Historical Channel Locations of the White River, RM 5 – RM 28, King County, Washington

Prepared for:

King County Department of Natural Resources and Parks
Flood Hazard Reduction Services Section
201 South Jackson Street
Seattle, WA 98104-3855

Report by:

Brian D. Collins and Amir J. Sheikh
Department of Earth & Space Sciences
Box 351310, University of Washington
Seattle, WA 98195

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Cover photo: Auburn Dam in 1919. The Auburn Dam, begun in 1914, permanently diverted the White River's historical course, northward through Auburn, southward into the former channel of the Stuck River and then into the Puyallup River.

Photo this page: Undated photo shows the abandoned bed of the White River in Auburn. Both photos from Inter-County River Improvement District.

SUMMARY

We made use of a Geographic Information System (GIS) to map locations of the White River's historical channel locations from the King County line upstream to Mud Mountain Dam on 13 sets of orthorectified aerial photographs between 1931 and 2000 and General Land Office plat maps from 1867-1891. We used these locations to compute average annual lateral migration rates, measured orthogonal to the White River valley centerline along 136 transects spaced 200 m apart and grouped into six segments on the basis of common valley width, migration rates, and river engineering histories. An additional 14 transects with the same spacing were established on the portion of the study area that falls downstream of the valley, on the Holocene White River Fan in the Puyallup-Duwamish trough. We also used the historical channel location maps to create occupation grids that represent the frequency with which channels historically occupied individual 1-m cells.

The White River upstream of about the R Street Bridge in Auburn is confined in a canyon, and downstream of the R Street Bridge opens out onto the White River Fan. In the canyon reach the river has been incising in the last few thousand years, which has created a series of terraces between 5 and 35 m above the floodplain, mostly in the upper part of the canyon. The floodplain varies in width from about 310 m to 860 m and averages 480 m. The river gradient declines only slightly in a downstream direction in the canyon from about 0.0075 to about 0.0055. The gradient of the much shorter study area downstream of the R Street Bridge on the fan declines more rapidly from 0.0055 to 0.003. The lower one-fifth of the canyon reach has been leveed since the late 1950s, and the river on the White River Fan was leveed beginning prior to the aerial photo record and progressively through the 20th century.

In the canyon, annual lateral movement between 1931 and 2000 averaged 7.4 m/yr. Within individual segments this average varies by a factor of 10, with the lowest being 1.7 m/yr in the uppermost, narrowly-confined segment (Transects 133-136) and the highest 19.9 m/yr lower in the canyon (T 27-39).

Normalizing the rate, by dividing by the active channel width measured from 2000 aerial photos, indicates that migration in the upper two segments (T 74-T 136) was roughly half that in the lower four segments relative to the channel width.

Mean annual migration rates for different time periods (bracketed by aerial photo years) for the entire canyon (T2-136) are not distinguishable statistically except that the 1931-1936 rate is higher than succeeding periods. This primarily reflects the effects of large storms in the early 1930s, with peak flows in 1932 (17,000 cfs), 1933 (16,500), and 1934 (28,000 cfs) all being considerably greater than the average annual peakflow of 9,100 cfs for the 1929-2002 period of record. A regression of the largest peak annual flood in each time period bracketed by aerial photos against average annual migration rate for the same periods accounts for about 75% of the variation in average annual migration rate.

Levees reduced lateral movement for individual time periods in individual segments. Levees built in the T2-T26 segment in the few years prior to 1959 reduced lateral migration compared to other segments. The average migration rate between 1931 and 1959 was indistinguishable from that between 1959 and 2000 for the segments upstream of the levees. In the T2-T21 segment, in which levees were maintained from 1959-2000, the rate before 1959 was more than two times greater than after 1959. Annual lateral movement prior to the closure of Mud Mountain Dam in 1948 is indistinguishable from movement in the succeeding 52 years for segments upstream of the levees.

Migration of the White River in the fan segment in 1931-2000 averaged 5.2 m/yr; downstream of the East Valley Highway bridge, where levees were built prior to 1931, it averaged 2.6 m/yr, and upstream of the bridge 7.2 m/yr. The rate diminished through time as the levee system was extended upriver and levees were moved closer to the river; rates were between 1 and 3 m/yr in the last few decades.

We defined three different historical channel zones. The first is encompassed by historical locations of the active channel (HCZ1); the second includes the historical active channel locations, and the area inclusive of floodplain sloughs mapped from the aerial photographs (HCZ2); the third expands the latter zone by including floodplain sloughs mapped from lidar (HCZ3). The HCZ1 and HCZ2 are generally comparable with the exception of a few areas where the latter is significantly wider than the former. Both zones are enlarged significantly in a few areas when the GLO channel locations are added to the aerial photo locations. Overall, the HCZ1 and HCZ2 (including the GLO channel locations) account for 65% and 69% of the valley bottom, respectively. In the different segments the percent ranges from 49% (segment 6) to 80% (segment 3) for the HCZ1/FPW ratio, and from 49% and 82% for the HCZ2/FPW ratio. The both are between 5 and 6 times wider than the year 2000 active channel width.

When channels mapped from lidar are included to delineate the HCZ3, on average the historical channel zone encompasses 87% of the floodplain, and ranges in individual segments between 72% and 93%. The channels identified on lidar very likely relate predominantly to relict channel locations previous to the historical record, and this implies that the White River has occupied nearly its entire floodplain in the recent past; how many years removed from the present isn't known without field study. It is also likely that a large portion of the floodplain channels detectable by lidar imagery remain active currently. This in turn would imply that the White River, when defined as the river and its floodplain sloughs, at present occupies nearly its entire floodplain.

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SCOPE

This report documents historical channel positions for the White River from the King County line at river mile (RM) 5 to roughly one river mile downstream of the Mud Mountain Dam at RM 29. (All river miles refer to river mile marks on USGS 7.5 minute topographic maps.) Channel positions are taken from 13 sets of orthorectified aerial photos from 1931 through 2000, and General Land Office plat maps from 1867-1874. Photographs were orthorectified, and maps were georeferenced, brought into a GIS, and channel features were digitized from them. Digital data accompanying this report include these maps, photos, and GIS layers. This report includes two analyses of channel position change in the time period covered by the data described above. The first examines the lateral change in position of channel centerlines for each time interval, measured along transects made orthogonal to the floodplain centerline at 200-m intervals. The second uses a grid analysis to characterize the pattern with which the river channel occupies the floodplain.

STUDY AREA

Geology and Topography

For the study area (Figures 1 and 2), we mapped the extent of the valley bottom, and valley bottom landforms (e.g. floodplain, terraces, and alluvial fans) using a combination of published geological maps (Booth and Sacket 2002), U.S. Geological Survey (USGS) topographic maps, and analysis of elevations from a DEM created from lidar north of the river (within King County), and the USGS 10-m DEM south of the river. Because the lidar DEM did not generally cover the south side (left bank side, within Pierce County) of the valley bottom, our delineation of the floodplain and alluvial terraces on that side has considerably less resolution and accuracy than on the right bank side.

The White River incised its valley in the last few thousand years through lahar and glacial deposits, creating a series of terraces, mostly concentrated in the upper half of the valley (Figure 3). Terraces range in height above the floodplain from about 5 to 35 m (Figure 4). (We use "terrace" in this report to refer to any continuous surface in the valley bottom that is several meters higher in elevation than the floodplain. We use "floodplain" to refer to the geomorphic floodplain, or the surface currently flooded by the river and inclusive of all floodplain sloughs. We use "slough" to refer to floodplain channels connected to the river typically at both ends, or in some cases at the downstream end and fed by floodwater, springs or wetlands at the other end.) The terraces account for a large part of the valley width in places; the valley width varies between about 350 and 1460 m and averages 780 m. The floodplain width varies between about 310 m and 860 m and averages 480 m. The valley is narrowest in the upper part (Figure 3). Elevations from lidar show that the floodplain includes some higher areas that are likely incipient terraces; these have not been distinguished from the floodplain. Floodplain topography reflects the existence of multiple small floodplain sloughs and the general trend toward valley incision (Figure 5).

The channel gradient is relatively constant in the canyon, gradually dropping in a downstream direction from 0.0075 to 0.0055. The channel gradient drops from 0.0055 to 0.003 on the White River Fan (Figure 6). The relatively narrow and steep White River valley in the study area is similar to the valleys of the nearby Cedar, Middle Green and Nisqually rivers, which were created by post-glacial fluvial incision (Figure 7A). All are considerably narrower and steeper than valleys such as the Puyallup-Lower Green-Duwamish, which were sculpted during the late stages of the last Pleistocene glaciation by subglacial meltwater (Booth 1994). The White River channel, similarly to the former group of valleys that include the Cedar, is steep relative to its drainage area (Figure 7B).

The lower part of the study area flows on a large Holocene alluvial fan built into the Pleistocene Puyallup-Duwamish trough. The White River valley was a shallow embayment of Puget Sound until mid Holocene, when the voluminous Osceola Mudflow [~5700 ybp (years before present); Dragovich et al. 1994] and subsequent lahars from Mt. Rainier began to fill the lower White River and Duwamish river valleys (Dragovich et al. 1994) and build the White River Fan.

History of River Engineering

Historically the White River flowed northward to join the Green River north of Auburn, and the Stuck River was a much smaller channel that diverged from the historical White River and flowed southward in the area of the modern White River (Figure 8; see Collins and Sheikh 2004, a companion study to this one, for detail). In the last decade of the 19th century, farmers on both sides of the river would dynamite logjams and bluffs to direct the White River away from their land, and this had the cumulative effect of widening the Stuck River (Stein 2001). In 1898, farmers dynamited a bluff and diverted much of the White River into the Stuck River. A November 14, 1906 flood built a large logjam and completely diverted the White River into the former Stuck River channel (Chittenden 1907; Roberts 1920).

Disagreement between King and Pierce counties on the proper course of the river was resolved in 1914 when the two entities established the Inter-County River Improvement District, which planned to enlarge and straighten the channel for flood conveyance, and to build levees and reinforce banks (Roberts 1920; King County Public Works 1988). Work began that year on the Auburn Dam, which permanently closed off the White River's historical northward-flowing path, and on a drift barrier near RM 12 (Figures 8 and 9).

Levees and bank protection were first built on the lower part of the relocated and channelized White River (downstream of the East Valley Highway; see Figures 10 and 11). In the mid 20th century, levees were built on the upper part of this fan segment, and progressively narrowed with time (Figure 10). Levees were also built in the lower part of the canyon in the middle 20th century (Figure 12). Between 1955 and 1959 (bracketed by aerial photography) dikes were built upstream to transect 26. The river breached the dikes between transects 22 and 26 in the late 1970s (Table 1).

For analysis purposes we divided the study area into six segments within the canyon and one segment on the fan (Table 1 and Figure 2). In the analysis we consider the canyon and fan areas separately because of their different topographic settings and river engineering histories.

Table 1. Analysis segments used for the White River Canyon portion of the study area. An additional 14 transects are located on the White River fan segment. River miles are from USGS topographic maps and are approximate. The White River Fan segment is from RM 4.9 to RM 7.6 (river kilometer 8 – river kilometer 12)

ANALYSIS SEGMENT	TRANSECTS	RIVER MILE/ (KILOMETER)	N	VALLEY WIDTH (M)	FLOODPLAIN WIDTH (M)	2000 ACTIVE CHANNEL WIDTH (M)	DESCRIPTION
ALL	ALL	7.6 - 28.0	135	863	691	104	
1	T2-T21	7.6 – 11.7 (12 – 19)	20	819	819	70	Levees from 1955-1959 to 2000
2	T22-T26	11.7 - 12.5 (19 - 20)	5	677	677	205	Levees from 1955-1959 to 1974-1980
3	T27-T39	12.5 - 13.2 (20 – 21)	13	826	740	168	Most rapid channel migration.
4	T40-T73	13.2 – 19.0 (21 – 31)	34	1117	963	146	Floodplain widens. Channel gradient declining
5	T74-T132	19.0 – 27.4 (31 – 44)	59	782	484	73	Relatively narrow floodplain; constant channel gradient
6	T133-T136	27.4 – 28.0 (44 – 45)	4	223	223	52	Narrow floodplain constrained by valley sides

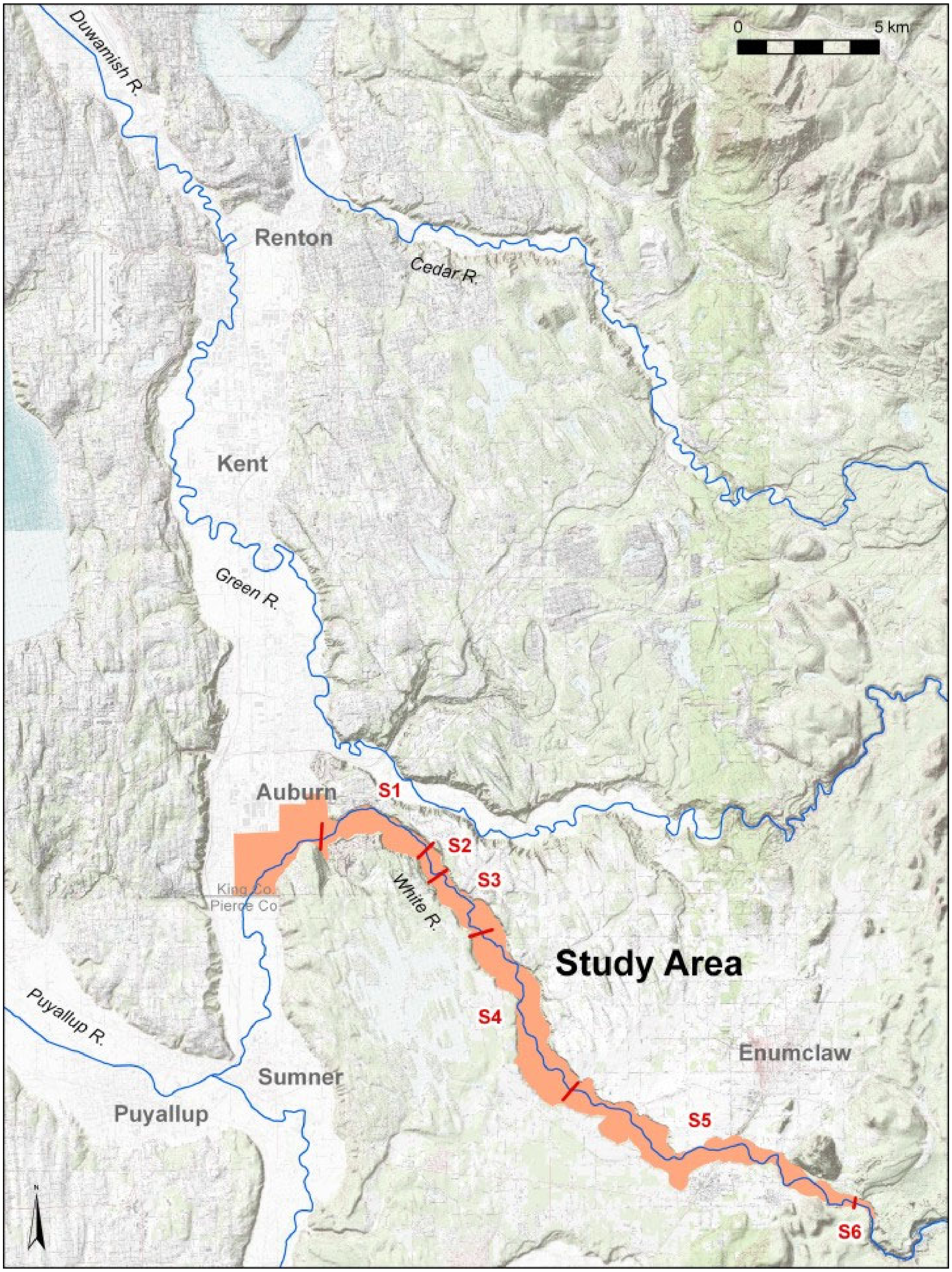


Figure 1. Location of the study area. Red lines mark segment boundaries, with segments in red ("S1" etc.); see Table 1 for detail.

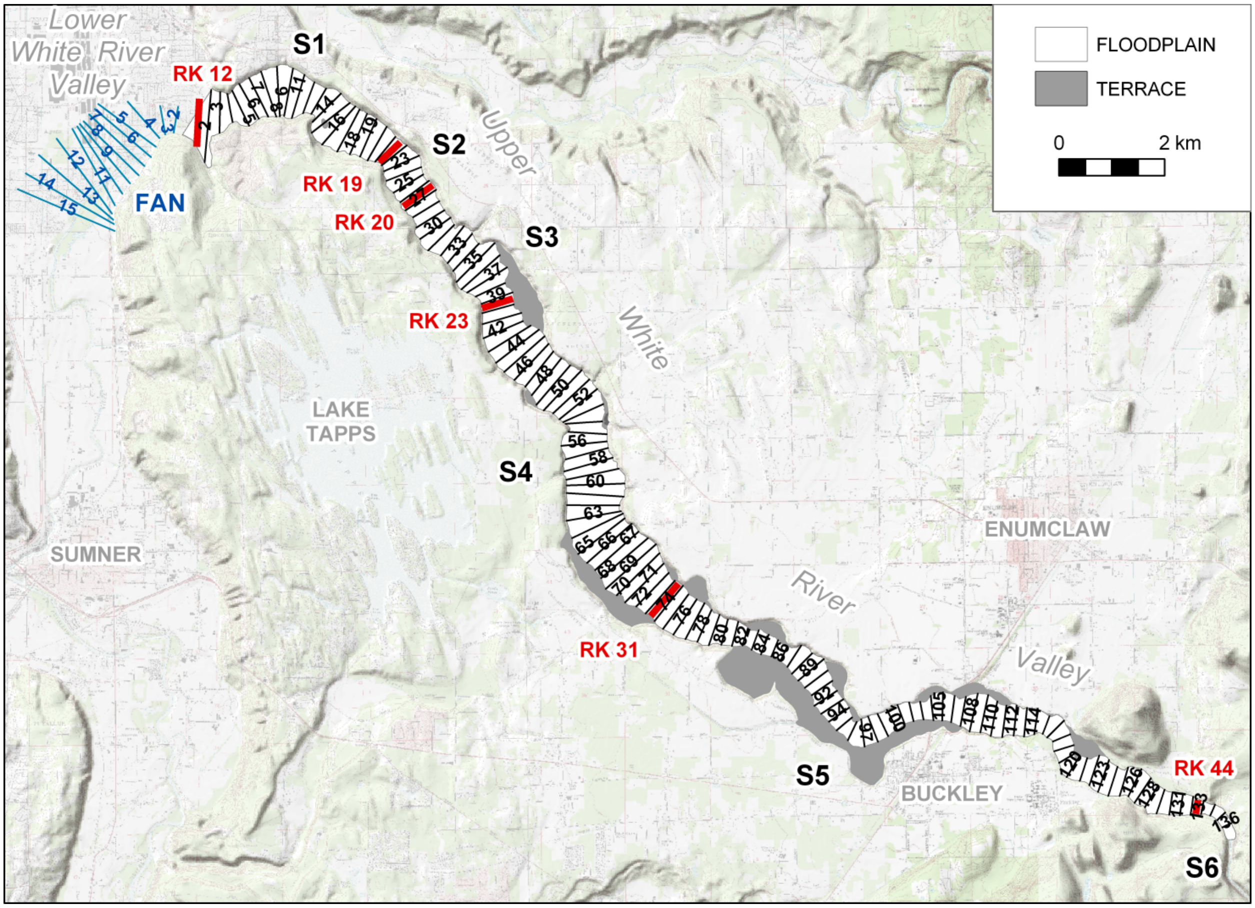


Figure 2. Extent of floodplain and river terraces in the study area and location of floodplain transects (numbered), and end points of study segments (Table 1) shown by red lines. "S1," "S2," etc. refer to segments identified in text and Table 1. Red numbers are approximate river kilometer (RK), measured from USGS topographic maps. Transect numbers are referred to in succeeding figures. Transects (numbered with blue letters) in lower White River valley have a numbering system independent of transects in the upper White River valley.

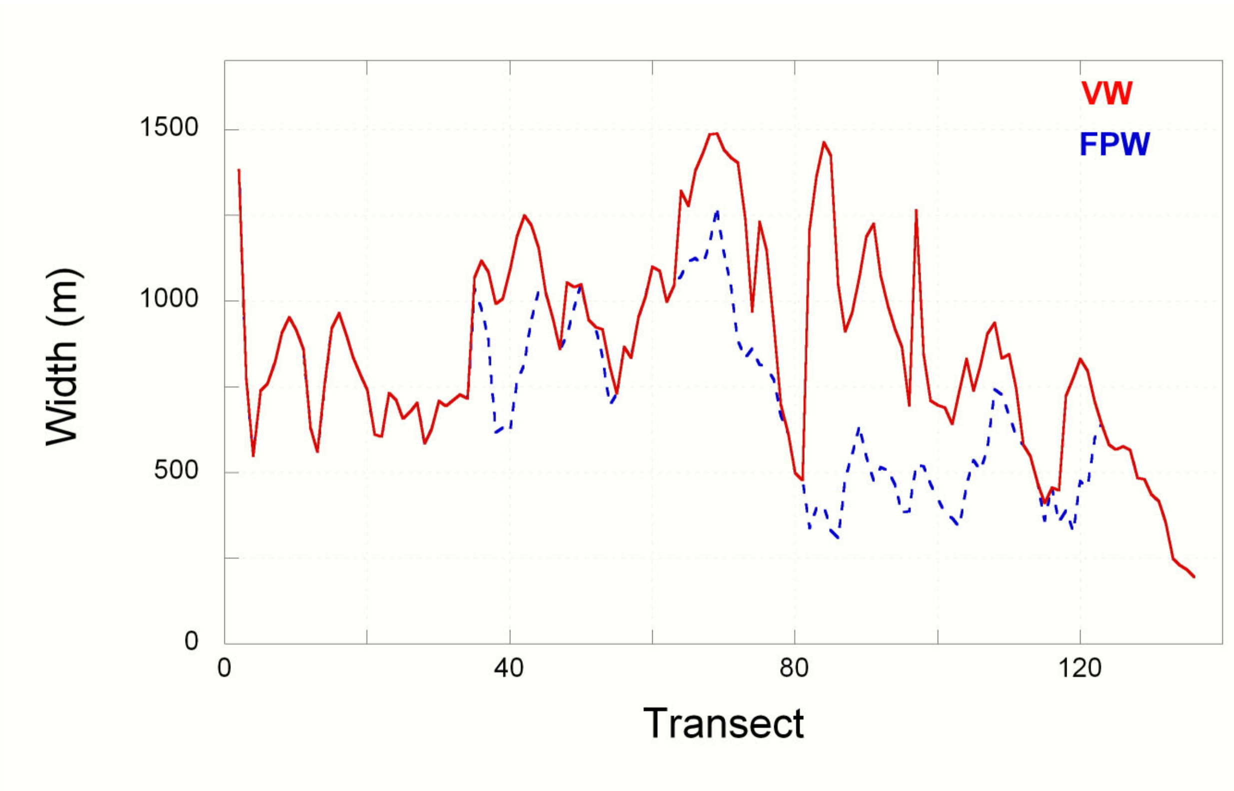


Figure 3. Floodplain width (dashed blue line) and valley width (solid red line), in meters. Transect numbers refer to Figure 2. Valley width includes alluvial terraces and fans.

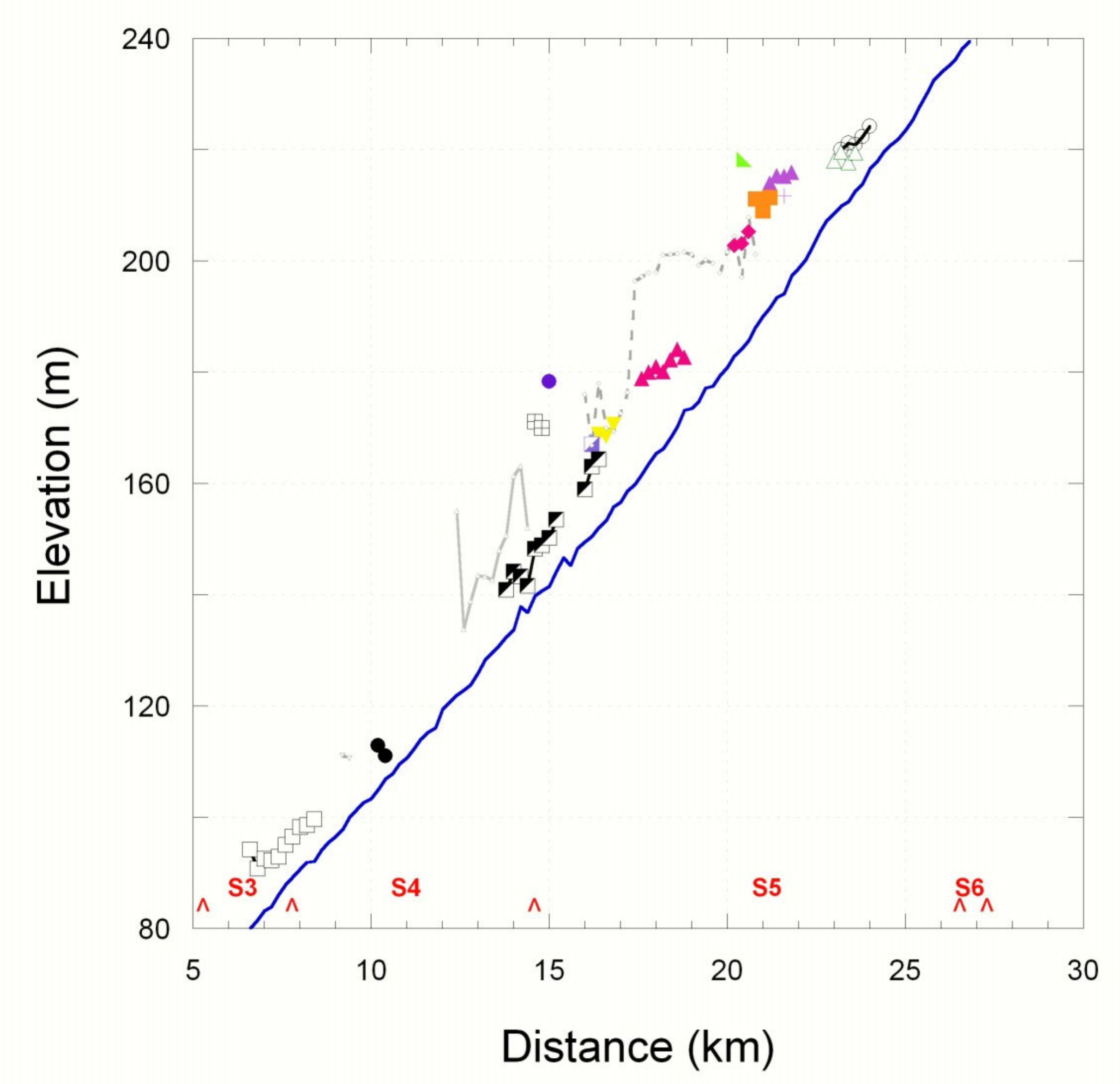


Figure 4. Floodplain and terrace elevations in the White River valley. Blue line represents the elevation of the lowest point on each transect (transects are shown in Figure 2). Each series of linked symbols represents the elevation of the same transects on individual mapped terraces, measured at the center point of the portion of the transect that crosses the terrace. Terraces represented by gray lines and no symbols are from the south side of the valley, where lidar is not available, and elevation control is poor. Red symbols and labels ("S1" etc.) refer to segment boundaries and segments, respectively; see Table 1.

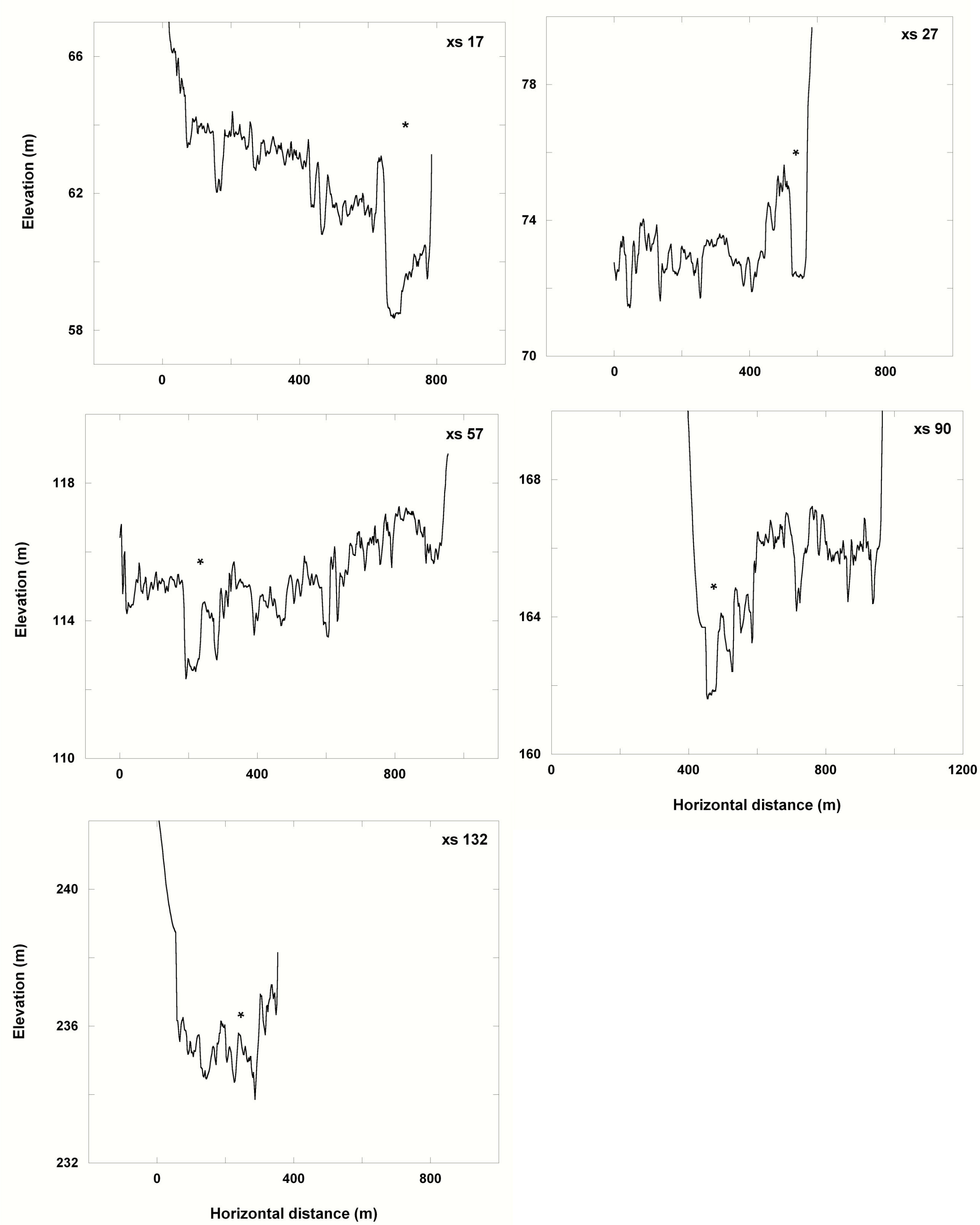


Figure 5. Representative valley cross-sectional profiles. Asterisk indicates White River channel; transect numbers refer to Figure 2. Vertical exaggeration = 100x.

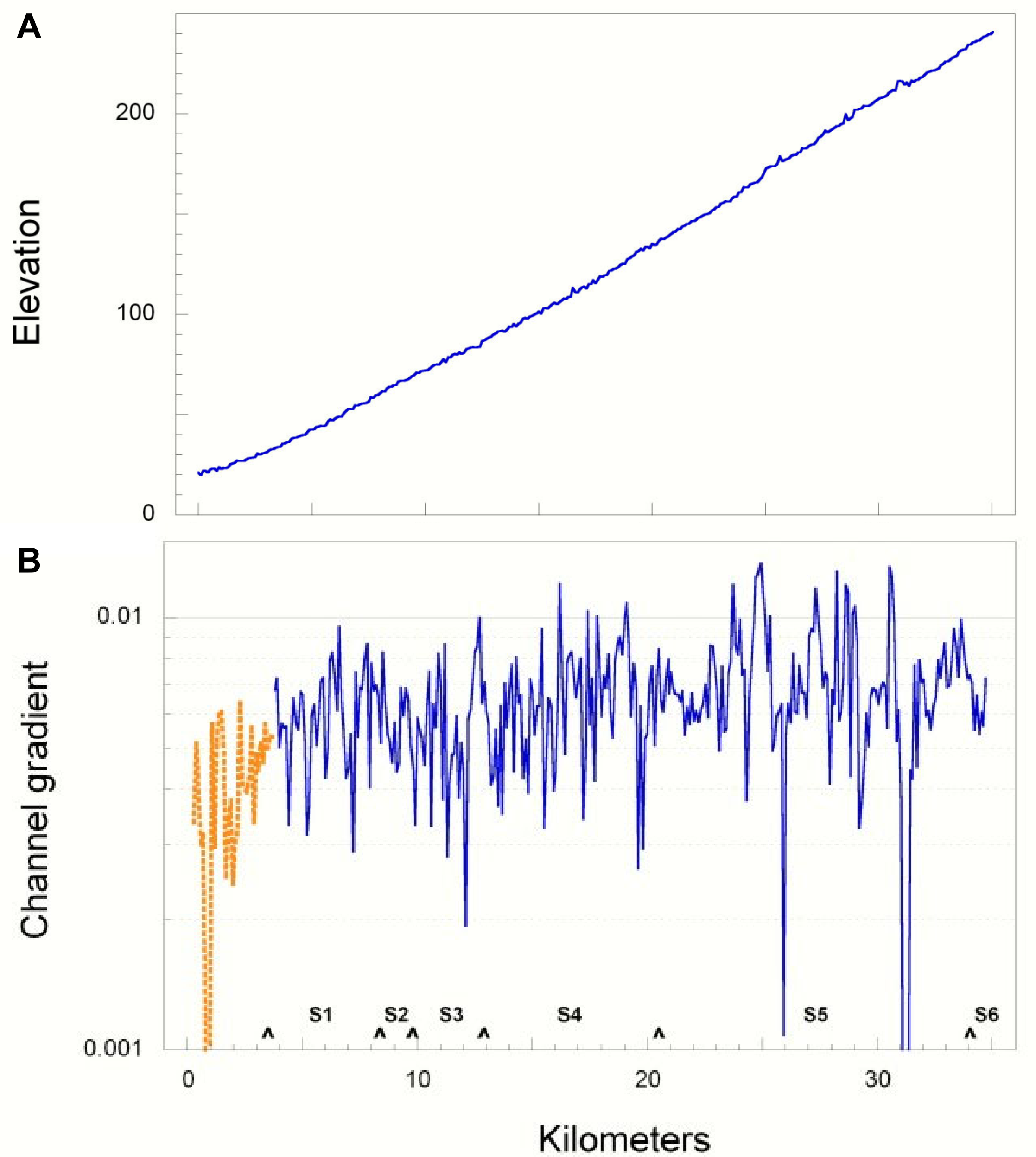


Figure 6. (A) Longitudinal profile of the White River from the King County line to the upper limit of study area, from lidar elevations sampled at 100-m intervals along the year 2000 channel low-flow centerline. (B) Channel gradient of the White River in the study reach. Dashed, orange line corresponds to the White River Fan segment. Gradients are calculated from a 7-point running average of elevations sampled every 100 m. Symbols and labels at bottom of panel B refer to analysis segments.

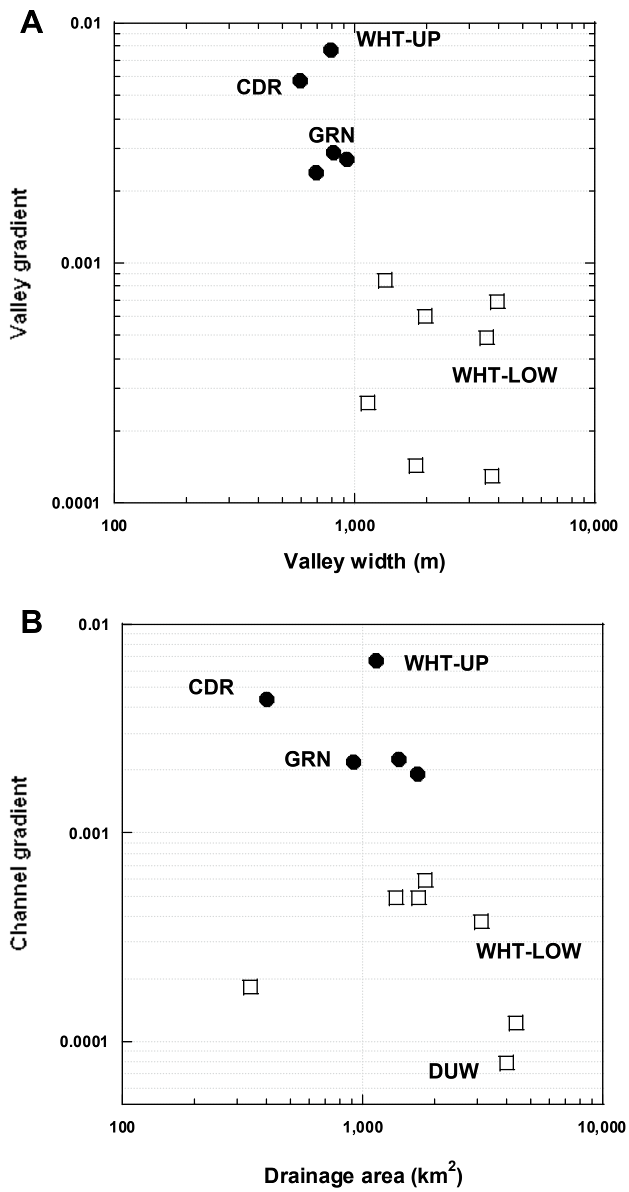


Figure 7. (A) Valley width and valley gradient (measured along the valley centerline) in valleys formed by Pleistocene subglacial meltwater (hollow square symbols) and in valleys formed by post-glacial fluvial incision (solid circle symbols). Post-glacial valleys are narrower and steeper than glacial valleys. "WHT-UP" is study area. (B) Drainage area and historical channel gradient (measured along channel centerlines from reconstructed historical channel locations); valley type symbols are as in panel A. Historical channels in post-glacial valleys are steeper than channels in glacial valleys having the same drainage area.

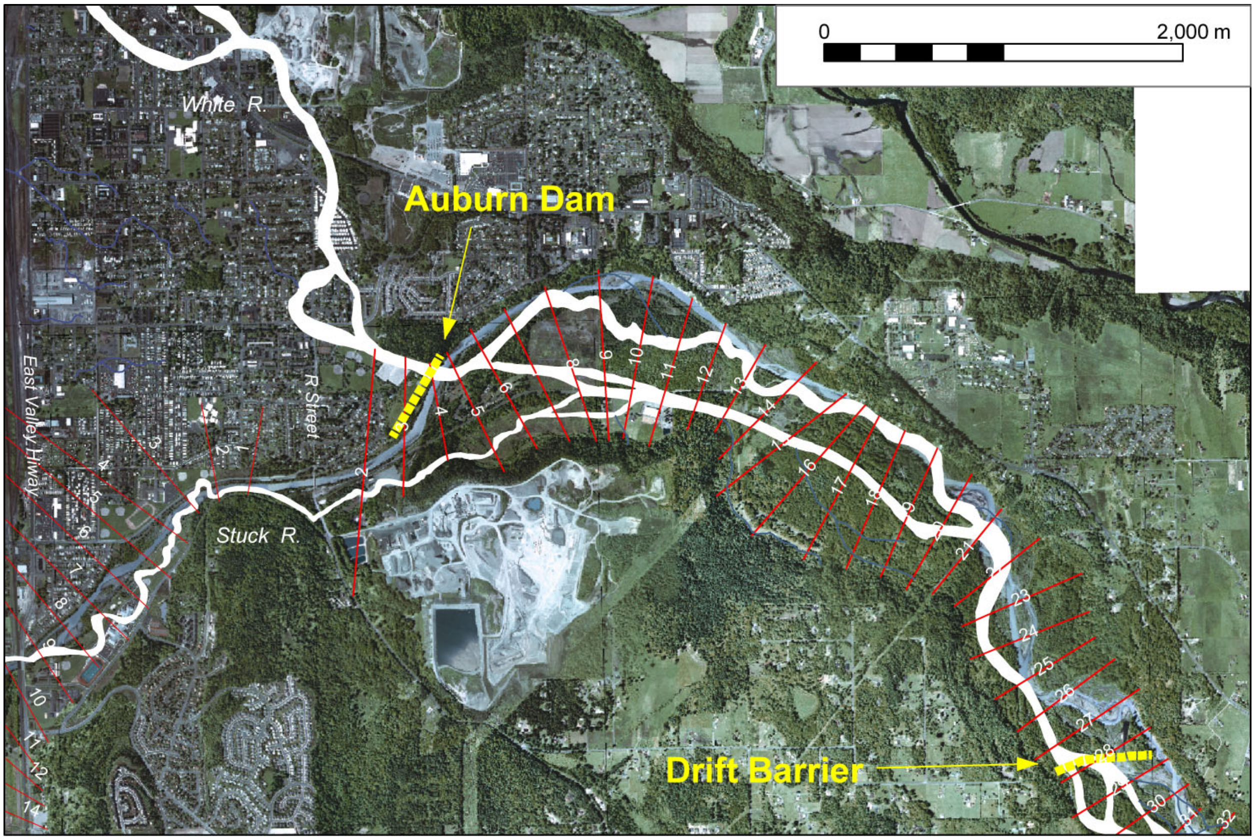


Figure 8. Location of the Auburn Dam and drift barrier built by the Inter-County River Improvement District in 1914. The location of the drift barrier was drawn from remnants of the drift barrier visible on aerial photographs from 1931 through 1985. The Auburn Dam location was drawn from 1931 photographs. Numbered transects are those used in this study and as shown in Figure 2 and Figure 12. Background image is 2000 aerial photo; overlay channel is from General Land Office plat maps.

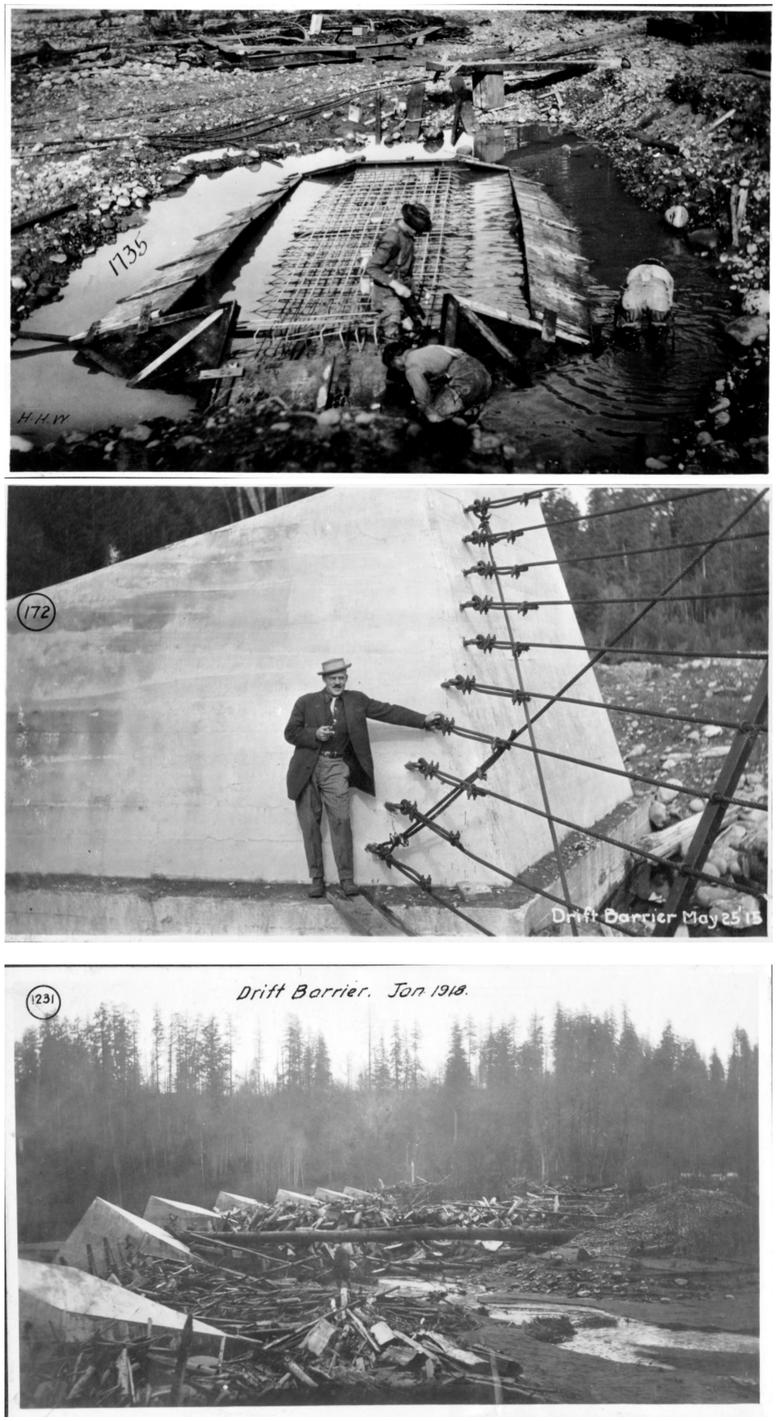


Figure 9. Drift barrier built in 1914 to collect wood upstream of Auburn (see Figure 7 for location). The barrier consisted of a linear series of large concrete blocks anchored in the riverbed with cable strung between. Photos from Inter-County River Improvement District (upper photo undated, probably 1914; middle photo 1915; lower photo 1918).

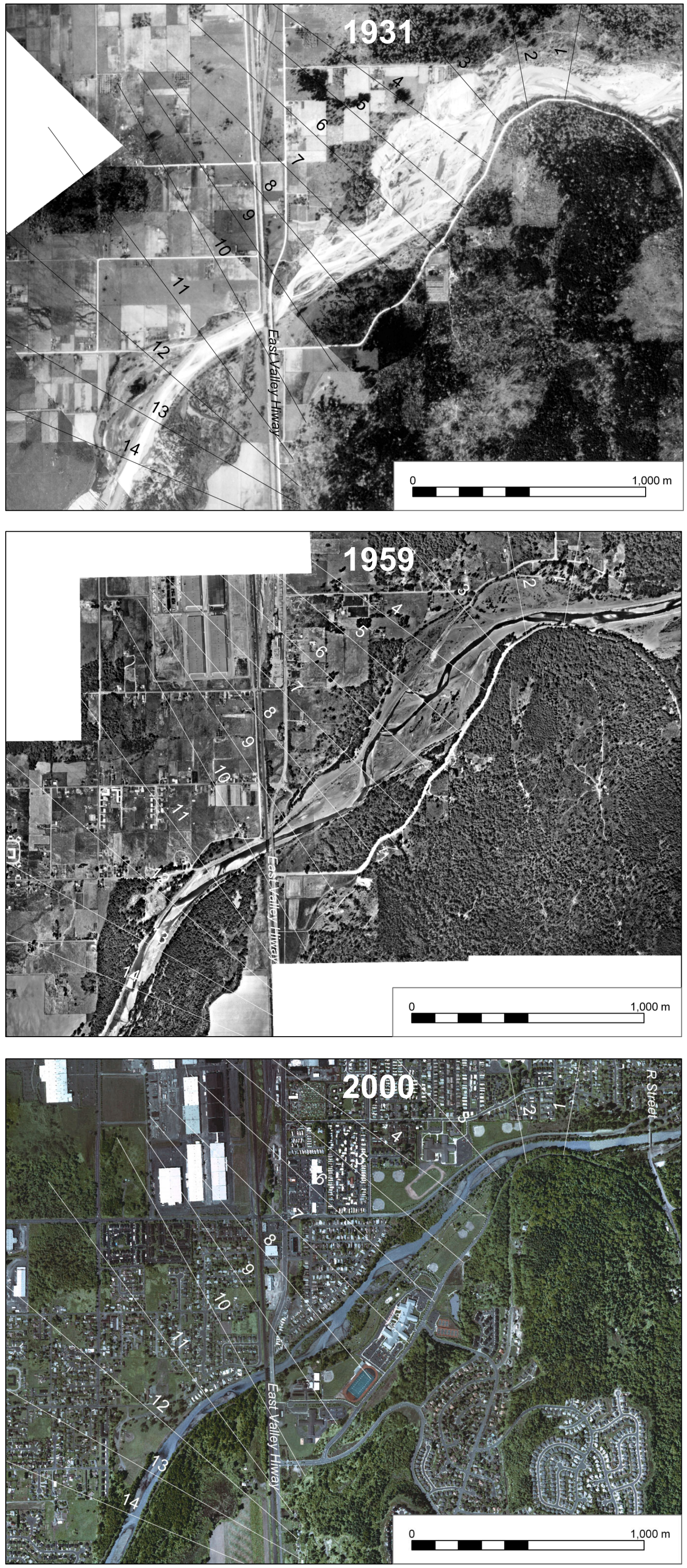


Figure 10. Aerial view of the White River fan segment in 1931, 1959, and 2000, showing transects and transect numbers for reference.

Figure 11. Early bank protection on the lower White River, constructed with brush and weighted with bags of concrete. Undated photo from Inter-County River Improvement District.

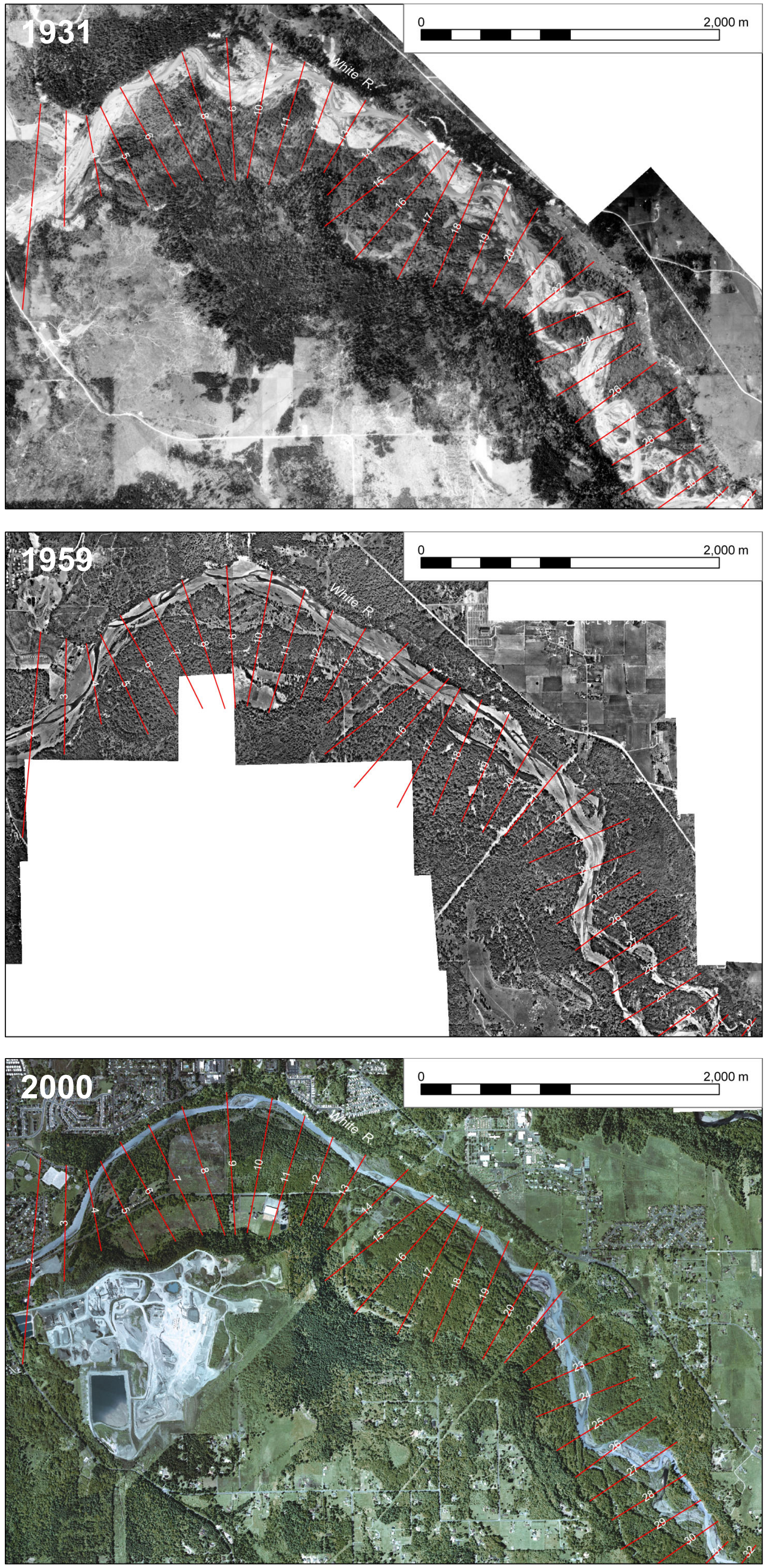


Figure 12. Aerial view of the White River above Auburn (T1-T-30, S1 and S2) in 1931, 1959, and 2000. Transect numbers shown for reference.

METHODS

Aerial Photos and Maps

We collected aerial photos and maps for the study area, aiming for an average spacing between photo sets of 5 years. We made use of 13 photo sets between 1931 and 2000, and General Land Office (GLO) cadastral survey maps between 1867 and 1874 (Table 2). We did not make use of an 1895 topographic map (USGS Tacoma 1:125,000) because it is considerably less accurate than other sources. The number of years between the GLO maps and earliest photographs (57 to 64 years) is considerably greater than the time between photographs (Figure 13). Because maps and photos did not always cover the entire study area, some periods between photographs or maps differed between parts of the study area (Figure 13).

The early General Land Office plat maps were our earliest map source. These maps are from surveys conducted in 1867-1874. In addition to the regular township plat maps, the Muckleshoot Reservation (in T20N R5E and T21N R5E) was resurveyed in 1874 (Table 2). We used scans made of original plat maps, available in digital form from the Bureau of Land Management, georeferenced them using the current Public Land Survey System (PLSS) records for corners and quarter corners, then digitized channels from these georeferenced images. From working with channel representations on plat maps elsewhere in the Puget Sound region we have concluded that the mapped channel outline represents the high flow channel (or active channel) rather than the low-flow channel. This interpretation is supported by the instructions given to surveyors current in the region at the time (see White 1991) which instruct to survey along "both banks" at the "ordinary mean high water mark" which was defined in an early court case as "river bed which the river occupies long enough to wrest it from vegetation." Rivers were meandered (measured with bearings and distances); our experience is that the horizontal accuracy of the channel location is most reliable where a section line crosses the river, but generally also accurate elsewhere. Channels drawn on plat maps were drawn from survey notes, and channel depictions are sometimes artificially and noticeably geometric in their representation. In North Puget Sound rivers, we found that surveyors drew channels on plat maps with varying fidelity to the field-measured widths, but on average widths were exaggerated on the plat maps by a few percent (Collins and Sheikh 2003).

We scanned a USGS 125,000-scale topographic maps from 1895 (Table 2), and georeferenced it using current PLSS records, but did not use the map in the analysis because it has considerably less horizontal accuracy than the other sources we used.

All photo sets were paper prints, which we scanned at 600 ppi, except for the 2000 digital photographs. Photo scale varied from 1:7,800 to 1:60,000. All photo series were black and white except 2000 digital color photos and 1980 infrared photos. We orthorectified all photographs, with ERDAS Imagine Orthobase, using the 1998 USGS DOQQs and a USGS 10-m DEM. We then mosaicked and tiled the orthorectified images. We did not perform an independent test of the accuracy of orthorectified imagery.

Digitizing

We digitized channel features on-screen in ESRI ArcGIS, generally at an approximate scale of 1:1,000. We mapped the active channel using the map units listed in Table 3. We designated the wetted channel at the time of the photos the “low flow channel” (coded as LF). The high flow channel (area between the banks) was mapped as “gravel bar” (coded as GR) or as “colonizing vegetation” (coded VC). We considered these three units together as the “active channel.” We mapped a vegetation patch as a “forested island” (coded FI) if the patch included mature trees, particularly mature conifers, these mature trees being taken as a surrogate for surfaces that had accreted vertically high enough to function as floodplain rather than gravel bar. Forested islands are not included in the active channel. We mapped the channel from General Land Office plat maps, as “active channel” (coded as AC), encompassing the low flow and high flow channel (Table 3), and also used “FI” for forested areas between major flow splits shown on the plat maps.

The accuracy with which the channel could be digitized varied with the scale and quality of aerial photos and with the presence or absence of streamside trees. For years with larger-scale photography (1:12,000 scale or larger), the error in digitizing channel features not obscured by vegetation or by glare is small. However, in locations on the same photographs where the channel margin is overhung by vegetation or the photographs have sun glare, we estimate a typical potential error to be $\pm$ 3 m. On the smaller-scale photography (1:12,000-scale or smaller), we estimate a typical error caused by vegetation cover or glare can locally be as much as $\pm$ 5 m. The 1980 photomosaics were the smallest scale photographs (1:58,000), with relatively poor image quality, and the potential maximum error in digitizing channel features from those photos locally could be as much as $\pm$ 7 m; the orthorectification error is also larger for these photographs. The migration analysis made use of centerlines we located visually and digitized on-screen, and this would also introduce another source of error, although on the other hand the use of the centerline would tend to smooth out local inaccuracy in digitizing the riverbanks, thus damping the potential error associated with riverbank digitizing. These digitizing errors are not systematic, and thus their effect would be to increase the variance of the migration rate data. This is a general assessment of the digitizing error; to assess the local precision of the digitization process, we recommend the user compare the GIS coverages to individual images (e.g. to determine the presence of overhanging vegetation or photo glare).

Definitions of Historical Channel Zones

How the zone of historical channel occupation is defined depends on whether the zone is expanded to include floodplain channels (outside of the active channel), which in turn depends on the nature of source materials used to map floodplain channels.

We defined three types of historical channel zones (abbreviated herein as “HCZ”). The first is the area that encompasses the historical locations of the active channel only (HCZ1), which is the zone commonly used in channel migration zone planning. We also delineated the area that also includes floodplain channels visible on aerial photographs (HCZ2). Finally, we also mapped the area that also includes features that we interpret to be floodplain channels on lidar imagery (HCZ3). The width of all three HCZs vary depending on the historical period used.

Aerial photographs of forested floodplains reveal only a small fraction of floodplain channels. To examine the extent to which this is the case in the study area, we mapped linear depressions from hillshade DEM from lidar in the portion of the study area covered by lidar (within King County, encompassing the right bank (or northern half of the valley). Numerous channels are apparent (Figures 14A and 15A) on the lidar that are not visible on the aerial photographs. Including these floodplain sloughs that cannot be seen from aerial photographs greatly expands the extent of the floodplain occupied by the HCZ (Figures 14B and 15B). A quantitative measure of this, and the ramifications for channel migration zone studies are discussed later in this report.

Channel Migration and Avulsion Analysis

We made two analyses of the channel location data. The first measures the lateral movement of the channel between time periods represented by the maps or photos. We made these measurements by first digitizing a centerline through our floodplain map unit, and then generating cross-valley transects orthogonal to this valley floodplain centerline, at 200 m intervals along the floodplain centerline (Figure 2). As indicated above, we also digitized centerlines through the low flow channel of all data sets. Where there were multiple channels, we chose the largest channel. The migration or avulsion distance between data periods was determined along each of these cross-floodplain transects. The channel migration or avulsion measurements thus reflect change in location orthogonal to the floodplain centerline.

The second analysis characterizes channel location in the period of record as an occupation grid. This analysis was made using digitized layers of the active channel (i.e., low flow channel, gravel bars, gravel bars with colonizing vegetation) and floodplain sloughs for all data periods. We then created grids with a

1 m cell size, and computed the number of times each grid was occupied by the active channel and floodplain sloughs, expressed as a percent.

We computed the width of the three historical channel zones described above, and the ratio of the zone to the floodplain width (HCZ/FPW) and the ratio of the historical channel zone to the year 2000 channel width (HCZ/CW). Because the lidar currently available does not encompass the entire floodplain, the width of the HCZ3 is not quantitatively comparable to the other two zones (which are defined using the entire floodplain). However, we compute the ratio of the HCZ3 to the width of the floodplain covered by currently available lidar to create an index comparable to that computed for the other two zone types.

"Average Annual Migration" in Theory and Practice

Historical *average annual* channel migration rates, for practical reasons, are subject to biases. Unbiased average annual migration rates can only be computed from aerial photographs or maps made *annually*. Such a record rarely exists, and it does not exist for the White River. Instead, average annual rates must be approximated using records made at various intervals of time. The longer the period is between successive photo or map record, the greater is the bias. This is because as the number of years increases between photo or map records, the likelihood increases that the full record of the river's activity in that time period will be obscured. For example, a river might migrate (or avulse) toward river right in one year, and then toward river left in a second year, and in the third year avulse again toward river right. Photographs taken bracketing this three-year period will only record the net change between the beginning and ending of the bracketing period (which could even result, in the example given here, in zero net migration, and an average annual migration rate of zero), not the actual annual average movement (e.g., in this example, the sum of the river's lateral movement in each year). The greater the time period between photos or maps, the more the measured migration rate underestimates the actual annual average rate. Thus, the longer the time periods used in a study, the more the estimated average annual migration rate will probably underestimate the actual average annual migration rate. This bias toward underestimating is greater in rivers characterized by frequent channel-switching avulsions, in which the channel is shunted by flood events from the main channel to a former channel, and by the next flood into another channel, because it is more likely that the river will have moved multiple times in opposite directions during a period between maps and photos. Rivers characterized by meandering—the more typical “migration” on which channel migration studies, and the concept of average annual migration have been premised—are likely to underestimate less, because the lateral movement tends predictably to be in one direction (“migration”) for a number of years in a row.

The bias varies for different time increments, when time increments are unequal. This problem is unavoidable in this region because in the earlier part of the historical record, prior to the availability of aerial photos, maps made of sufficient quality, or even maps of any kind, were not made with the frequency at which aerial photographs were later flown, and aerial photographs were commonly flown less frequently in the earlier part of the aerial photographic record than in recent decades. The potential to underestimate “average annual migration rate” is greater in the earlier part of the historical record.

It is possible to correct for unequal time increments by regressing time increment against migration rate (e.g. Figure 8 in O’Connor et al. 2003) to develop a correction factor. However, this assumes migration rate and time increment are independent variables, which is not likely the case because time increment correlates positively with time. In other words, longer time increments occurred in the earlier part of the historical record, and shorter increments in the later part of the record, and migration rates may differ between the two time periods; there is reason to expect that migration rates would have differed with time, on account of the dramatic changes to land uses that occurred throughout the historical record. For this reason, we have not made this correction. Instead, we calculate migration rates for the aerial photo period of record (1931-2000) only to minimize the bias introduced by differences in period duration.

In summary, for the purposes of this study, it should be kept in mind that average annual estimates are underestimates of the actual annual average because we do not have data from every year. Additionally, the White River historically has had at different times and locations either an anabranching or braided channel pattern, characterized by channel switching (see later in report). This means that the average annual estimates for lateral migration are more biased (more of an underestimate) in the White River than would be the case in a meandering river such as the Snoqualmie River.

Figure 13. Years of aerial photo and map coverage in the study area.

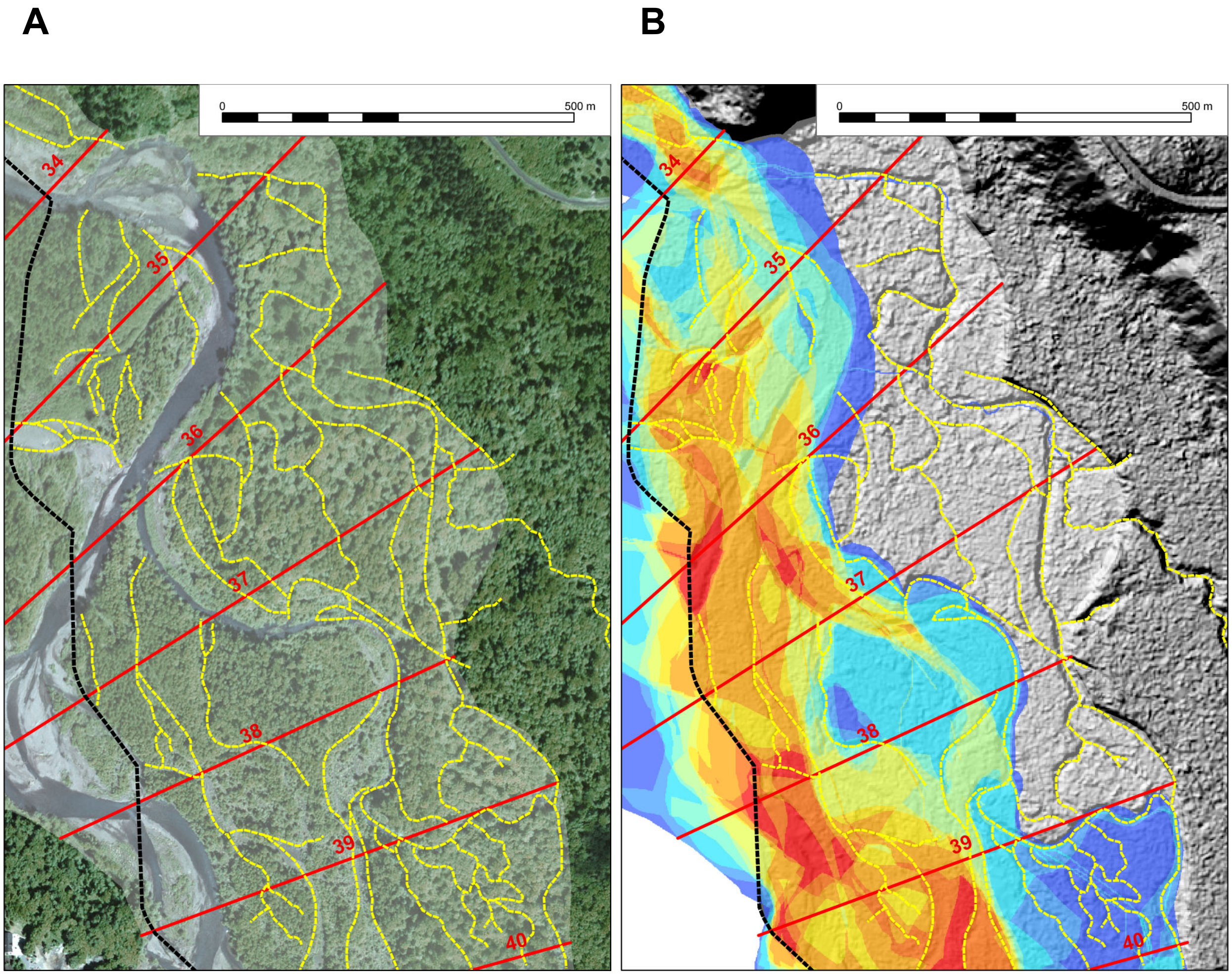


Figure 14. White River floodplain between Transect 34 and Transect 40 (transects are shown with red lines). Transparent white shading indicates the extent of floodplain. Heavy dashed black line to left of panels indicates extent of lidar coverage. (A) Yellow dashed lines are floodplain channels drawn from a hillshade DEM made from lidar data (shown in panel B). Background is year 2000 aerial photography. (B) The same channels as in panel A, superimposed on DEM and on grid that includes all former channel locations shown on historical maps and photos used in this study (see later in report, Figures 22 and 23).

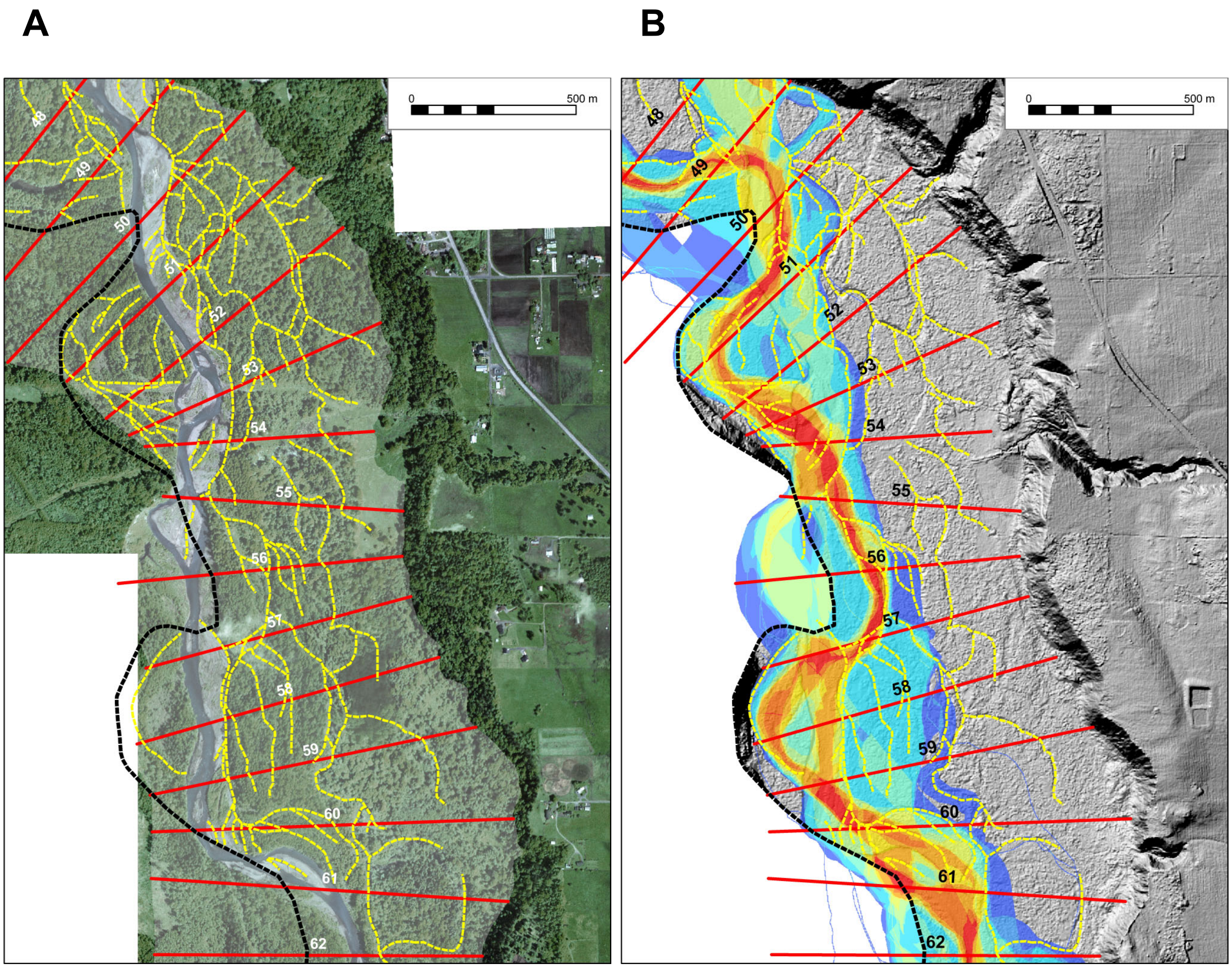


Figure 15. White River floodplain between Transect 48 and Transect 62 (transects are shown with red lines). Transparent white shading indicates the extent of floodplain. Heavy dashed black line to left of panels indicates extent of lidar coverage. (A) Yellow dashed lines are floodplain channels drawn from a hillshade DEM made from lidar data (shown in panel B). Background is year 2000 aerial photography. (B) The same channels as in panel A, superimposed on DEM and on grid that includes all former channel locations shown on historical maps and photos used in this study (see later in report, Figures 22 and 23).

Table 2. Maps and aerial photos used. Sources: (1) Intercounty River Improvement District (ICRID); (2) US Army Corps of Engineers, Seattle District; (3) UW Libraries: Suzallo Library Map Collection; (4) King County Dept. of Natural Resources and Parks; (5) King County Conservation District.

YEAR	SCALE	MAP NAME or PHOTO PROJECT ID	TYPE	SOURCE
1867-1891	1:31,680	T21N R4E (1867) T20N R5E (1872) T20N R6E (1872) T19N R6E (1873) Muckleshoot Indian Reservation, parts of T20N & T21N R5E (1874) T 19N R7E (1891)	General Land Office plat maps	5
1931	1:20,000	-	BW	1
1936	1:10,500	-	BW	4
1940	1:12,000		BW	2
1944	1:20,000	Army Orthophoto Maps	BW	3
1955	1:20,000	ENK	BW	5
1959	1:7,800	KC-L-9	BW	4
1965	1:60,000	WF	BW	3
1970	1:12,000	KP-70	BW	3
1974	1:24,000	DNR orthophotos from NW-H-74	Paper orthophoto prints	3
1980	1:58,000	HAP 80	IR	3
1985	1:24,000	Sound Block 85	BW	3
1989	1:13,500	SP89	BW	4
1995	1:12,000	NW-95	BW	3
2000	-	Emerge Natural Color Derivative Aerial Photography	C	4

Table 3. Mapping categories used in digitizing channel features on aerial photographs and General Land Office plat maps.

GEOMORPHIC LOCATION	TYPE CODE	DESCRIPTION
Active Channel	LF	Low flow channel at the time of the aerial photograph.
	VC	Colonizing vegetation.
	GR	Gravel bar.
Active Channel	AC	Active channel, undifferentiated. Includes LF, GR and VC. Used for General Land Office plat maps.
Forested Floodplain	FI	Forested island. Patch of trees between branches of active channel.

MIGRATION RATES

The White River upstream of about the R Street Bridge in Auburn is within a confining valley, and downstream of the R Street Bridge opens out onto the White River fan. Prior to 1906 the river flowed north through the town of Auburn, departing from the current course northward through the Auburn Game Farm Park immediately upstream of the R Street Bridge. The two parts of the study area are considered separately below.

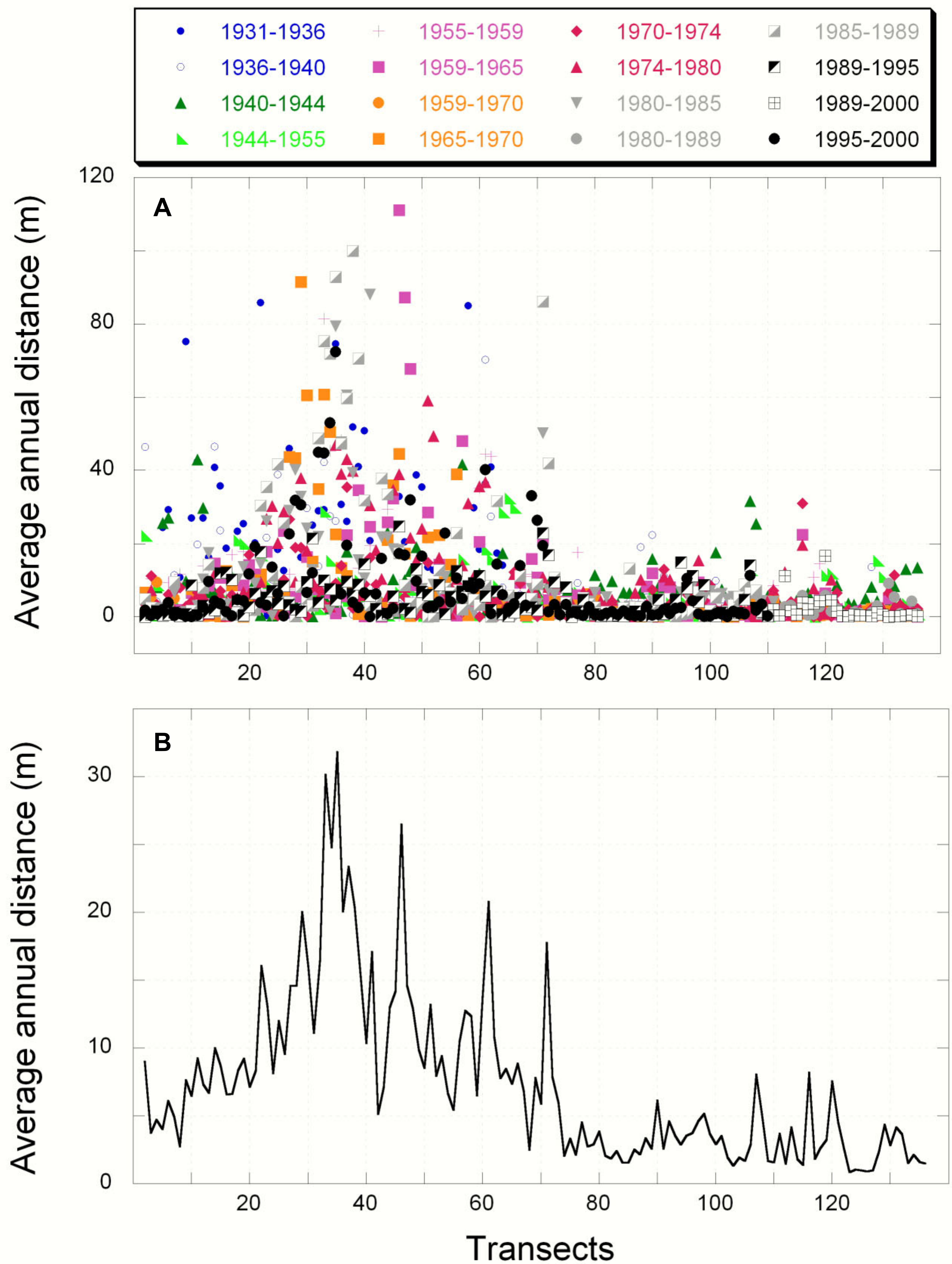
Figure 16A shows average annual migration rates, for all time periods, for each floodplain transect. The figure shows the highest rates, and greatest variation in rate, in the third and fourth segments, or roughly between T27 and T73. In Figure 16B, the annual rate is time weighted—at each transect, each time interval is multiplied by the number of years in the interval, this product is summed for all intervals, and the sum is divided by the total time interval at that transect. The overall time-weighted average annual lateral movement on all transects between 1931 and 2000 is 7.4 m/yr (Table 4). Within individual segments this average varies by a factor of 10X, with the lowest being 1.7 m/yr in segment 6 and the highest 19.9 m/yr in segment 3.

The time-weighted average is normalized in Figure 16C by dividing with the active channel width measured from 2000 aerial photos. This normalization has the effect of reducing the amount of variation in average migration rate that is due to differences in channel width between the different regions of the study area. It shows migration in the upper two segments (T74-T136) has been roughly half that in the lower four segments relative to the channel width.

Figure 17 shows the mean annual migration rate and one standard error of the estimate for each time period. The rates are not distinguishable statistically (within a 95% confidence) except for that between 1931-1936, which is higher than succeeding periods. This primarily reflects the effects of large storms in the period, with peak flows in 1932 (17,000 cfs), 1933 (16,500), and 1934 (28,000 cfs), all considerably greater than the average annual peak flow for the 1929-2002 period of record of 9,100 cfs (Figure 18A). A regression of the largest peak annual flood in each time period bracketed by aerial photos against average annual migration rate for the same periods accounts for about 75% of the variation in average annual migration rate (Figure 18B).

The average migration rate for individual time periods (Figure 19) also varies in some segments because of the effects of levee construction. Levees built in the T2-T21 segment (S1) in the few years prior to 1959 reduced the lateral migration rate compared to other segments (Table 4). The average migration rate between 1931 and 1959 was statistically indistinguishable from that between 1959 and 2000 for the segments upstream of the levees. There is no statistically significant change in annual migration rate between the time prior to the closure of Mud Mountain Dam (1948) and after (Table 4). Comparing the segments upstream of the levees shows that annual migration was essentially the same in the periods 1931-1944 and 1944-2000.

The 1931-2000 average annual migration along the White River on the White River Fan was 5.2 m/yr (Figure 20). The average was 2.6 m/yr in the lower part of the segment (T10-14, downstream of the East Valley Highway) where levees were constructed prior to 1931, compared to 7.2 m/yr for T2-9. The rate overall diminished through time (Figure 21) as the levee system was extended upriver and as levees were moved closer in to the river, with rates between 1 and 3 m/yr in the last few decades.



1931-1936
1936-1940
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1944-1955
1955-1959
1959-1965
1959-1970
1965-1970
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A
B
Average annual distance (m)
Transects

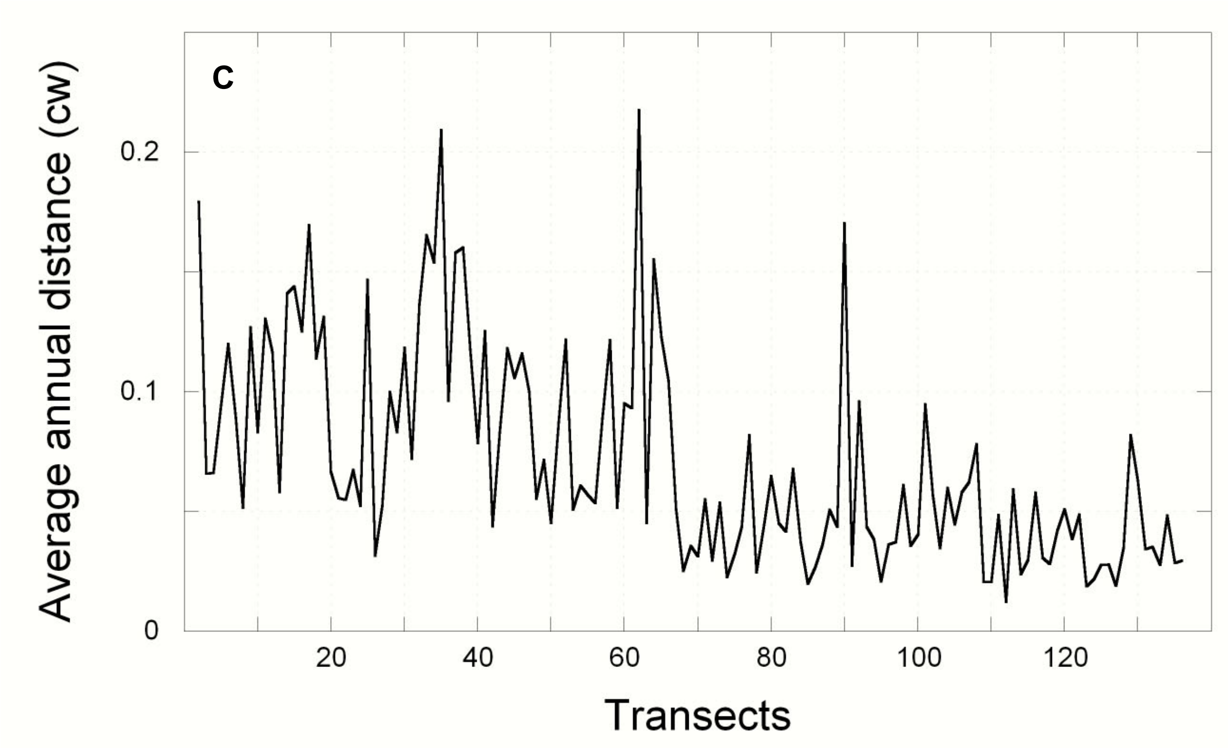


Figure 16. (A, preceding page) Average annual distance moved by channel centerline for individual time increments, for period of photo record. (B, preceding page) Time weighted average annual distance moved by channel centerline for period of photo record. Note that scale of y-axis differs from that of panel A. (C) Time weighted average annual distance moved by channel centerline normalized by the width of the active channel in 2000, as measured from aerial photographs. Transect numbers refer to Figure 1.

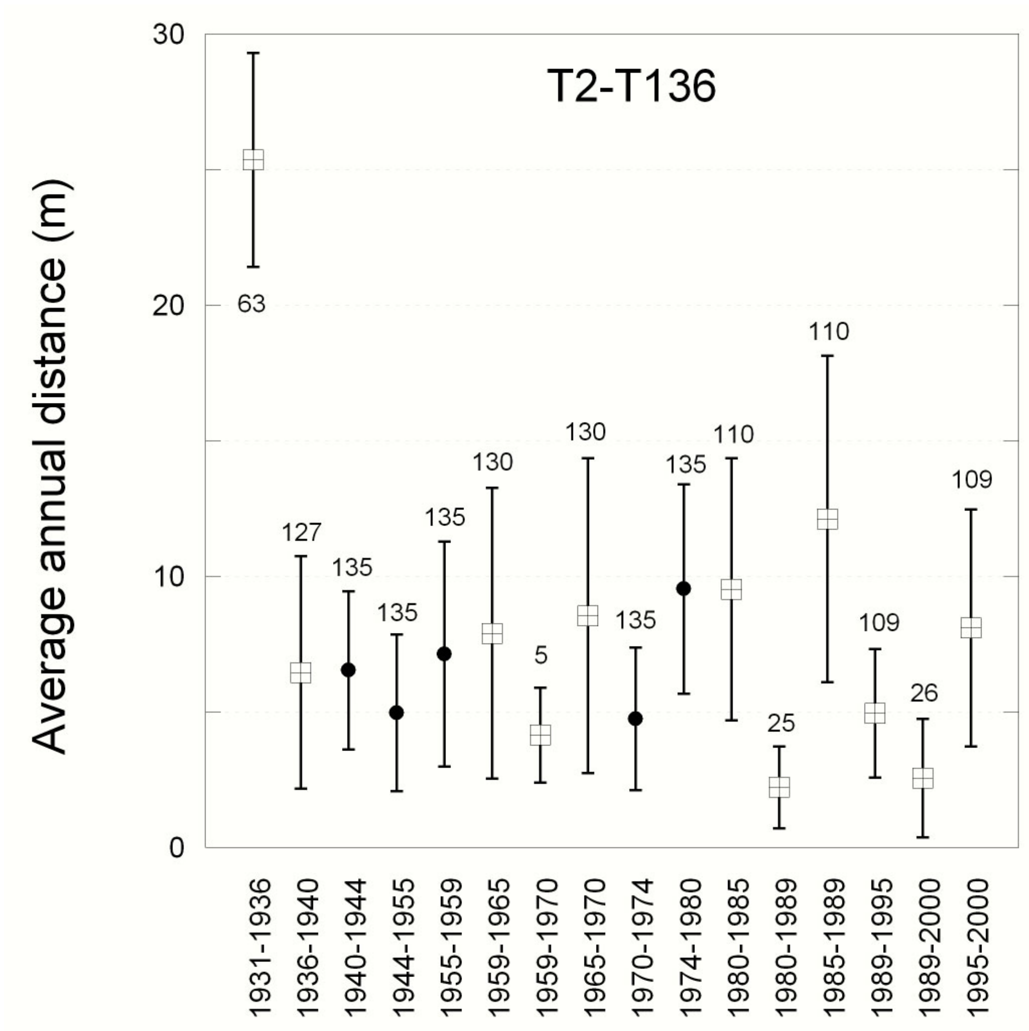


Figure 17. Mean and one standard error of annual channel movement, for individual time periods, for all transects. Time periods having open square symbols overlap and have different sample sizes that are less than the full 135 transects, reflecting incomplete photo coverage in some years; sample size for each point is shown on figure.

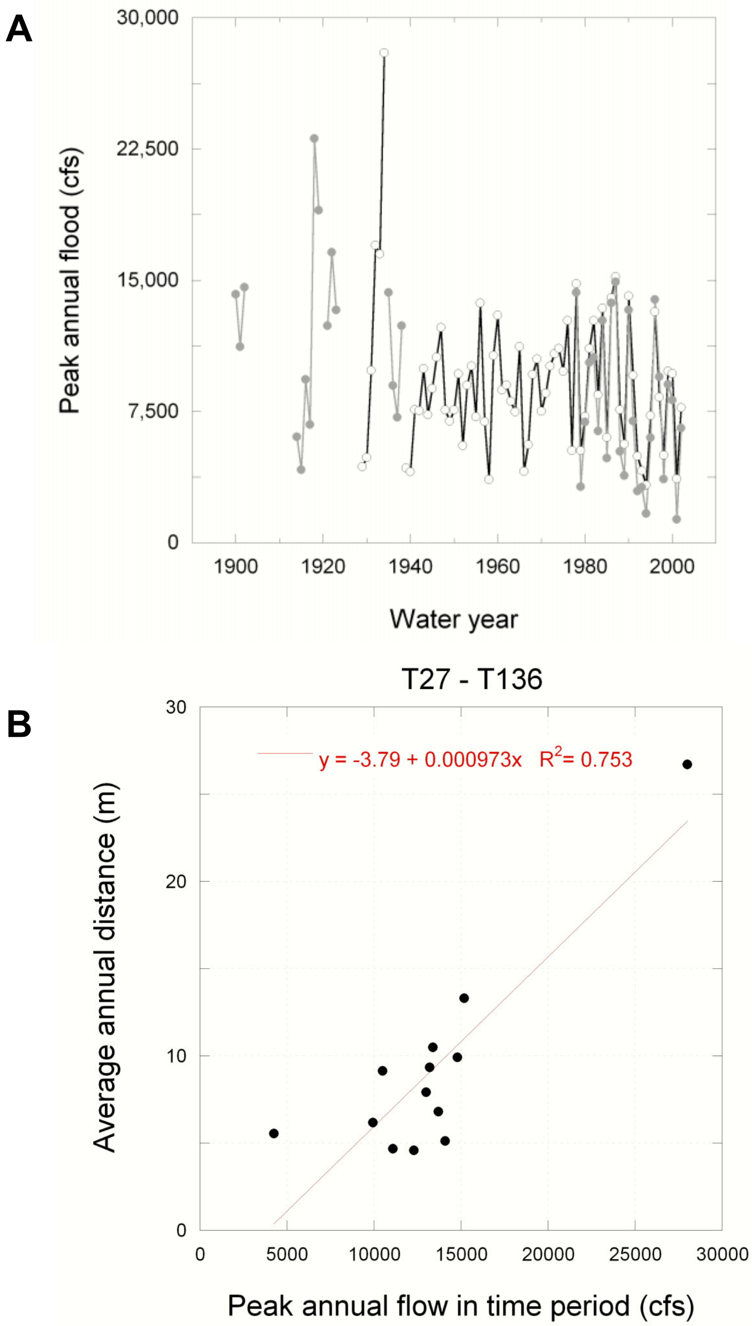


Figure 18. (A) Peak annual discharge from the USGS “White River near Buckley” gage 12100000 (black line and open circle) and USGS “White River at Buckley” gage 12098500 (gray line and solid gray circle). (B) Linear regression of largest annual peakflow in periods bracketed by aerial photos and the average annual migration in the same periods. The period prior to 1931 is not included.

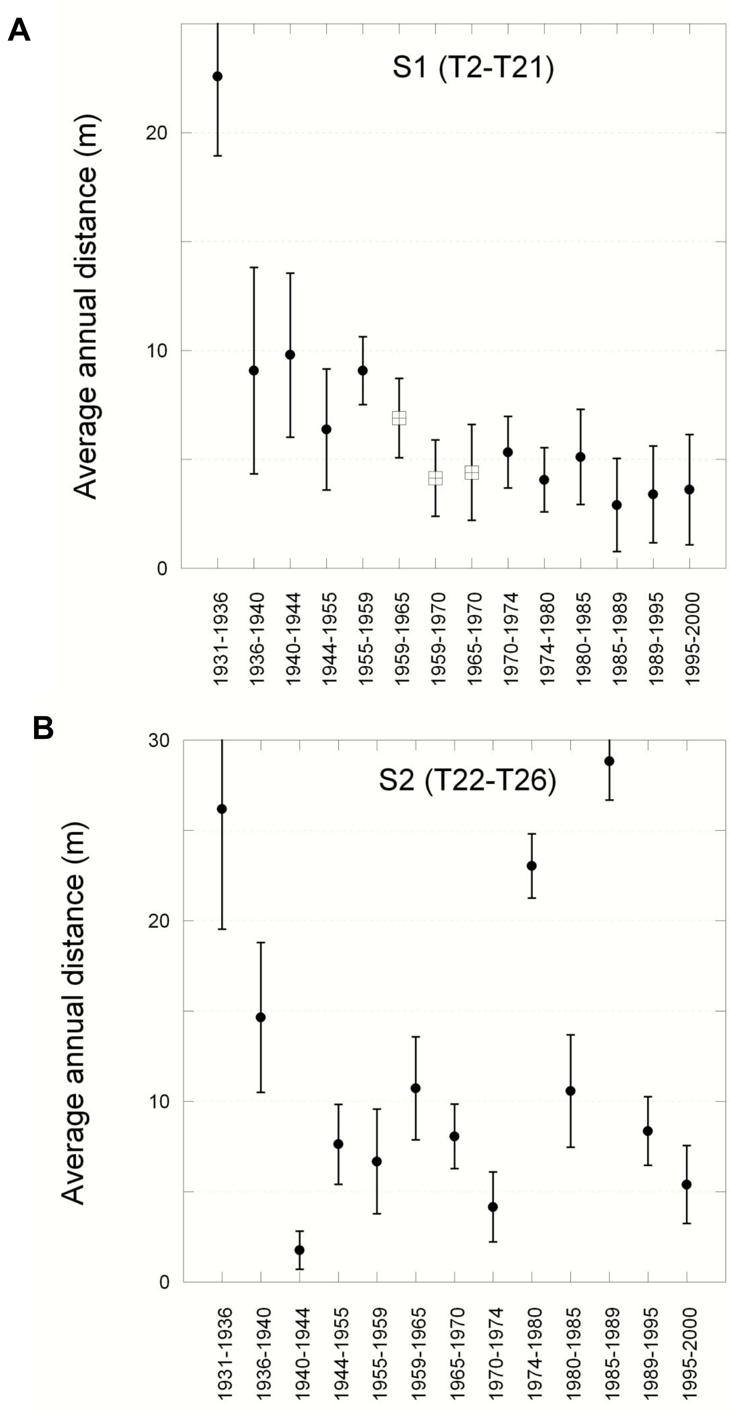
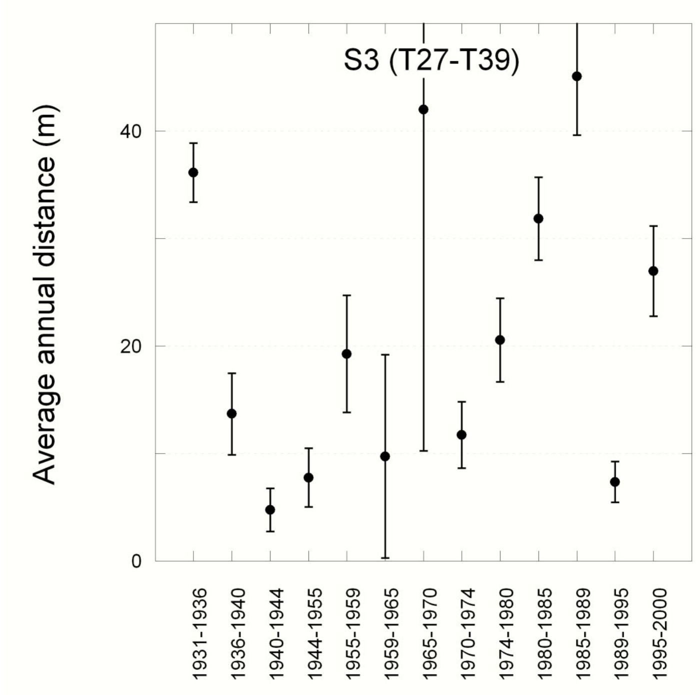


Figure 19 (continued on following pages). Mean and one standard error of annual channel movement, for individual time periods. (A) Segment 1; (B) Segment 2. Time periods having open square symbol in panel A overlap and have different sample sizes. Scale of vertical axis varies between panels.

C



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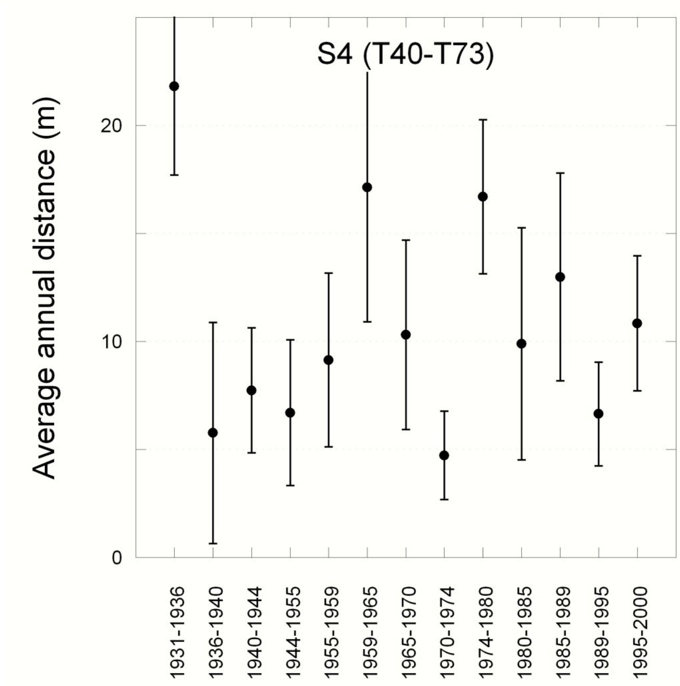


Figure 19 (continued). Mean and one standard error of annual channel movement, for individual time periods. (C) Segment 3; (D) Segment 4. Scale of vertical axis varies between panels.

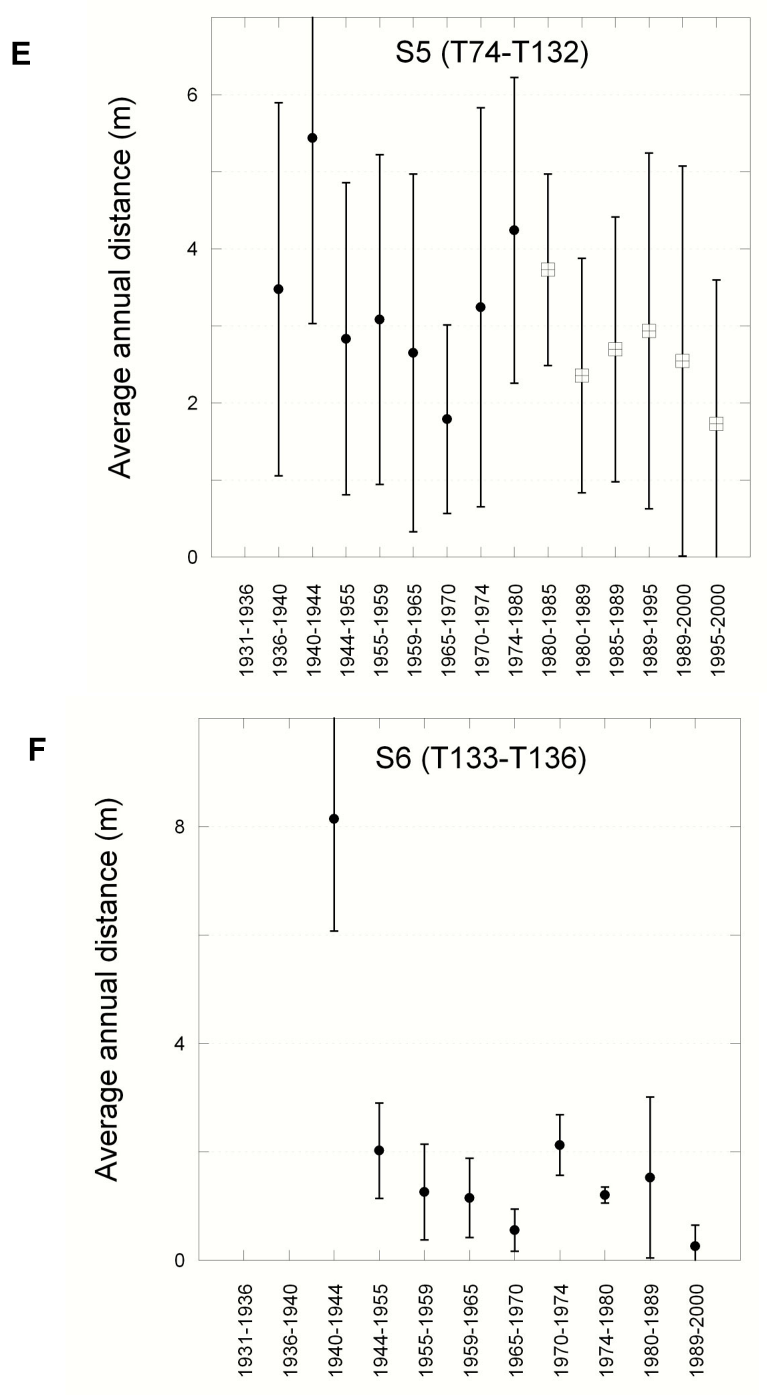


Figure 19 (continued). Mean and one standard error of annual channel movement, for individual time periods. (E) Segment 5; (F) Segment 6. Time periods having open square symbol overlap and have different sample sizes. Scale of vertical axis varies between panels.

Table 4. Time-weighted, average annual migration rates, measured along transects shown in Figure 1, and averaged for study segments described in Table 1. Migration rate is mean and one standard deviation, in meters. Note that comparisons between 1931-1944 and 1944-2000 and between 1931-1959 and 1959-2000 are restricted to segments 2-64 for which there is 1931 photo coverage.

SEGMENT	N	1931-2000 (m/yr ± SD)	1931-1944 (m/yr ± SD)[1]	1944-2000 (m/yr ± SD)[1]	1931-1959 (m/yr ± SD)[1]	1959-2000 (m/yr ± SD)[1]
ALL (2-136)	135	7.4 ± 6.3	15.1 ± 9.3	11.0 ± 7.1	9.6 ± 5.5	12.1 ± 9.0
T27 - T136	110	7.3 ± 6.8	15.4 ± 8.8	14.1 ± 7.3	11.7 ± 7.5	16.1 ± 9.1
T2 - T21	20	6.9 ± 2.0	14.5 ± 10.0	5.1 ± 2.2	10.5 ± 4.6	4.4 ± 1.9
T22 - T26	5	11.8 ± 3.1	15.1 ± 11.5	11.0 ± 2.3	11.0 ± 7.9	12.3 ± 2.7
T27 - T39	13	19.9 ± 6.2	19.6 ± 7.7	20.0 ± 6.5	14.9 ± 8.2	23.4 ± 7.4
T40 - T73	34	10.5 ± 4.9	13.2 ± 8.7	11.0 ± 5.6	10.0 ± 6.7	12.4 ± 7.6
T74 - T132	59	3.1 ± 1.7	-	-	-	-
T133 - T136	4	1.7 ± 0.3	-	-	-	-

[1] Restricted to segments 2-64 only.

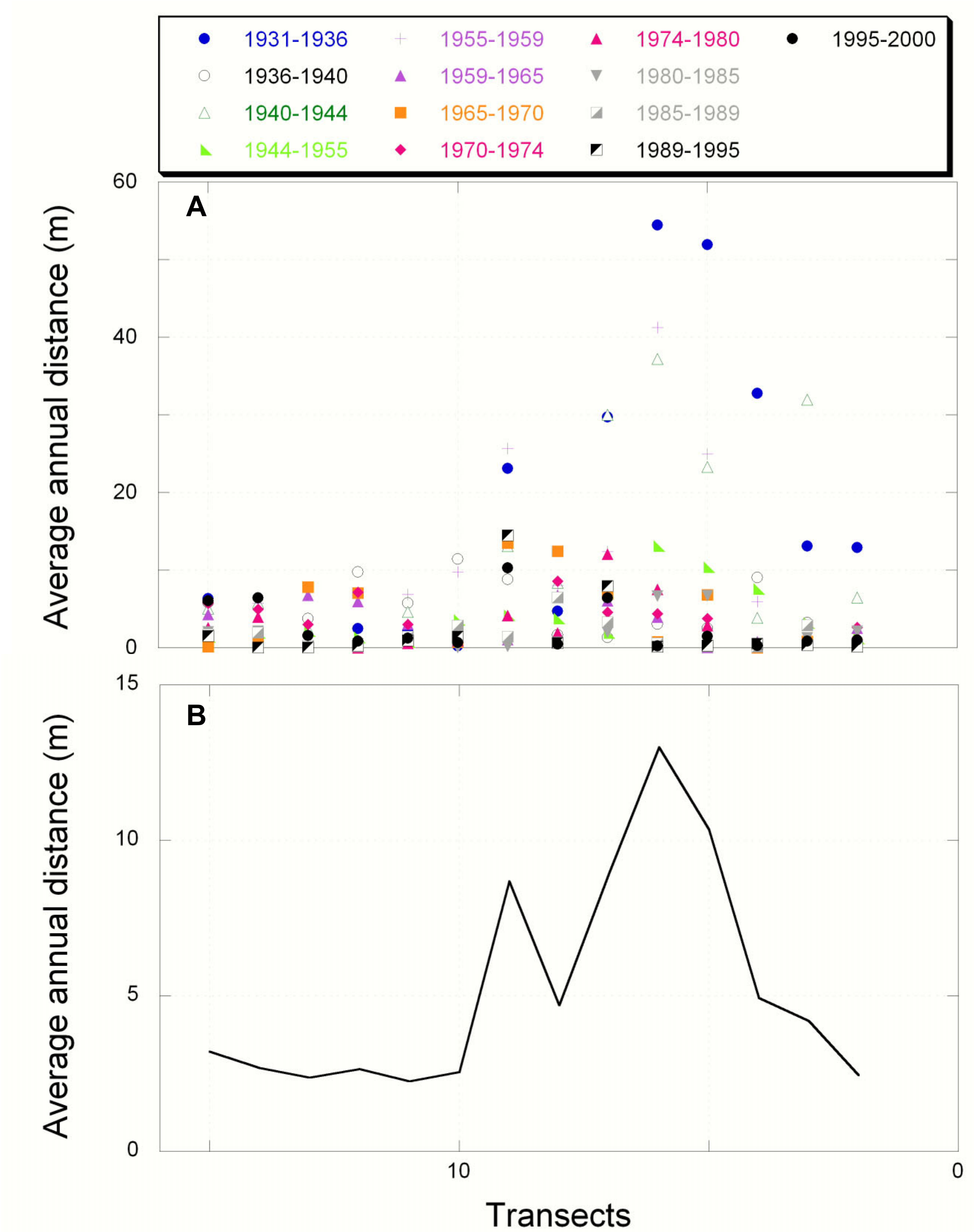


Figure 20. (A) Average annual distance moved by channel centerline for individual time increments, for period of photo record, on White River Fan. Transect numbers refer to Figure 2 and Figure 9; because these transects are numbered in an upstream-to-downstream direction, the x-axis in the figure has been reversed so that left to right represents downstream to upstream. (B) Weighted average annual distance moved by channel centerline for period of photo record.

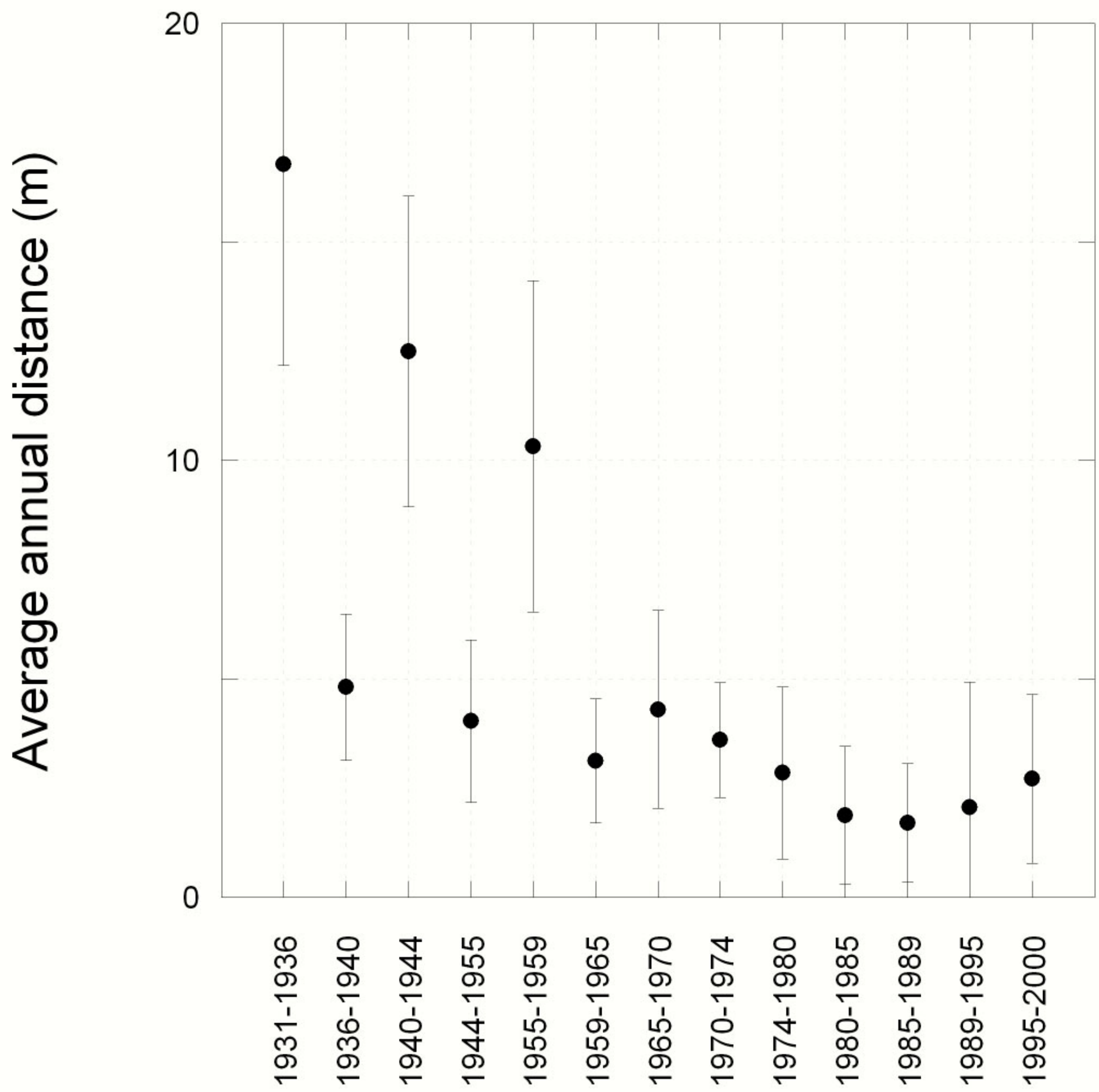


Figure 21. Mean and one standard error of annual channel movement, for individual time periods, for all transects on the White River Fan segment. N = 14 for all periods.

PATTERNS OF HISTORICAL FLOODPLAIN OCCUPANCY

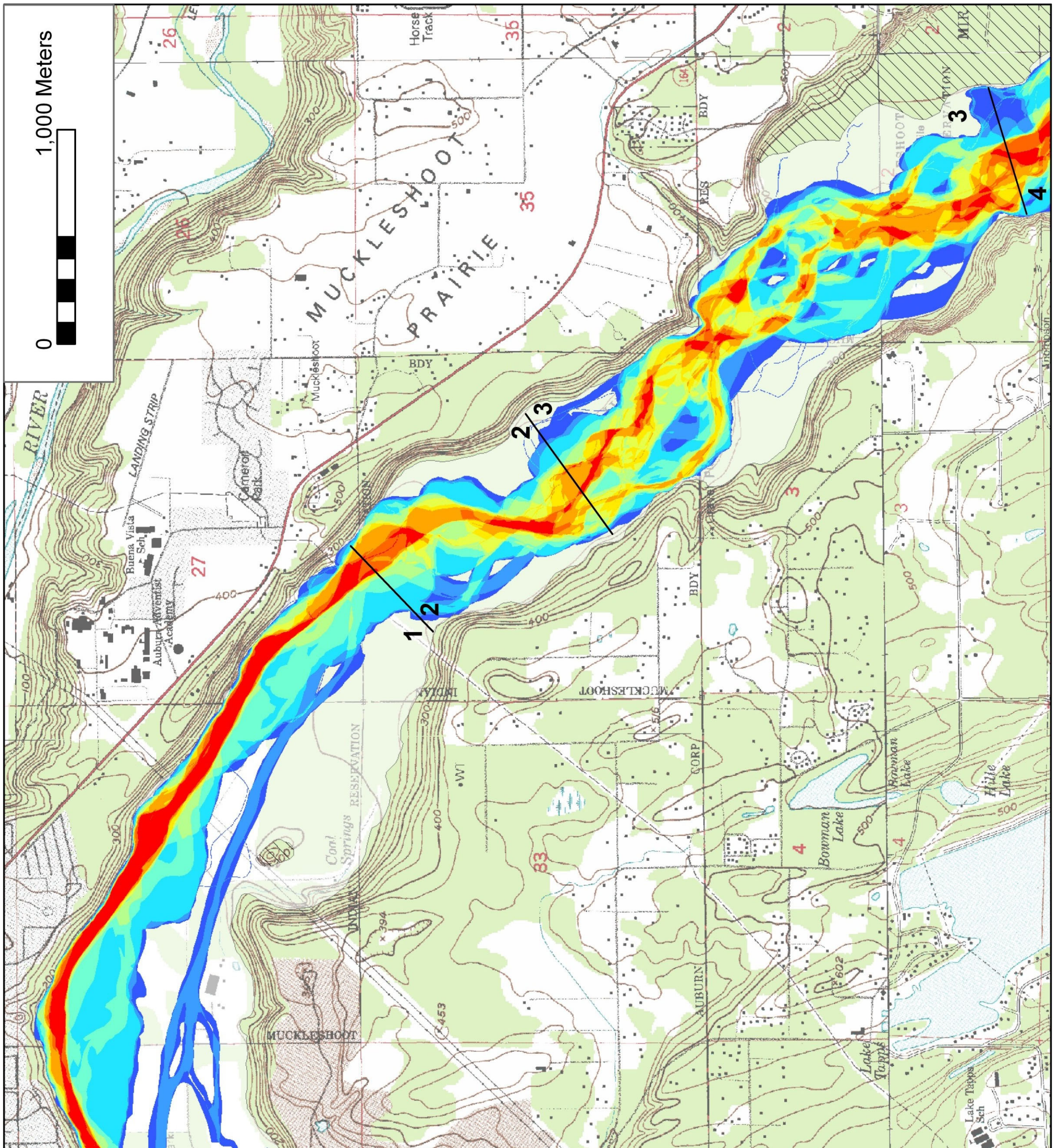
Figure 22 shows an occupation grid for the study area, for the entire period of record (1867-2000), and Figure 23 shows the same grid for the aerial photo era (1931-2000) only. The grids show the percent of the record during which each 1-m cell was occupied by the active channel (i.e., low flow and high flow channels) and floodplain sloughs. In other words, if twelve sets of aerial photos or maps cover a particular 1-m cell, and the active river or a floodplain slough occupied that cell six of the possible twelve times, then the "percent of years occupied" is fifty percent. The inclusion of floodplain sloughs mapped from aerial photographs, but excluding those inferred from lidar, make the representation of channel positions in these two figures consistent with the "HCZ2" as previously defined. The occupation pattern reflects a combination of meander migration and channel avulsion.

As indicated previously, we defined three different historical channel zones. (We did not make this analysis for the fan reach because it is not meaningful to compare the relocated and leveed White River to the width of the Duwamish-Puyallup trough.) The first is the area encompassed by historical locations of the active channel (HCZ1) and excludes floodplain sloughs to be consistent with general practice in defining historical channel zones. The second is the area encompassed by the historical active channel locations, and the area inclusive of floodplain sloughs mapped from the aerial photographs (HCZ2), and the third expands the latter zone by including floodplain sloughs mapped from lidar (HCZ3). The HCZ1 and HCZ2 are generally comparable with the exception of a few areas where the latter is significantly wider than the former (Figure 24). Both zones are enlarged significantly in a few areas when the GLO channel locations are added to the aerial photo locations (Figure 25).

Overall, the HCZ1 and HCZ2 (including the GLO channel locations) account for 65% and 69% of the floodplain, respectively (Figure 26 and Table 5). In the different segments the percent ranges from 49% (segment 6) to 80% (segment 3) for the HCZ1/FPW ratio, and from 49% to 82% for the HCZ2/FPW ratio. The width of both zones is between 5 and 6 widths of the active channel as measured from year 2000 aerial photographs.

When the channels identified on lidar are included, as HCZ3, on average the historical channel zone encompasses 87% of the floodplain, and ranges in individual segments between 72% and 93% (Figure 27 and Table 5). The channels identified on lidar are very likely predominantly related to relict channel locations previous to the historical record, which implies that the White River has occupied nearly its entire floodplain in the recent past; how many years removed from the present isn't known without field study. It is also likely that a large portion of the floodplain channels detectable by lidar imagery remain active currently, which could be confirmed by fieldwork. This would imply that the White River, when defined as including its floodplain sloughs, at present occupies nearly the entire floodplain.

Figure 22 (four following pages). Occupation grids for the period of map and aerial photo record (1859-2000). Analysis segments are from Table 1 (S1-S6). All panels have a common scale. Background image is mosaicked USGS 7.5' topographic maps. Area shown in white represents the floodplain, as delineated in this study. Holocene terraces and alluvial fans are shown with hatched pattern.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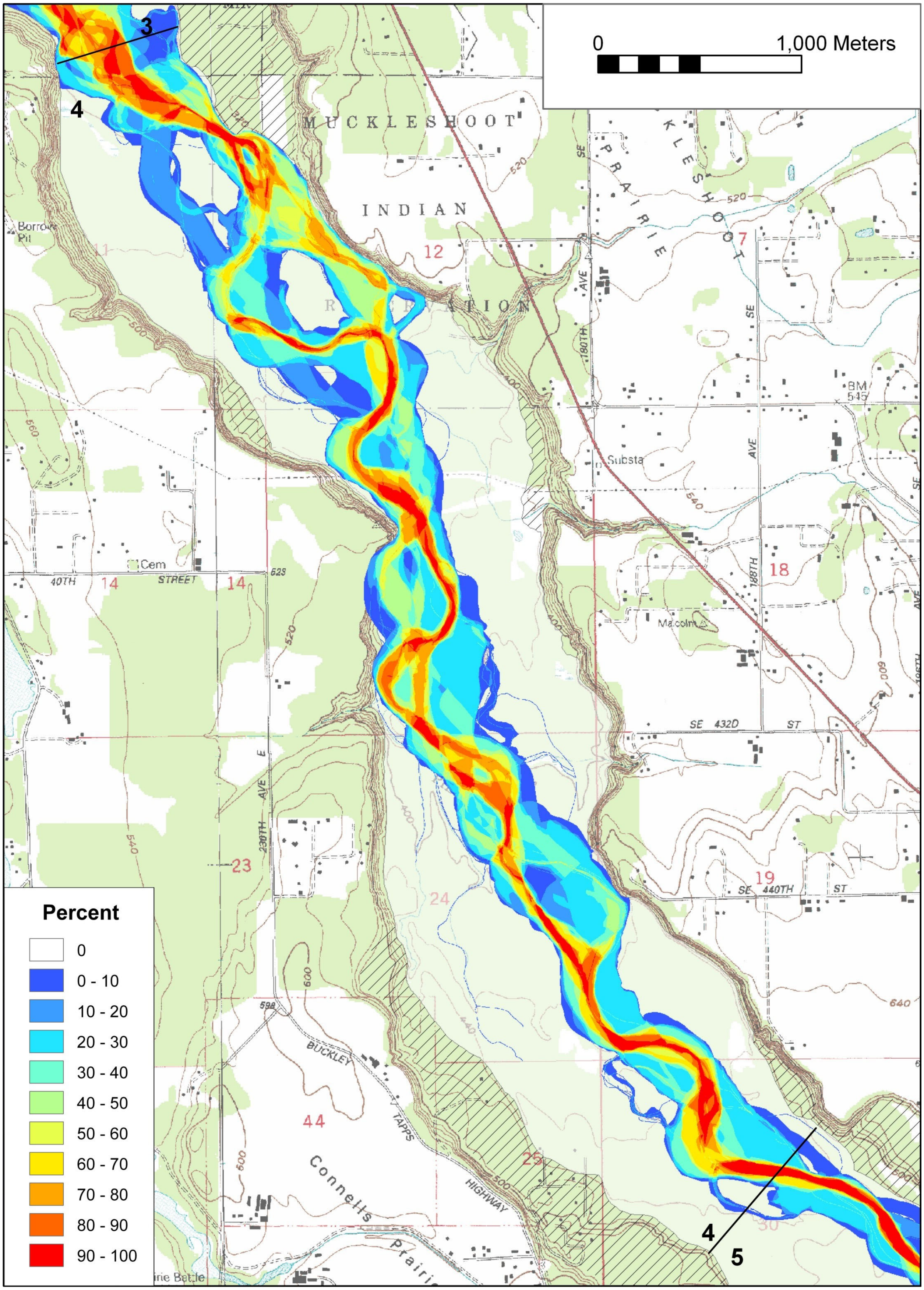
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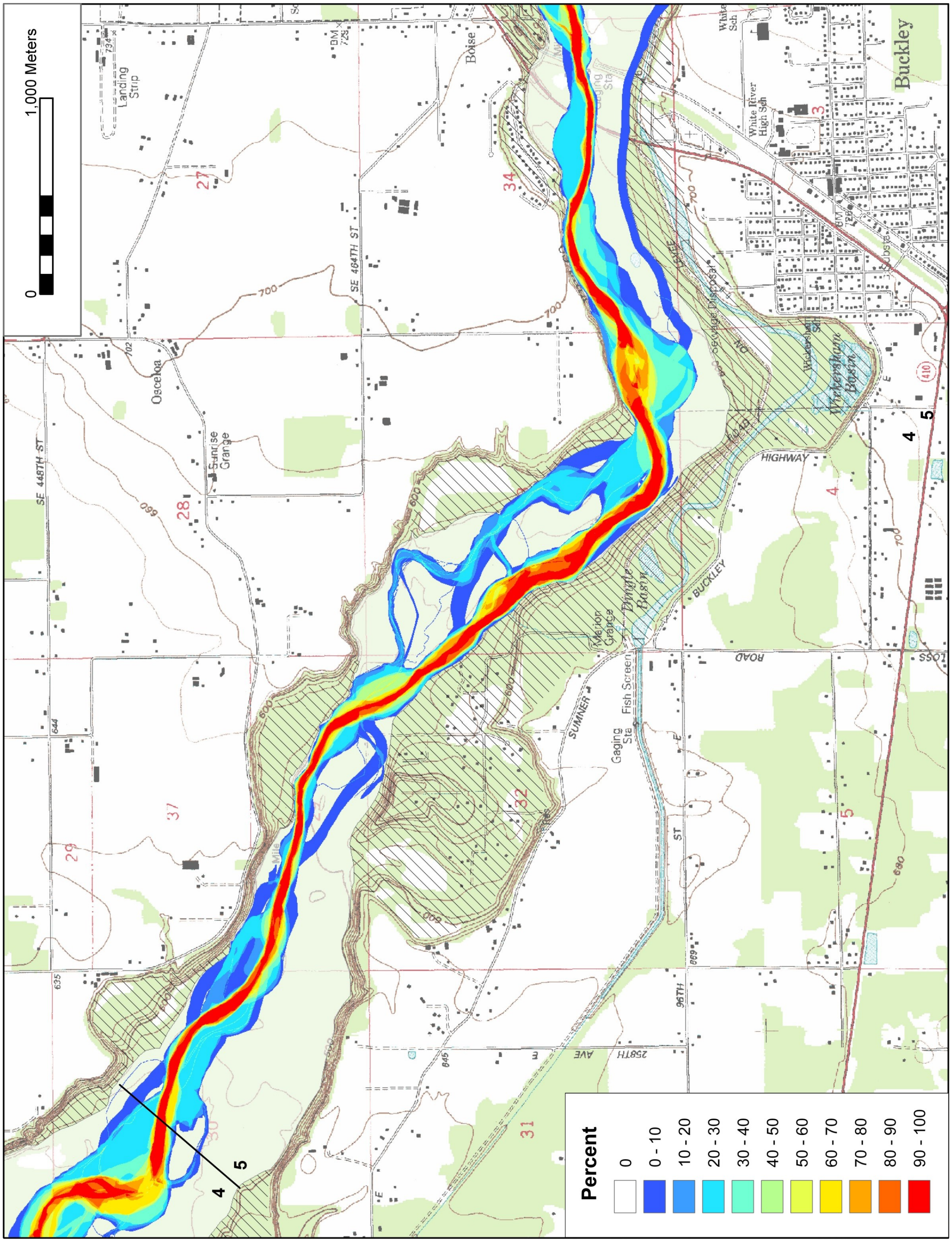

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Major Grange
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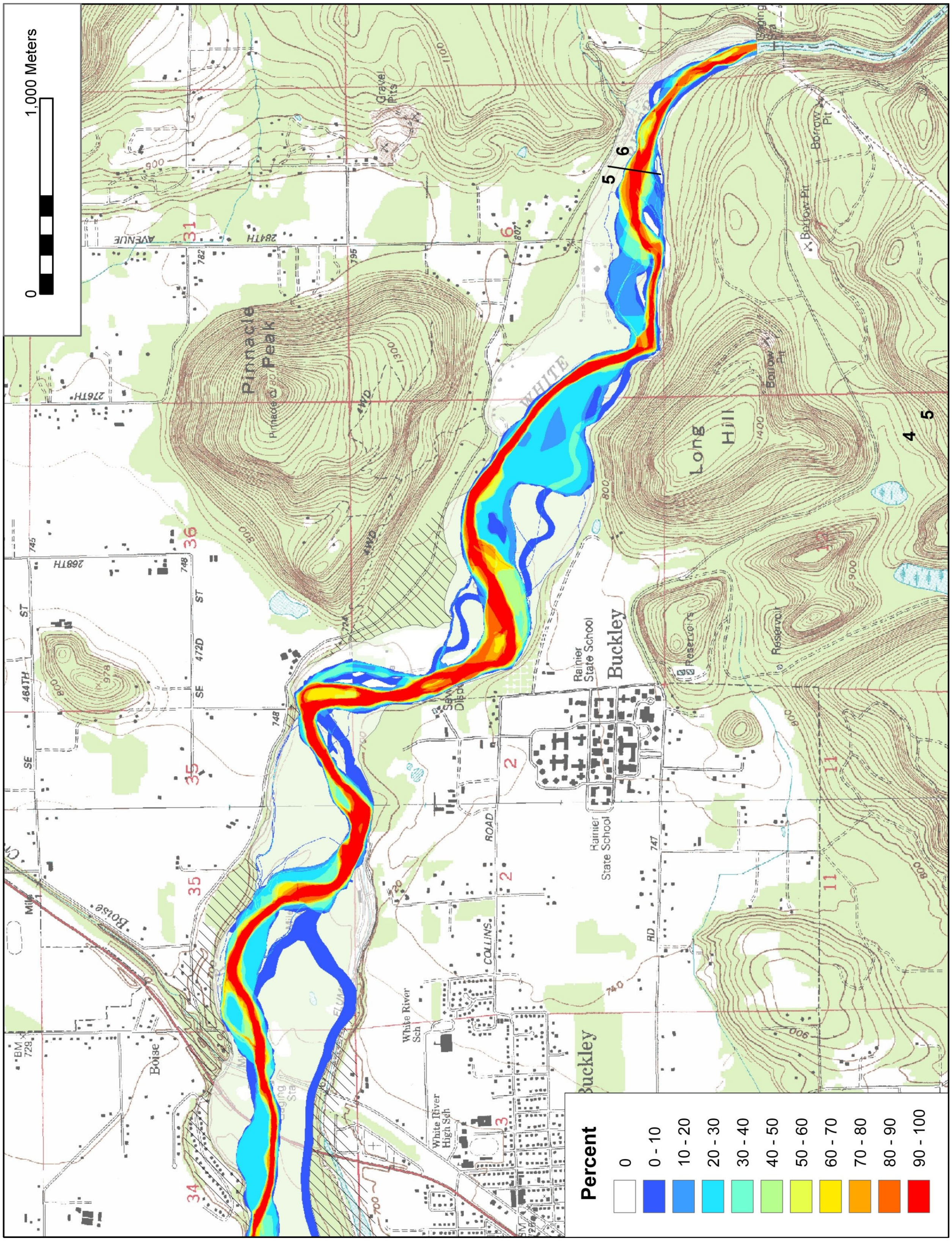
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Buckley
Rainier State School
White River Sch
White River High Sch
Boise
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Gravel Pits
Borrow Pit
Reservoir
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6
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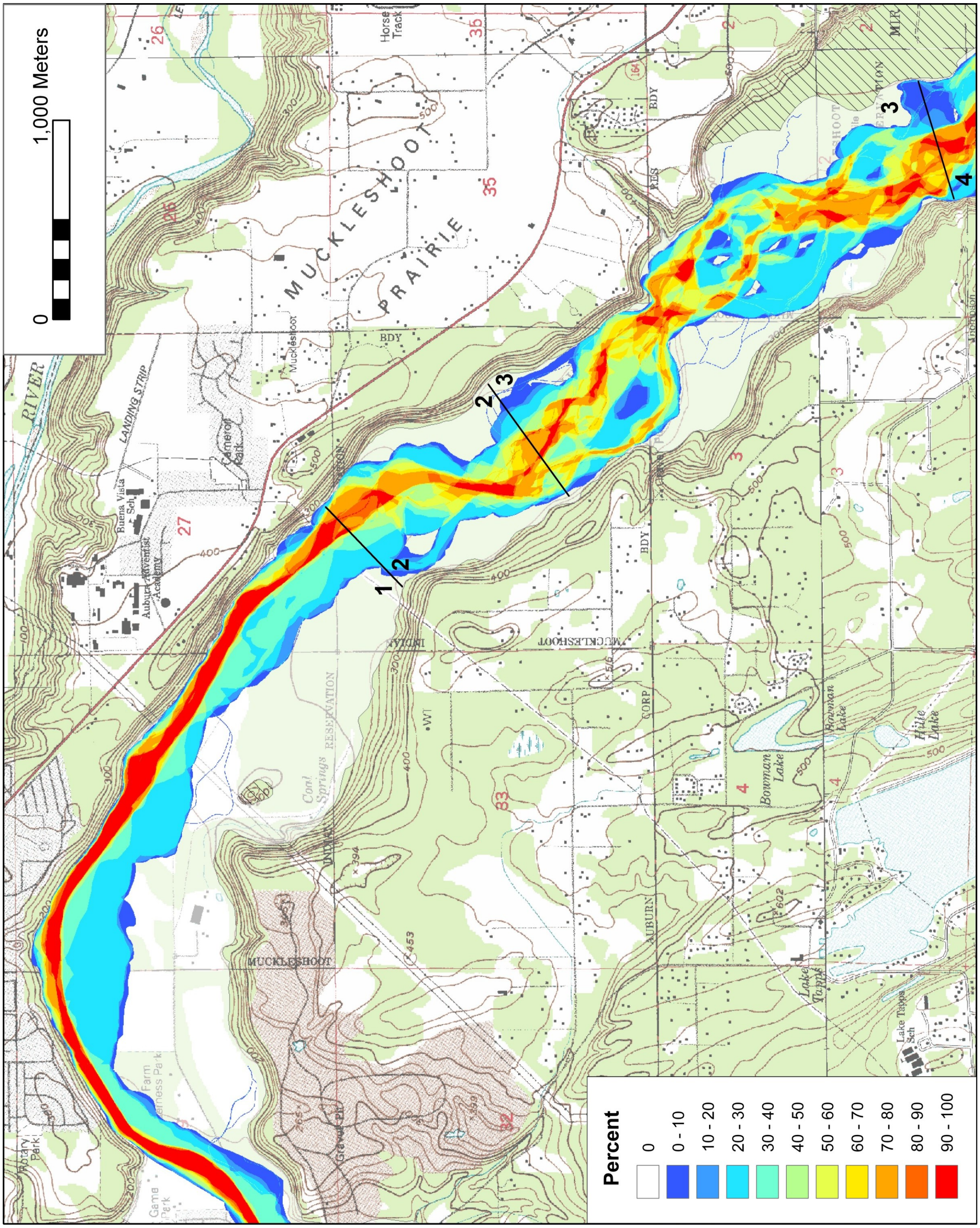
Figure 23 (four following pages). Occupation grids for the period of aerial photo record (1931-2000). Analysis segments are from Table 1 (S1-S6). All panels have a common scale. Background image is mosaicked USGS 7.5' topographic maps. Area shown in white represents the floodplain, as delineated in this study. Holocene terraces and alluvial fans are shown with hatched pattern.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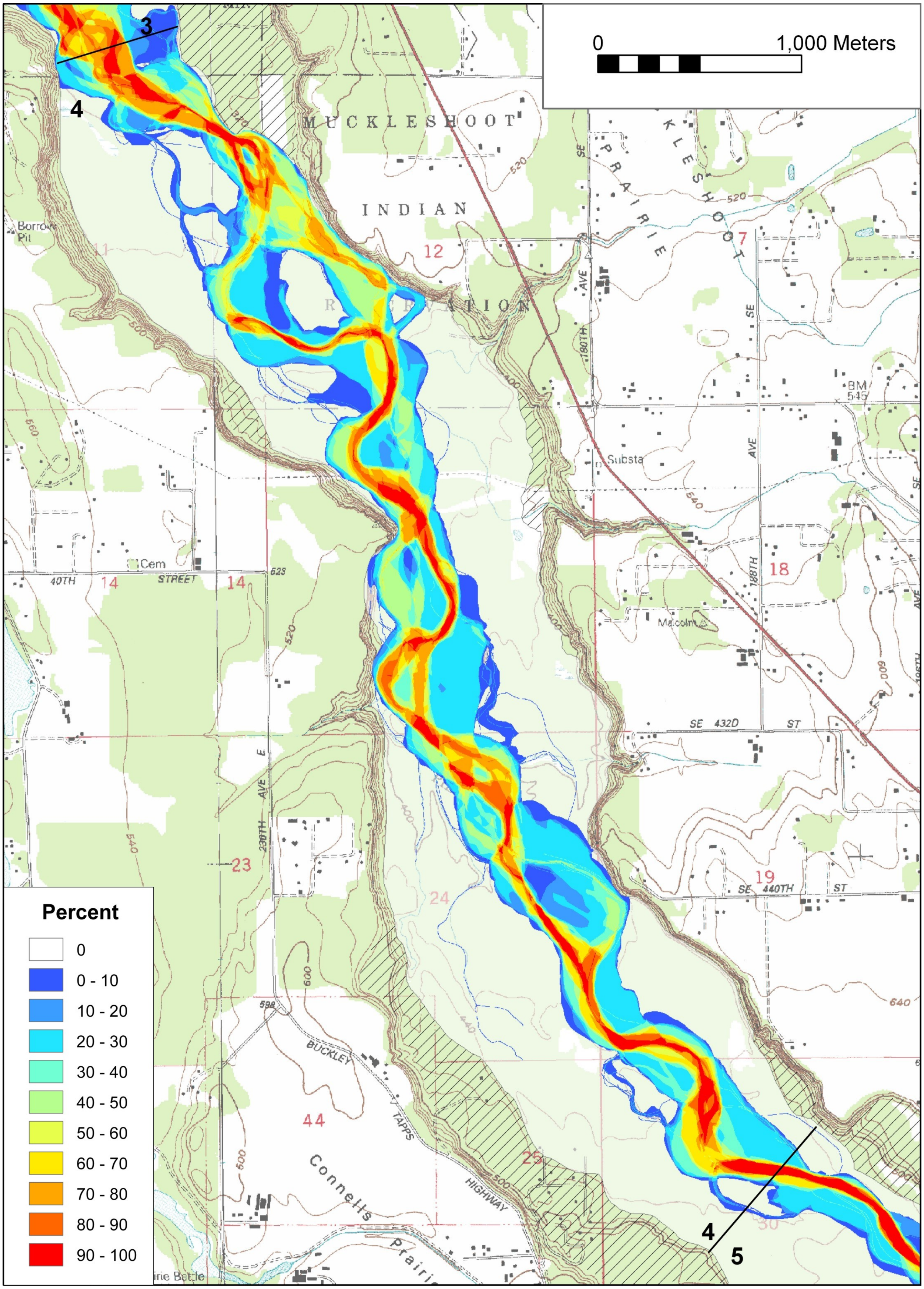

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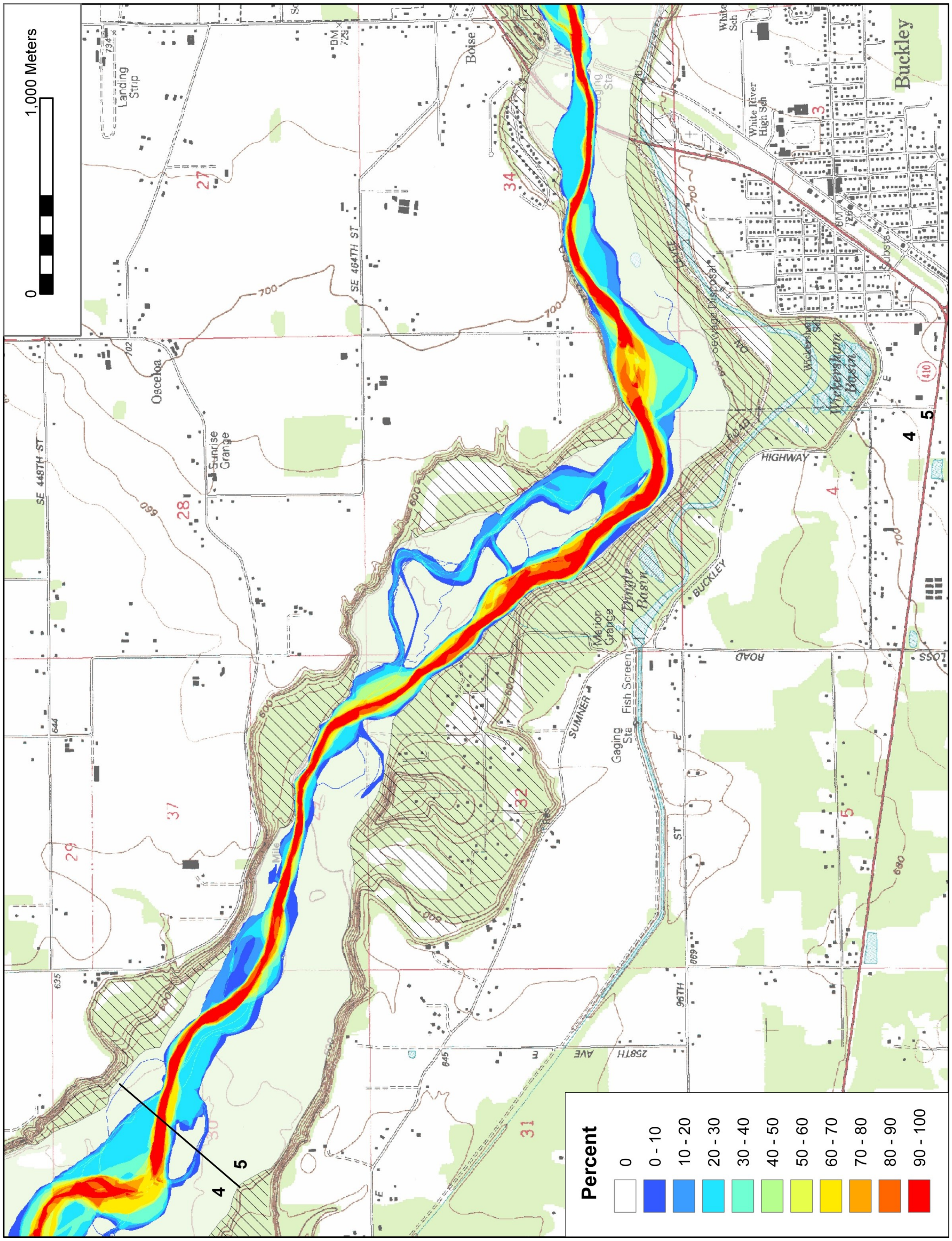
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Sunrise Grange
Landing Strip
White River High Sch
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Wickersham Basin
Major Grange
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ROAD
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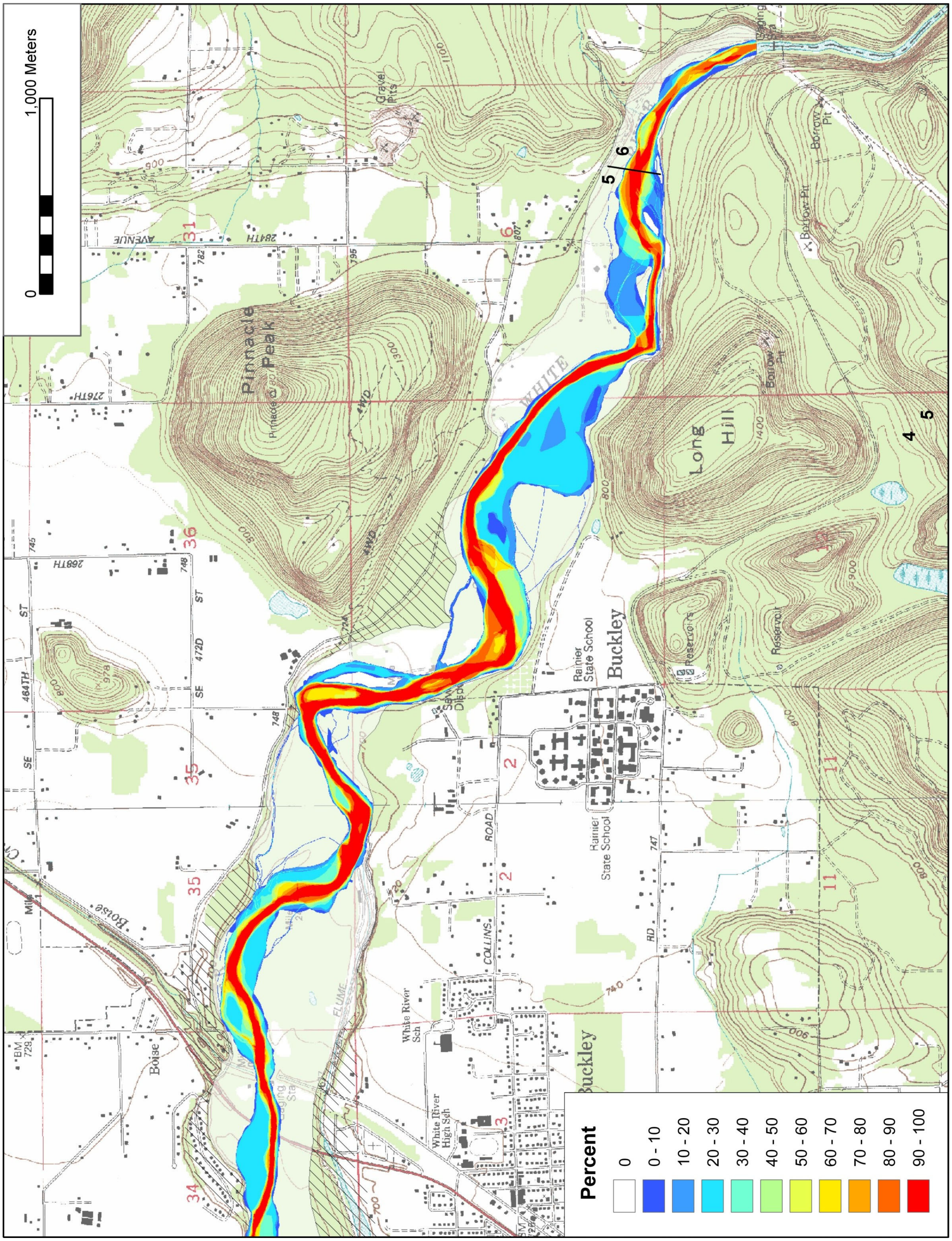
Sewage Disposal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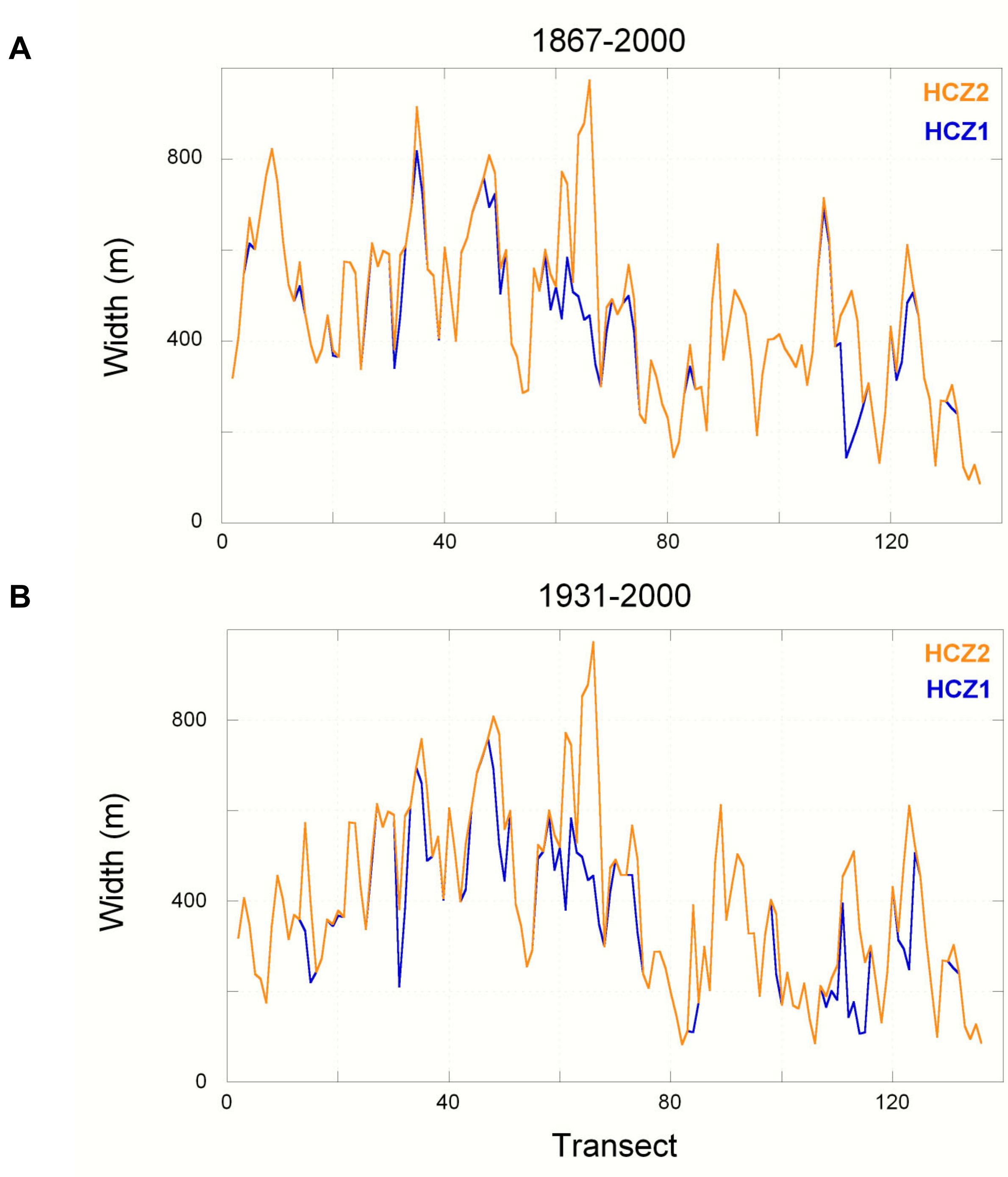

Figure 24. The historical channel zone width for (A) 1867-2000 period and (B) 1931-2000 period. HCZ1 = zone encompassing historical active channel locations; HCZ2 = zone encompassing historical active channel and floodplain sloughs mapped from aerial photos.

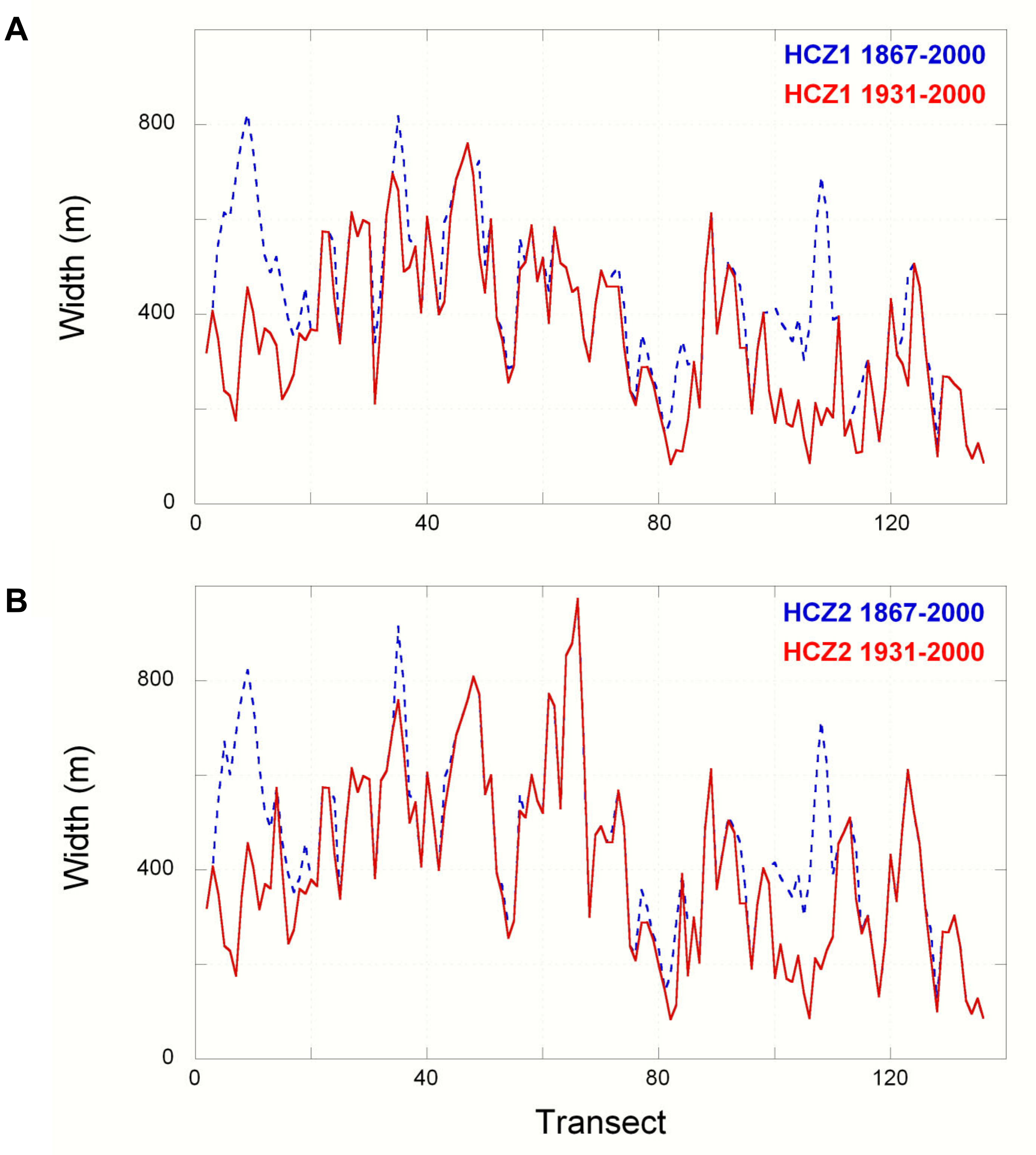

Figure 25. The historical channel zone width for (A) HCZ1 (zone encompassing historical active channel locations) for the 1867-2000 period and 1931-2000 period, (B) HCZ2 (zone encompassing historical active channel and floodplain sloughs) mapped from aerial photos for the same two periods.

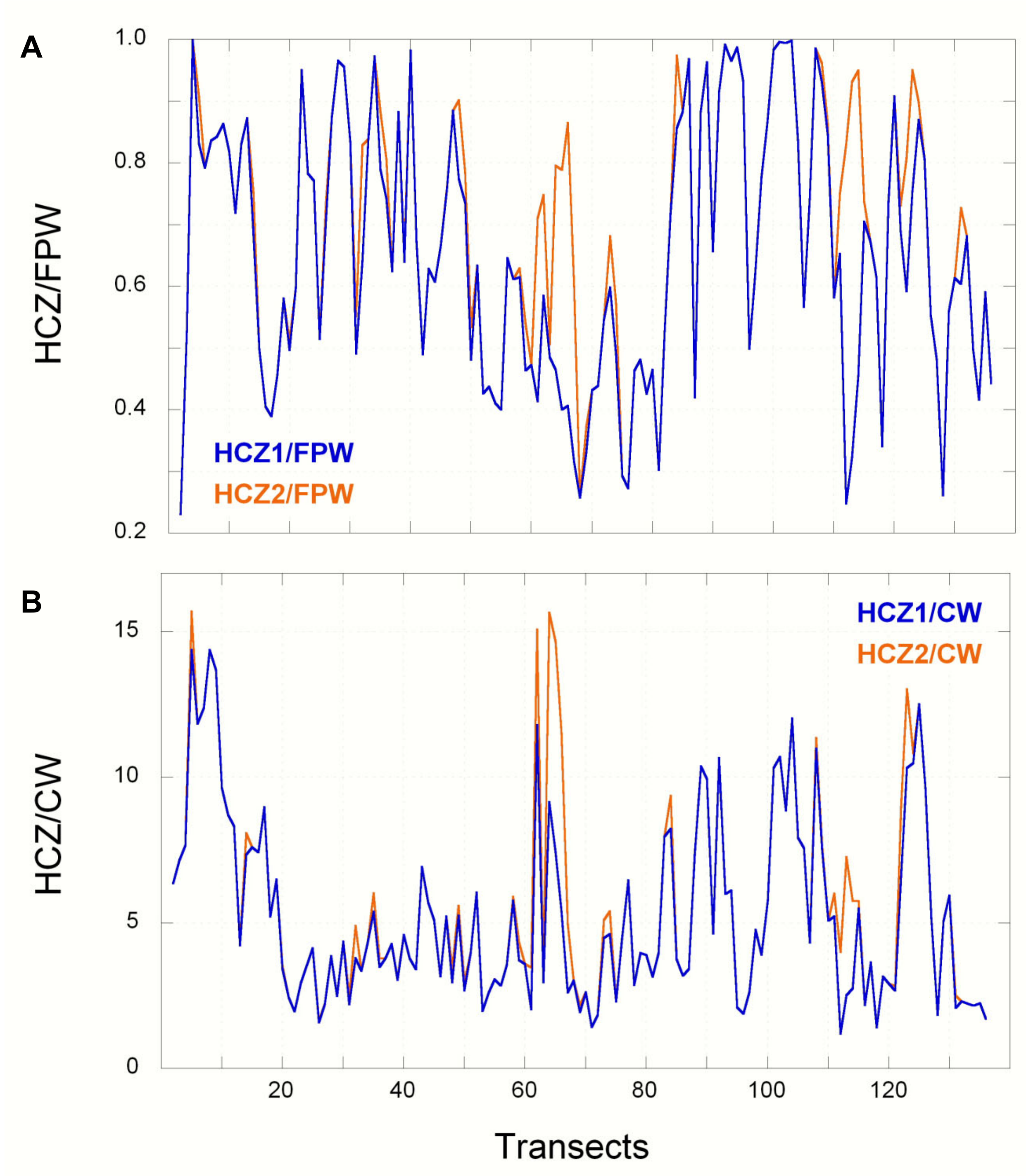

Figure 26. (A) Ratio of the historical channel zone width to the floodplain width, and (B) ratio of the historical channel zone width to the width of the active channel in 2000. The two historical channel zones (HCZ1 and HCZ2) are as defined previously. Both historical channel zones include the entire period of record (include GLO plat maps).

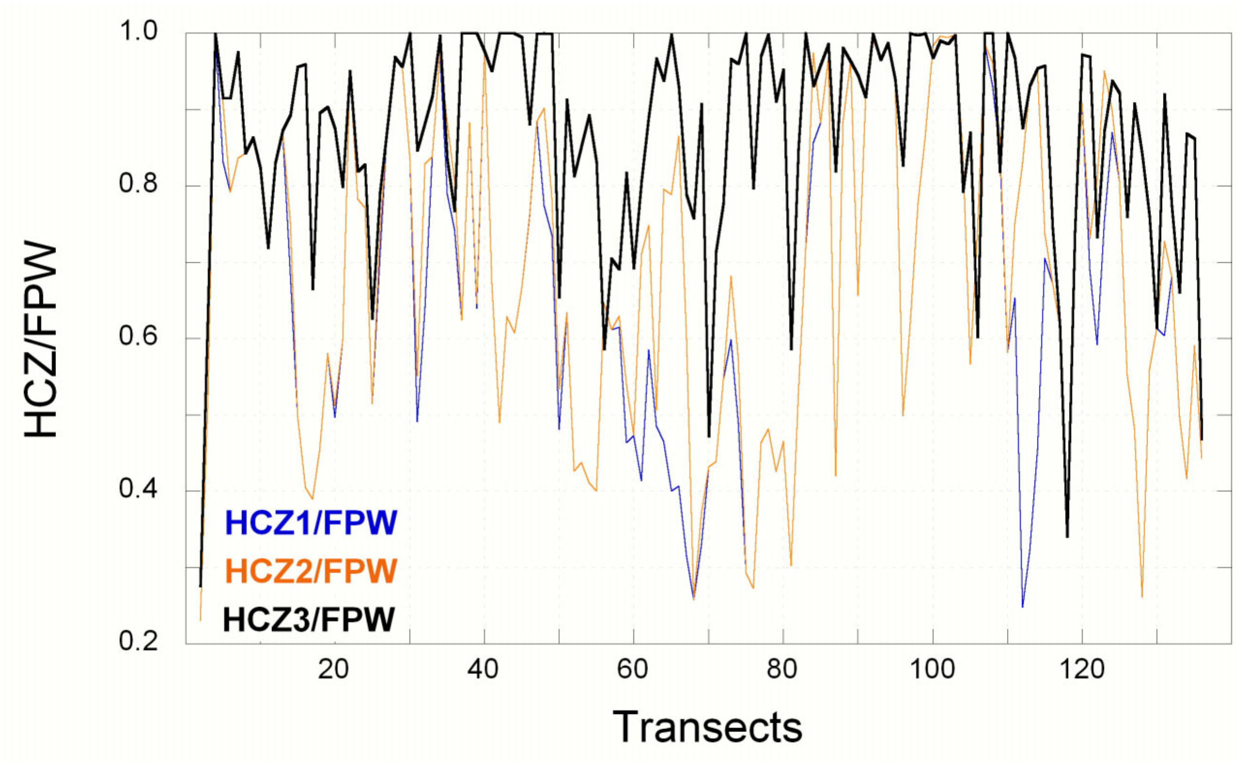

Figure 27. Ratio of the historical channel zone width to the floodplain width. HCZ1 = zone encompassing historical active channel locations, HCZ2 = zone encompassing historical active channel and floodplain sloughs, HCZ3 = HCZ2 plus zone encompassing floodplain channels visible on lidar imagery for King County portion of valley bottom. Each zone type is for the entire period of record (1867-2000). See text for more explanation on the derivation of HCZ3 data.

Table 5. Ratio between the width of the zone in which the channel has been located historically (HCZW) to the floodplain width (FPW) and to the channel width (CW) in 1998, averaged for study segments, and all in meters. The historical channel zone (HCZ) width is measured along transects and excludes floodplain sloughs; the 2000 channel width includes the low flow and high flow channels and is measured perpendicular to the 2000 channel at the intersection of transects. The ratios are dimensionless numbers; the HCZ/CW ratio is multiplied by 100 and expressed in percent for clarity.

SEGMENTS and (TRANSECTS)	HCZ1 WIDTH (M)	HCZ2 WIDTH (M)	FPW (M)	YR 2000 CW (M)	HCZ1/ FPW (%)	HCZ2/ FPW (%)	HCZ3/ FPW (%)	HCZ1/ CW (CW)	HCZ2/ CW (CW)
ALL (n=135)	432	465	691	104	65.1	69.3	86.7	5.2	5.6
S1 (T2-21) (n=20)	522	528	819	70	66.4	67.2	83.1	8.4	8.5
S2 (T22-26) (n=5)	503	507	677	205	74.5	75.1	80.3	2.8	2.8
S3 (T27-39) (n=13)	579	605	740	168	78.9	82.1	92.7	3.6	3.8
S4 (T40-73) (n=34)	432	465	691	104	65.1	69.3	85.8	5.3	5.7
S5 (T74-132) (n=59)	344	370	484	73	71.3	76.2	88.8	5.7	6.1
S6 (T133-136) (n=4)	108	108	223	52	48.7	48.7	71.5	2.1	2.1

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References Cited

Booth, D. B. 1994. Glaciofluvial infilling and scour of the Puget Lowland, Washington, during ice-sheet glaciation. Geology 22: 695-698.

Booth, D. and J. Sacket. 2002. SURFGEOL (digital surficial geology Arc/Info coverage), King County Water and Land Resources, Seattle, WA.

Chittenden, H. M. 1907. Report of an investigation by a board of engineers of the means of controlling floods in the Duwamish-Puyallup valleys and their tributaries in the State of Washington. Lowman & Hanford S. and P. Co., Seattle , WA.

Collins, B. D. and A. J. Sheikh. 2003. Historical aquatic habitat in river valleys and estuaries of the Nooksack, Skagit, Stillaguamish, and Snohomish watersheds, May 2003. Report to Northwest Fisheries Science Center, National Marine Fisheries Service, P.O. Box 157, 2725 Montlake Blvd. E. Seattle, WA 98112.

Collins, B. D. and A. J. Sheikh. 2004. Historical aquatic habitats in the White River Valley, King County, Washington. October 2004. Report to King County Department of Natural Resources and Parks, 201 South Jackson Street, Seattle, WA 98104.

Dragovich, J. D., P. T. Pringle, and T. J. Walsh. 1994. Extent and geometry of the mid-Holocene Osceola Mudflow in the Puget Lowland—Implications for Holocene sedimentation and paleogeography. Washington Geology 22: 3-26.

King County Department of Public Works, Surface Water Management Division. 1988. The White River and the Inter-County River Improvement District. May, 1988. Unpublished report. King County Department of Natural Resources and Parks, 201 South Jackson Street, Seattle, WA 98104-3855

O'Connor, J. E., M. A. Jones, and T. L. Haluska. 2003. Flood plain and channel dynamics of the Quinalt and Queets rivers, Washington, USA. Geomorphology 51: 31-59.

Roberts, W. J. 1920. Report of W. J. Roberts, Chief Engineer, in: Report on flood control of White-Stuck and Puyallup rivers; inter-county river improvement, King and Pierce Counties, State of Washington.

Stein, A. J. 2001. White River valley. http://www.historylink.org/

White, C. A. 1991. A history of the rectangular survey system. U. S. General Printing Office, Washington, D. C.