changes in subsurface flow paths may change environmental conditions that could reduce populations or even locally eliminate species. For example, down cutting of the primary channel in McRae Creek and loss of the extensive hyporheic exchange flows would have eliminated oxygen and labile dissolved organic carbon (DOC) supplied to the streamside aquifer. Similar changes to the hyporheic environment would be expected at the subreach scale in Lookout Creek where changes in channel configurations change patterns of subsurface flow. Near-stream portions of the hyporheic zone previously supplied with well-aerated channel water were located further from the stream or at the distal end of exchange flow paths after the flood. Because biogeochemical processes alter water chemistry over the length of flow paths [*Vervier and Naiman*, 1992; *Findlay*, 1995], environmental conditions can be dramatically changed, even in locations where alluvium remained in place and the extent of the hyporheic zone did not change.

4.4. Implications for River Management

Some of the examples of geomorphic processes presented here are unique to mass-movement-prone, mountain-stream networks in forested landscapes. However, most stream networks are influenced by a variety of geomorphic processes that drive changes in channel morphology at the scales considered here. Typical examples include lateral-channel migration, formation of secondary channels and localized down cutting or in filling of channels. Consequently, the spatial and temporal dynamics of streams and their hyporheic zones described here may be common to most river networks. We hypothesize that naturally formed channels may experience little net change in the extent of the hyporheic zone in response to geomorphic processes at reach and larger scales, despite numerous local changes. Further, river networks are buffered from flood-caused impacts, to some extent, by the spatial heterogeneity of disturbances [*Swanson et al*., 1998].

We speculate that some engineering practices that alter channel morphology may have marked impacts on hyporheic zones. Human alterations to many river networks are of equal or larger magnitude to those resulting from geomorphic processes. These alterations include direct modifications to straighten channels and eliminate secondary channels, changes that are maintained by construction of dikes and revetments. Indirect modifications may also contribute to stream simplification as well as modify the effects of floods on stream channels. These indirect effects may result from removal of LWD or road construction on wide valley floors in unconstrained reaches of mountain stream networks. Human alterations are extensive, influencing most stream networks within the landscape, and have been maintained through time. Unlike geomorphic processes, we suggest that these alterations have had long-lasting and unidirectional impacts on the extent and function of hyporheic zones in stream ecosystems. The need to reestablish natural flow regimes is now widely recognized in river conservation and restoration, in part because of the relationship between the natural flow regime and channel morphology [*Poff et al*., 1997]. We believe that this concept could be extended to include the full suite of geomorphic processes occurring in any river network, and to allow these processes to shape rivers and their channels, floodplains, and hyporheic zones.

5. Conclusions

This study showed that channel and valley floor morphology control exchange flows between streams and hyporheic zones. A major flood caused dramatic changes to channel morphology and markedly altered subsurface flow paths. However, these effects were scale dependent. At the channel-unit scale, scour and deposition changed the pool-step structure of channels and caused large changes in the location of down-welling and upwelling zones. In the most extreme case, congested transport of LWD converted pool-step sequences into a continuous riffle which contributed to a reduction in the extent of the hyporheic zone.

At the reach scale, breaching of debris jams led to scour and down cutting of the streambed over a 200-m-long reach. The effect of down cutting on the hyporheic zone was dependent upon the configuration of primary and secondary stream channels. Where down cutting converted multiple channels to a simple, incised channel, the extent of the hyporheic zone was reduced. Where down cutting and lateral-channel movement increased head gradients through a meander bend, the extent of the hyporheic zone increased. In a large, unconstrained stream reach, lateral-channel jumps caused major changes in the direction of hyporheic flow paths, but the extent of the hyporheic zone did not change. Thus at subreach scales large changes in the location and extent of the hyporheic zone and the pattern of subsurface flow paths were observed. Little net change in the extent of the hyporheic zone was observed at the reach scale because increases in the extent of the hyporheic zone in one location were offset by decreases in other locations.

The flood-induced changes observed in the hyporheic zones at all three study sites are likely to have large and long-lasting effects on the stream ecosystem. Both direct and indirect disturbances can reduce or locally eliminate populations of stream invertebrates. For example, the hyporheic zone was not a safe refuge where major floods, debris flows and the congested transport of LWD scoured and reworked streambed sediment. Changes in subsurface flow paths and the extent of the hyporheic zone can alter the rates or types of biogeochemical processes. Also, loss of riparian vegetation and changes in subsurface flow paths change the linkages between aquatic and terrestrial components of riparian ecosystems. Recolonization of the hyporheic zone by stream invertebrates and regrowth of streamside vegetation are necessary before ecosystem processes of the hyporheic zone can be fully restored.

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