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Geomorphic response to flow regulation and channel and floodplain alteration in the gravel-bedded Cedar River, Washington, USA

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ABSTRACT

Decadal- to annual-scale analyses of changes to the fluvial form and processes of the Cedar River in Washington State, USA, reveal the effects of flow regulation, bank stabilization, and log-jam removal on a gravel-bedded river in a temperate climate. During the twentieth century, revetments were built along ~60% of the lower Cedar River's length and the 2-year return period flow decreased by 47% following flow regulation beginning in 1914. The formerly wide, anastomosing channel narrowed by over 50% from an average of 47 m in 1936 to 23 m in 1989 and became progressively single threaded. Subsequent high flows and localized revetment removal contributed to an increase in mean channel width to about 34 m by 2011. Channel migration rates between 1936 and 2011 were up to 8 m/year in reaches not confined by revetments or valley walls and less than analysis uncertainty throughout most of the Cedar River's length where bank armoring restricted channel movement. In unconfined reaches where large wood and sediment can be recruited, contemporary high flows, though smaller in magnitude than preregulation high flows, form and maintain geomorphic features such as pools, gravel bars, and side channels. Reaches confined by revetments remain mostly unmodified in the regulated flow regime. While high flows are important for maintaining channel dynamics in the Cedar River, their effectiveness is currently reduced by revetments, limited sediment supply, the lack of large wood available for recruitment to the channel, and decreased magnitude since flow regulation.

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1. Introduction

Contemporary fluvial forms and processes of rivers draining the temperate Puget Lowland of the Pacific Northwest in Washington State, USA, were established after the retreat of the Cordilleran Ice Sheet at the end of the Pleistocene (Mullineaux, 1970; Booth, 1995; Collins and Montgomery, 2011). Like most rivers in the Puget Lowland, the Cedar River was modified starting in the mid-nineteenth century (Collins et al., 2003a) by direct anthropogenic alteration, such as revetment construction and removal of large wood from the channel as well as by indirect modifications, such as riparian deforestation and flow regulation for flood control and the City of Seattle's municipal water supply. As a result of regulation, flows capable of maintaining sediment and channel conditions have been reduced thus affecting the availability and quality of habitat for aquatic biota, including anadromous Pacific salmonids (*Oncorhynchus* spp.), within the Cedar River. Several species of salmonids including native Chinook salmon (*Oncorhynchus tshawytscha*), coho salmon (*Oncorhynchus kisutch*), and steelhead trout (*Oncorhynchus mykiss*) and introduced sockeye salmon (*Oncorhynchus nerka*) spawn within the Cedar River. Of these species, Chinook salmon and steelhead trout are listed as threatened under the federal Endangered Species Act resulting in a habitat conservation plan that includes flow-management strategies to adaptively meet the needs of fish and people (Seattle Public Utilities, 2000).

For many rivers, flows with a recurrence interval of about two years provide significant ecologic benefits by mobilizing bed material and maintaining channel morphologic features such as pools and riffles (e.g., Kondolf and Wilcock, 1996; Poff et al., 1997; Wald, 2009). In regulated alluvial rivers where peak-flow hydrology has been altered, larger flows with recurrence intervals > 10 to 20 years may be especially important in forming and maintaining fluvial features such as gravel bars, riffles, pools, and floodplain surfaces (Wolman and Miller, 1960; Doyle et al., 2007; Wald, 2009). Such channel-forming flows entrain new sediment from upstream (Leopold et al., 1964), scour below the coarse surface layer and redeposit fresh gravel thereby improving salmonid habitat (Kondolf and Wilcock, 1996; Trush et al., 2000), and recruit large wood that improves channel complexity and in-stream habitat (Keller and Swanson, 1979; Montgomery et al., 1996, 2003; Fox and Bolton, 2007). The effects of channel-forming flows within the Cedar River have not been specifically analyzed, though the Washington Department of Fish and Wildlife published general guidelines for the magnitude and frequency of channel maintenance and channel-forming flows in regulated systems in Washington (Wald, 2009).

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The cumulative geomorphic work accomplished by multiple channel-maintenance and channel-forming flows plays an important role in the development of floodplain and channel morphology over decadal timescales. In many fluvial systems, direct human alterations to the channel and floodplain, or to the flow regime itself, also influence the development of floodplain and channel morphology (James and Marcus, 2006; and references therein). Information about historical river conditions from sources including streamflow gaging records, aerial photography, and topographic data has been widely used to understand the response of rivers to anthropogenic changes like flow regulation and bank armoring (e.g., Gurnell, 1997; Draut et al., 2008; Güneralp and Rhoads, 2009; Konrad et al., 2011). Analyses of channel dynamics over decadal and longer timescales provides important context for determining the current dynamics of a human-altered fluvial system and its response to channel maintenance and channel-forming flows. A high-flow event that may have produced or maintained geomorphic features in an unaltered fluvial system may not produce such features in a fluvial system where bank stabilization, floodplain deforestation, or flow regulation has modified the channel and floodplain.

In this paper we summarize the geomorphic history of the Cedar River, its present geomorphic condition, and the role of high flows in creating and maintaining ecologically significant geomorphic features. The Cedar River's Holocene geomorphic history is summarized from previous investigations of the local and regional Pleistocene and Holocene geology and geomorphology (Mullineaux, 1970; Booth, 1995). Geomorphic changes and channel dynamics during the nineteenth and twentieth centuries are assessed through analyses of historical maps, orthoimagery, and long-term stage-discharge relations at streamflow gaging stations. The present geomorphic processes and condition of the Cedar River is inferred through analyses of channel surveys, substrate surveys, and the observed geomorphic effects of recent floods in 2009 and 2011. Collectively, these data and analyses show how the Cedar River's channel and floodplain have developed during the Holocene, responded to anthropogenic alterations during the twentieth century, and are now adjusted to the present hydrologic regime.

2. Cedar River

2.1. Physiographic setting

The Cedar River drains 477 km^2 of western Washington State, heads in the Cascade Range, flows through the glacially modified Puget Lowland, and empties into Lake Washington (Fig. 1). The upper 203 km^2 of the Cedar River drainage basin is located above the Masonry Dam at the outlet of Chester Morse Lake. Although Chester Morse Lake was formed by a moraine of the Puget Lobe of the Cordilleran Ice Sheet during the Pleistocene (Mackin, 1941), its level was raised by the construction of a timber crib dam in 1904 and subsequently the Masonry Dam in 1914 that increased the storage of Chester Morse Lake to ~50 million cubic meters and provided limited peak-flow regulation. Water has been diverted from the Cedar River downstream of Chester Morse Lake at the Landsburg Diversion Dam for the City of Seattle's municipal water supply since 1901. Prior to 1912, the Cedar River joined the Black River, a tributary of the Duwamish River, but was permanently diverted into Lake Washington through an engineered channel in the City of Renton (Chrzastowski, 1983). The construction of the Lake Washington Ship Canal, completed in 1916, lowered the level of Lake Washington by ~3 m, drying the Black River and establishing the present connection of the Cedar River to Puget Sound through the Lake Washington Ship Canal (Chrzastowski, 1983).

2.2. Late Pleistocene and Holocene history

The present-day drainage pattern of the Cedar River was primarily influenced by the most recent advance and retreat of the Puget Lobe of the Cordilleran Ice Sheet during the late Pleistocene (Booth, 1995). During the Puget Lobe's most recent retreat, a river formed along its eastern margin supplied by glacial meltwater and rivers draining the adjoining Cascade Range. This ice-marginal river occupied progressively more northern channels, eventually occupying the Cedar River valley (Thorson, 1980), eroding a new channel, and depositing thick sequences of outwash through the upper Cedar

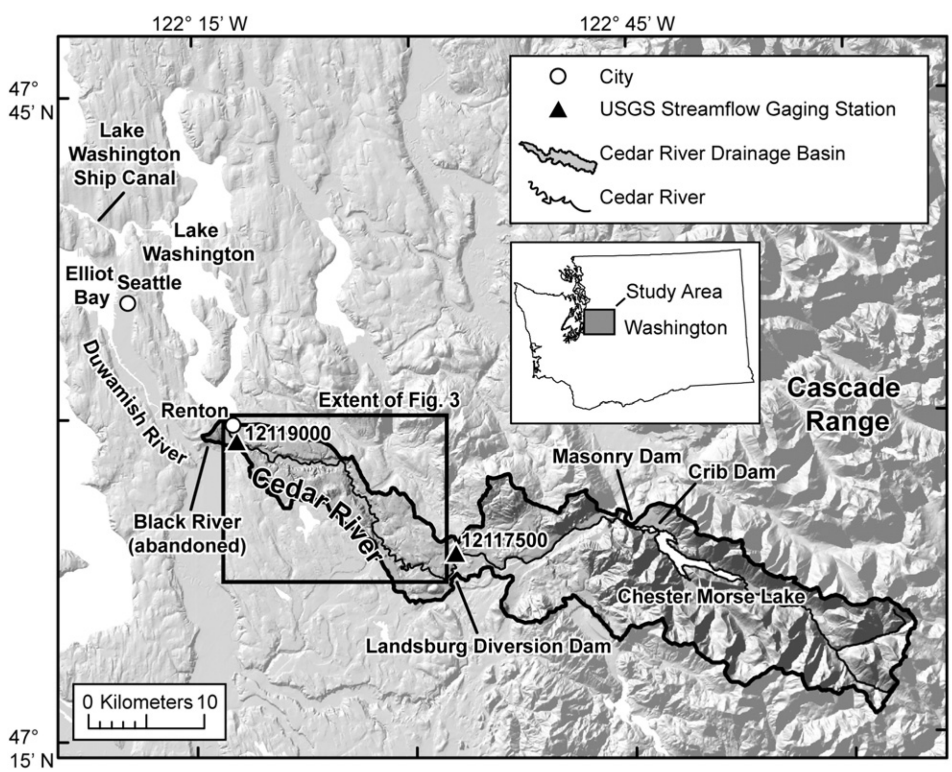

Fig. 1. Map showing location of the Cedar River drainage basin, Washington.

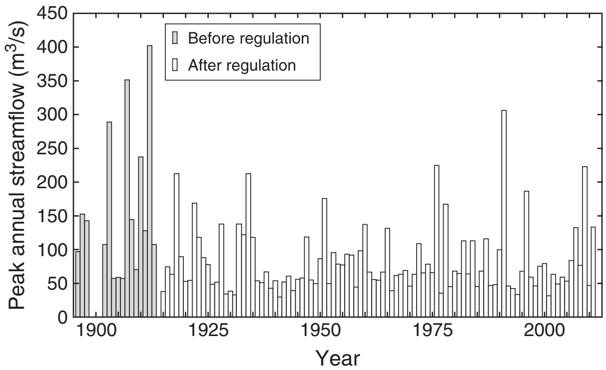

Fig. 2. Annual peak streamflow of the Cedar River near Landsburg (U.S. Geological Survey streamflow-gaging station 12117500) for water years 1896–1898, 1902–1913, and 1915–2011. Peak annual streamflows before regulation in 1914 are shaded.

River valley (Mullineaux, 1970; Booth, 1995). Deposits of multiple glacial advances preserved within the walls of the lower Cedar River valley suggest that the modern Cedar River did not reoccupy its pre-late Pleistocene channel (Booth, 1995). Subsequent northward retreat of the Puget Lobe shifted the lower Cedar River drainage onto its present course along till-mantled uplands. The Cedar River incised into its present valley following progressive drops in base-level as a series of pro-glacial lakes progressively drained during deglaciation.

The Cedar River's valley has provided a primary control on the geomorphic development of the Cedar River throughout the Holocene. Collins and Montgomery (2011) showed that the Cedar River and other Puget Lowland rivers that occupy post-glacial, fluvially carved valleys have relatively low sinuosity anastomosing, multithreaded channel pattern, and are currently incising.

2.3. Anthropogenic changes from the nineteenth century to the present

Flow regulation, bank armoring, and floodplain alteration since the early twentieth century have contributed to changes in geomorphic processes of the Cedar River resulting in channel narrowing (Perkins, 1994). Wide, multithreaded channels surveyed by the General Land Office (GLO) between 1865 and 1880 have been confined to mostly single-threaded channels. In addition, floodplain deforestation has removed large wood that formed key pieces of forested islands and log jams that promoted channel avulsion and side channel formation. In recent years, river managers have taken measures to restore the historical geomorphic function of the Cedar River through the creation of engineered side channels, the emplacement of engineered log jams, and the removal of bank stabilization structures. In these newly unconfined reaches, channel migration rates and active channel width have increased markedly following significant peak-flow events.

2.4. Hydrology

Mean annual streamflow measured on the Cedar River near Landsburg at the U.S. Geological Survey (USGS) streamflow-gaging station 12117500 was 19.2 m^3/s between 1897 and 2010. The highest mean monthly streamflow was in January (27.8 m^3/s), and the lowest mean monthly streamflow was in September (9.1 m^3/s). Most precipitation falls as snow and rain during the fall and winter months with a snowpack that generally persists until mid-June at higher elevations.

The Masonry Dam, constructed in 1914, is primarily used to manage water supply but partially regulates high flows as well. The Masonry Dam enhanced a natural impoundment at the outlet of Chester Morse Lake and thus did not affect downstream sediment supply. The Landsburg Diversion Dam at the upstream end of the study reach, does not alter high flows and passes bedload. Three of the four highest peak flows measured at the Cedar River near Landsburg were during the 14 years of measurements prior to flow regulation in 1914 (Fig. 2). The largest peak flow recorded before regulation at the Cedar River near Landsburg was on 19 November 1911 (402 m^3/s). The 2-, 10-, and 100-year recurrence interval floods at the Cedar River near Landsburg decreased by 47%, 54%, and 56%, respectively, following regulation (Table 1). The largest peak flow recorded after regulation was on 24 November 1990 (306 m^3/s). During the study, two large peak flows occurred on 8 January 2009 (223 m^3/s) and on 17 January 2011 (133 m^3/s).

3. Methods

3.1. Geomorphic floodplain and river kilometer conventions

Two reference systems are used within this paper to refer to locations of floodplain and channel features and to calculate geomorphic metrics over different periods of analysis (Fig. 3). Channel metrics calculated between 1936 and 2011 are referenced to a 'geomorphic floodplain,' which provides a common reference system to compare channel change and migration over the period of analysis (O'Connor et al., 2003). The geomorphic floodplain was delineated from a 2010 bare-earth light detection and ranging (LiDAR) digital elevation model that encompasses the post-glacial, fluvially modified area between flanking valley walls and the engineered channel through the City of Renton. A centerline was drawn through the geomorphic floodplain with transects every kilometer, which are referred to as geomorphic floodplain kilometers (GFPkm) throughout this report. Present-day geomorphic metrics and analyses are presented in reference to the second reference system, river kilometers (Rkm), digitized from 2010 orthoimagery and measured along the river centerline.

3.2. Present: longitudinal profile analysis and substrate survey

Present channel dynamics and geomorphic processes were measured along a longitudinal profile of the Cedar River between the Landsburg Diversion Dam and Lake Washington by measuring water-surface elevation, bed elevation, channel width, and substrate

Table 1
Summary of peak-flow recurrence intervals before and after flow regulation for the Cedar River near Landsburg.

Recurrence interval (year)	Pre-regulation discharge (m^3/s)	95% confidence lower limit (m^3/s)	95% confidence upper limit (m^3/s)	Post-regulation discharge (m^3/s)	95% confidence lower limit (m^3/s)	95% confidence upper limit (m^3/s)
2	129	96.5	172	68.9	63.2	75.0
5	224	169	335	108	98.6	120
10	303	220	497	140	126	159
25	420	290	778	189	166	222
50	520	346	1050	232	200	278
100	633	406	1390	281	238	344

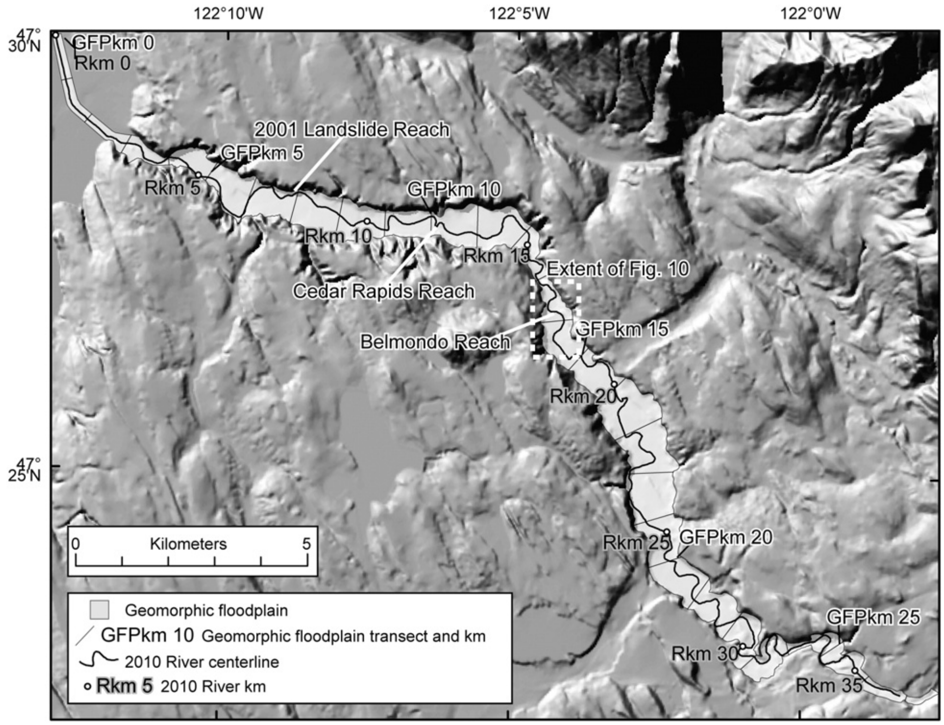

Fig. 3. Extent of the Cedar River's geomorphic floodplain and 2010 channel centerline.

particle size. Water-surface elevation was surveyed from a kayak following the thalweg of the Cedar River on 29 April 2010 and again on 11 July 2011, bracketing a peak flow of 133 m^3/s. Both surveys were conducted using a kayak-mounted, survey-grade global positioning system (GPS) at 5-s intervals resulting in a median point spacing of 8.5 m. Bed surface was concurrently measured by a digital depth sounder attached to the kayak. The substrate size distribution of recently deposited sub-aerial bars was characterized through Wolman (1954) pebble counts between April and June 2010. At each location, 100 particles were selected at regular intervals along a transect parallel to the river and classified into one-half ϕ-size classes ranging from <2 mm (sand) to 512 mm (boulders).

Pool frequency and residual pool depth were calculated from these survey data (after Madej, 1999) to examine changes in the streambed during the 2011 high-flow season. Residual pool depth was calculated as the difference between the deepest part of a pool and the downstream riffle crest (i.e., the maximum pool depth if streamflow became zero; Lisle, 1987). Following the analysis of Madej and Ozaki (2009) on similarly sized Redwood Creek, California, pools with residual depths of <1 m or less than 10% of the active channel width were excluded from analysis.

The measured water-surface profile and the longitudinal variation of the 2-year return period flood were used to calculate unit stream power (Bagnold, 1966). The distribution of unit stream power also regulates the formation of important geomorphic features of aquatic habitat including channel geometry, variation in particle size distributions, and channel stability. Downstream changes in stream power provide insight into areas of potential sediment erosion, transport, and deposition. Unit stream power was calculated between Rkm 0.0 and 35.0 as

$$\omega = \frac{\rho g Q S}{w} \quad (1)$$

where ω is stream power (watts/m), ρ is the density of water (1000 kg/m^3), g is gravity (9.8 m/s^2), Q is the discharge (m^3/s), S is the energy slope which was assumed equal to the water-surface slope (m/m), and w is the mean active channel width (m). The 2-year return-period flow was selected for analysis because it provides an index of overall fluvial energy distribution in the channel (Wharton, 1995).

For our analysis, we calculated each point in the profile by fitting a power function relating discharge to upstream contributing area for the 2-year return period flows estimated at the Cedar River streamflow gages at Renton (Rkm 2.3) and near Landsburg (Rkm 39.9). Water-surface slope was averaged over a 1.0-km moving average for each point in the profile, which smoothed local variability in the water-surface slope, but remained representative of reach-scale channel characteristics (Jain et al., 2006). The width of the active channel, which would be inundated during the 2-year return period flow, was averaged from the 2010 digitization of the active channel over a 1.0-km moving average.

3.3. Twentieth century: historical orthoimagery analysis and incision/aggradation trends

Although the GLO produced the first known maps of the Cedar River between 1865 and 1880, the first detailed information about the form of the Cedar River and its floodplain was recorded by 1936 orthoimagery. Channel characteristics and migration rates were measured from 14 orthoimagery sets from 1936 to 2011 (Table 2). Channel features (including the wetted low-flow channel, gravel bars, young vegetation patches, and forested islands within the 1936–2000 orthoimagery sets) were digitized by Collins et al. (2003b) at 1:1000 scale; channel features within the 2002 through 2011 orthoimagery sets were digitized for this study using the same methods.

The active channel was defined as the area within the geomorphic floodplain where high flows have prevented the establishment of woody vegetation (O'Connor et al., 2003). This includes the wetted low-flow channel, gravel bars, and young vegetation patches. Forested islands, which include mature trees, were excluded from the active channel. Channel features were classified into primary and secondary channel features, which were separated from the primary channel by forested islands and were estimated to transport little water and

Table 2
Summary of orthoimagery sources for historical channel mapping.

Year	Orthoimagery source	Scale/ resolution	Estimated orthorectification error (m)	Total error of digitized channel margins (m)
1865–1880	General Land Office	1:31,680	–	–
1936	King County, WA	1:10,500	10.3	11.4
1948	King County, WA	1:21,000	16.3	17.0
1964	King County, WA	1:21,000	9.0	10.3
1970	King County, WA	1:12,000	5.0	7.1
1980	University of Washington	1:58,000	10.0	11.2
1989	King County, WA	1:13,500	7.2	8.8
1995	University of Washington	1:12,000	6.0	7.8
2000	King County, WA	0.6 m	2.7	5.7
2002	King County, WA	0.3 m	1.5	5.2
2005	King County, WA	0.3 m	2.5	5.6
2006	USDA NAIP	1.0 m	1.8	5.3
2009	USDA NAIP	1.0 m	2.4	5.5
2010	King County, WA	0.2 m	0.8	5.1
2011	USDA NAIP	1.0 m	2.0	5.4

sediment during bankfull flows (Wallick et al., 2011). Channel centerlines were digitized as the approximate center of the primary channel. The channel sinuosity was calculated by dividing the stream centerline length by the geomorphic floodplain centerline length for each of the orthoimagery sets. Channel features were distinguished as either primary or secondary channel features, where secondary channels were separated by large floodplain islands and were not expected to transport large quantities of sediment during high flows. The active channel widths were computed for each year, over each GFPkm segment, by dividing the total area of active channel (low-flow channel, gravel bars, and vegetation patches of the primary channel) by the length of the centerline.

Collins et al. (2003b) and Draut et al. (2008) estimated horizontal errors of as much as ± 5 m in digitizing channel features (E_{dig}) where the channel was overhung by vegetation or had sun glare. Errors resulting from orthorectification (E_{rec}) were quantified by calculating the difference between the horizontal coordinates of landmarks and their location within the orthoimagery at 20 or more locations and are reported at a 95% confidence level for each orthoimagery set in Table 2. The total error for digitizing the channel features (E_{tot}) was calculated as (Gaeuman et al., 2003; Draut et al., 2008):

$$E_{tot} = \sqrt{E_{rec}{}^2 + E_{dig}{}^2}. \quad (2)$$

Annualized channel migration rates were calculated from the area between successive pairs of channel centerlines divided by the mean centerline length and the number of years between them similar to the method of Gillespie and Giardino (1996). Channel migration rates were averaged over each 1-GFPkm segment to determine longitudinal variations in lateral channel stability. The error in annualized rates of channel change (E_a) for each successive pair of channel centerlines was calculated by assuming that the total error of each orthophoto set (E_{tot}) was independent and dividing by the time interval (t) between orthophoto sets (Draut et al., 2008):

$$E_a = \frac{\sqrt{E_{tot,1}{}^2 + E_{tot,2}{}^2}}{t}. \quad (3)$$

Trends in aggradation and incision were calculated at the USGS streamflow gages at the Cedar River at Renton and near Landsburg by calculating the temporal variation in the stage-discharge relation for the median discharge of 14.2 m^3/s at Renton and 15.9 m^3/s near Landsburg (after Blench, 1969). Changes in the level of the hydraulic control raise or lower the stage at a particular discharge in response to aggradation or incision, respectively.

3.4. Pre-twentieth century: General Land Office and topographic analysis

The pre-twentieth century Cedar River channel forms are shown by GLO surveys conducted between 1865 and 1880 and LiDAR topographic data surveyed in 2010. Collins et al. (2003b) digitized the GLO Public Land Survey System (PLSS) surveys of the Cedar River, which show the inferred channel extent at 'mean high-water elevation… at the margin of the area occupied by the water for the greater portion of each average year' (Bureau of Land Management, 1973). This may have led to the local inclusion of overflow channels within the floodplain that remain invisible and unmapped in subsequent aerial photographs. Channel widths and locations are most accurate where the river crosses a PLSS section line. While direct, quantitative comparisons between GLO channel survey data and digitized channels from aerial photographs are difficult to make, the overall map pattern indicates the pre-settlement channel form. These map patterns are retained in the present topography, as indicated by LiDAR acquired in 2010. These LiDAR measurements within the geomorphic floodplain were normalized to the low-flow water surface using the height above water surface (HAWS) method of Jones (2006). This normalization enhances visualization of fluvial topographic features where it has not been obscured by subsequent development, particularly within the lower river (GFPkm 0–10), development where roads, buildings, and gravel pits have covered much of the geomorphic floodplain.

4. Results

4.1. Present channel dynamics and characteristics

By 2010, revetments and other bank-stabilization structures largely confined the Cedar River's lower 35 km (Fig. 4), especially on outside of meander bends of the river. In some reaches, revetments completely confined both river banks (Rkm 0.0–3.0). In addition to revetments, valley walls naturally confined the Cedar River in several areas. The mean width of the 2010 active channel was 33 m between Rkm 0.0 (outlet at Lake Washington) and 35.0 (Landsburg Diversion Dam) and varied from 23 m to 57 m (Fig. 5A). The Cedar River was also wider within the engineered channel just upstream of its outlet to Lake Washington. The mean water surface slope between Rkm 0.0

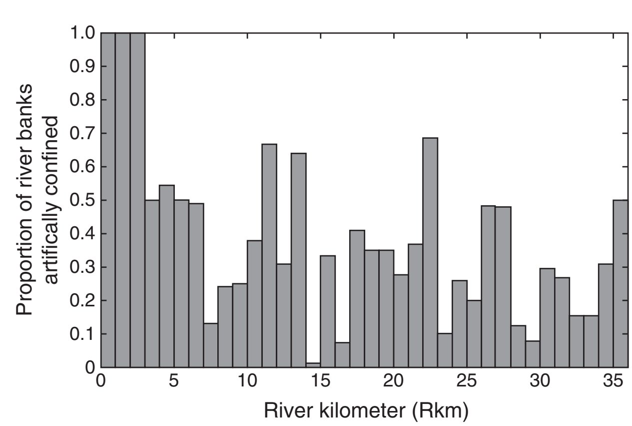

Fig. 4. Proportion of river banks artificially confined by revetments or other bank stabilization structures in 2010.

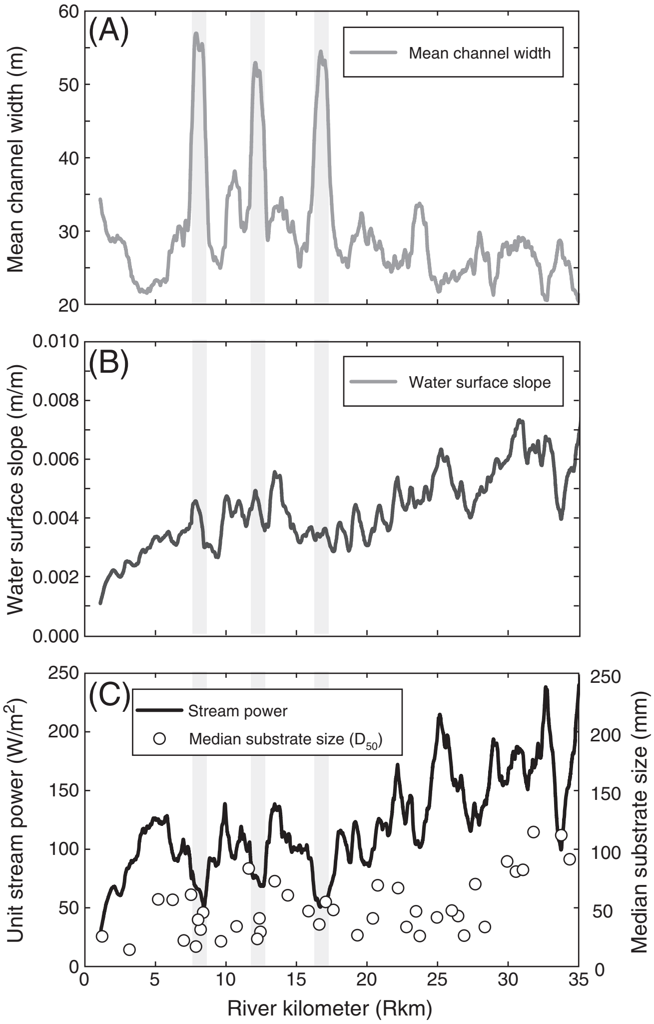

Fig. 5. Longitudinal variation in active-channel width, water-surface slope, stream power, and median substrate size (D_{50}) of the Cedar River between Rkm 0 and 35. Gray areas indicate longitudinal extent of unconfined reaches in between Rkm 7.5–8.5, Rkm 11.5–12.5, and Rkm 16.0–17.0.

and 35.0 was 0.004 m/m. Water-surface slope was greatest downstream of the Landsburg Diversion Dam and was smallest at the outlet of the Cedar River at Lake Washington (Fig. 5B). Unit stream power of the Cedar River decreases from over 200 W/m^2 downstream of the Landsburg Diversion Dam (Rkm 35) to <50 W/m^2 at the outlet of the Cedar River to Lake Washington (Fig. 5C). Local minima in unit stream power occur at wide, unconfined sections of the Cedar River including in the vicinity of a 2001 landslide (Rkm 7.5–8.5), a section where bank stabilizations were recently removed to enhance channel migration known as Cedar Rapids (Rkm 11.5–12.5), and a section that has remained largely unconfined during the twentieth century known as Belmondo (Rkm 16.0–17.0). Median particle size of sediment (D_{50}) varied between 14 and 115 mm and generally decreased downstream with the largest particle sizes measured downstream of the Landsburg Diversion Dam and the smallest near the Cedar River's mouth at Lake Washington (Fig. 5C).

The geomorphic response of the river to the high-flow events of January 2009 (~30-year recurrence interval) and January 2011 (~7-year recurrence interval) was a function of the degree of confinement and distance downstream from the Landsburg Diversion Dam. Though planform morphology of river reaches confined by revetments or valley walls remained mostly unaltered by high flow, observed changes along the river corridor included sediment redistribution, localized channel widening, limited avulsions, and recruitment of large wood. In confined reaches, gravel was eroded and redeposit on bars that were topographically higher than the low-flow channel. This process of transport of spawning gravel away from the low-flow channel was most prevalent in the reaches closest to Landsburg. In unconfined reaches, sediment was deposited in gravel bars spanning the width of the channel. Following deposition of these wider gravel bars, subsequent smaller flow events redistributed and incised into these deposits. The large flows also deposited gravel within and at the upstream and downstream ends of side channels, reducing access of side channels for spawning and rearing salmonids. Localized sedimentation occurred downstream of avulsions, and wood was consolidated in jams resulting in a net increase in the size of large wood accumulations. However, these assemblages of wood generally formed above the low-flow channel in such a manner that less wood was present in the low-flow wetted channel mitigating the wood's ecological benefits.

Pools with a residual depth of more than 1 m occurred at a mean frequency of 1.5 pools/km during the 2010 survey and 1.6 pools/km during the 2011 survey (Fig. 6). Pools were least frequent within the engineered channel above Lake Washington (Rkm 0–5) where pools occurred at an average of 0.8 and 0.6 pools/km during the 2010 and 2011 surveys, respectively. The highest frequency of pools was observed in the relatively unconfined section between Rkm 15 and 20 where pools occurred at a frequency of 3.0 pools/km in 2010 and 2.4 pools/km in 2011. There was little change between the 2010

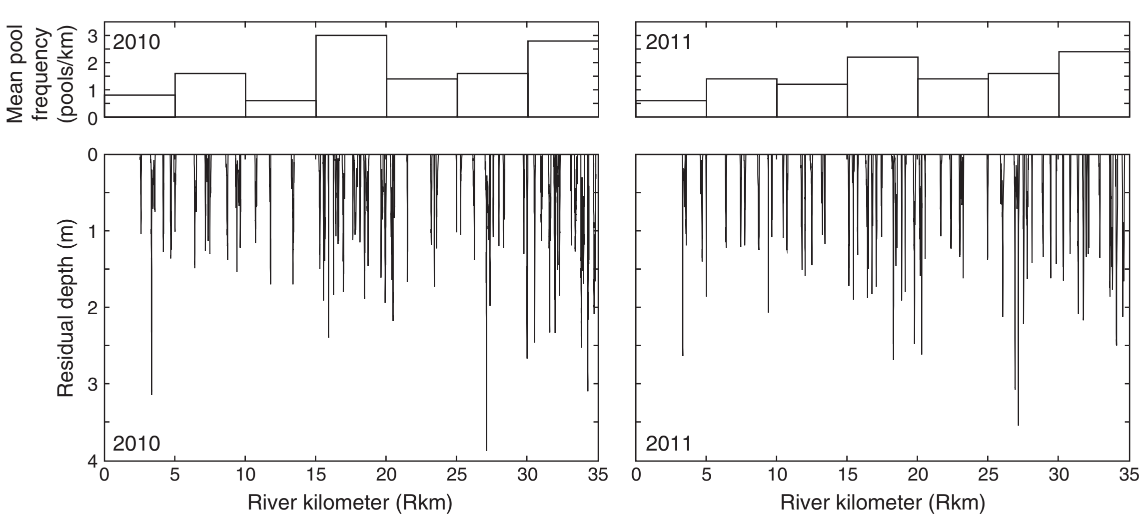

Fig. 6. Residual pool depth and frequency between Rkm 0 and 35 surveyed in April 2010 and July 2011.

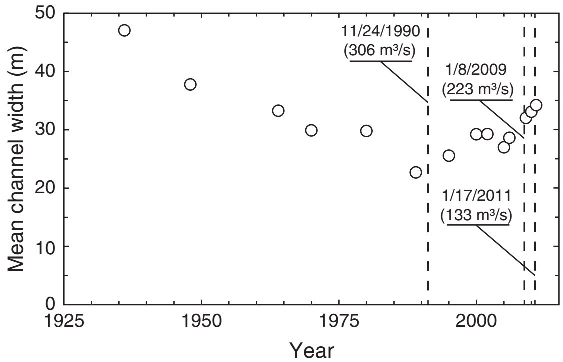

Fig. 7. Mean channel width for the Cedar River downstream of the Landsburg diversion dam measured from 13 orthoimagery sets between 1936 and 2011. The time of notable peak streamflows measured near Landsburg at USGS streamflow gaging station 12117500 is shown by vertical dashed lines.

and 2011 surveys likely because the influence of the 2009 high-flow event was still widespread.

4.2. Twentieth century channel dynamics and characteristics

4.2.1. Channel width and channel migration

Mean channel width of the Cedar River downstream of Landsburg decreased markedly between 1936 and 1989, with most narrowing occurring before 1964. Recently, channel width increased from 1989 to 2011 (Fig. 7). The channel did not widen throughout the entire geomorphic floodplain between 1989 and 2011, but widened in unconfined reaches where the river banks were never armored, where revetments were removed, or where additional sediment was added to the channel by landslides from adjacent valley walls. In reaches confined by valley walls or revetments, channel width remained constant or decreased from 1989 to 2011. Reaches where revetments were installed after 1936 narrowed.

Between Rkm 11.5 and 12.5, channel migration and the formation of fish habitat has been intentionally encouraged by removal of revetments and the installation of engineered log jams in 2008. The flood in January 2009 significantly altered this reach resulting in an expansion to ~50 m in 2010. For comparison, this reach remained relatively unmodified and narrow during the November 1990 post-regulation flood of record illustrating the effectiveness of stabilization by revetments in maintaining channel position. Few reaches of the Cedar River below the Landsburg Diversion Dam have remained unconfined throughout the twentieth century; the reach between Rkm 16.0 and 17.0, however, has largely been free of revetments and, similar to the recently unconfined reach between 11.5 and 12.5, widened in response to the January 2009 high-flow event.

Channel migration within the lower Cedar River was generally less than the uncertainty associated with orthophoto rectification and channel digitization during the twentieth century (Table 3). The channel was most stable in artificially confined reaches such as GFPkm 9–10 (Fig. 8A), which was typical of much of the Cedar River throughout the twentieth century. Local rates of channel migration, however, were as high as 7.8 m/year in GFPkm 14 when a large avulsion occurred during the 1991 post-regulation peak of record (Fig. 8B). Landslides, notably the 2001 landslide near GFPkm 7, also caused the river channel to move.

4.2.2. Sinuosity

The overall sinuosity of the Cedar River between Lake Washington and the Landsburg Diversion Dam varied from 1.27 to 1.32 between 1936 and 2011. Although the Cedar River is within the 'sinuous' classification of Leopold et al. (1964) (sinuous <1.5 as opposed to meandering >1.5) at this large scale, notable exceptions exist at the scale of individual GFPkm. The Cedar River is almost straight (sinuosity ≈ 1) near its outlet to Lake Washington as it passes through an engineered channel (GFPkm 1–3) and in other confined reaches whether it is naturally confined by valley walls or artificially straightened by levees (GFPkm 5, 8, and 28). The Cedar River is meandering (sinuosity >1.5) throughout much of the 1936–2011 period in several reaches (GFPkm 7, 18, and 22–24).

4.2.3. Aggradation and incision trends

The change in stage for the median streamflow that was derived from the gaging record of the Cedar River at Renton (Fig. 9A) showed net aggradation of ~2.5 m from 1950 to present resulting in periodic channel dredging of the engineered channel in Renton. Prior to the twentieth century, the Cedar River formerly aggraded in this area and created an alluvial fan. In addition, more efficient sediment conveyance within the modern confined channel may have contributed to aggradation in this area. Conversely, the gage on the Cedar River near Landsburg (Fig. 9B) showed no net aggradation or incision. The vertical datum of the streamflow gaging station near Landsburg was adjusted in 1929 resulting in an instantaneous change in the stage–discharge relation not related to aggradation or incision. Consistent with the conclusions of Perkins (1994), these observations suggest a general trend of sediment transport from middle reaches of the Cedar River to downstream reaches near Renton where stream power is reduced.

4.3. Pre-twentieth century channel dynamics and characteristics

The anastomosing channel form of the pre-twentieth century Cedar River became progressively narrower and single-threaded (Figs. 7 and 10) as revetments were built and floods decreased in

Table 3
Summary of channel migration data.

Time interval	Maximum migration rate over GFPkm intervals (m/year)	Total error (m/year)	GFPkm intervals with migration rates larger than total error	Peak flow at Cedar River near Landsburg during time interval (m^3/s)
1936–1948	1.7	1.8	None	119 (14 December 1946)
1948–1964	2.5	1.3	9–10; 10–11; 17–18	176 (11 February 1951)
1964–1970	2.2	2.4	None	131 (30 January 1965)
1970–1980	1.7	1.5	6–7	225 (4 December 1975)
1980–1989	1.6	1.8	None	116 (24 November 1986)
1989–1995	7.8	2.3	13–14	306 (24 November 1990)
1995–2000	4.7	2.4	13–14	186 (30 November 1995)
2000–2002	5.5	5.2	6–7	63.4 (14 April 2002)
2002–2005	1.3	3.5	None	59.2 (29 January 2004)
2005–2006	3.4	10.5	None	83.5 (14 January 2006)
2006–2009	2.9	3.5	None	223 (8 January 2009)
2009–2010	3.3	10.3	None	46.1 (3 June 2010)
2010–2011	8.0	10.3	None	133 (17 January 2011)

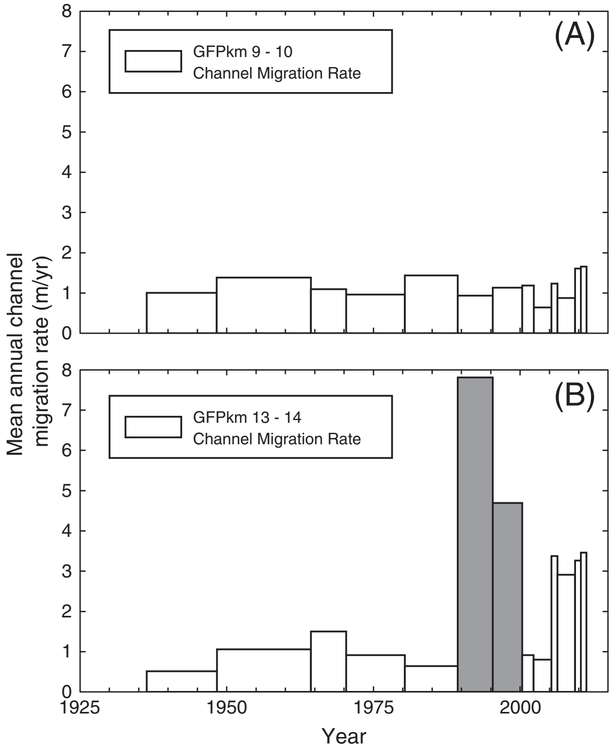

Fig. 8. Mean annual channel migration rate (A) between GFPkm 9 and 10 and (B) GFPkm 13 and 14. Migration rates greater than the total error from orthorectification and digitization are shaded gray.

frequency and magnitude during the twentieth century. Most revetments were built between 1960 and 1970 (Edmondson and Abella, 1988). The active channel mapped by the GLO between 1865 and 1880 was wider than the contemporary river and included multiple anastomosing channels (Fig. 10D). The GLO mapped large sections of anastomosing channels in several areas of the geomorphic floodplain including GFPkm 7–8, 12–18, and 20–21; in other areas, the river was mapped as a single channel suggesting relative channel stability prior to anthropogenic alteration of the Cedar River and its floodplain. The LiDAR-based HAWS maps showed the topographic remnants of anastomosing channels throughout much of the floodplain including anastomosing channels mapped during the GLO surveys (Fig. 10E). Scroll bars, oxbow lakes, and other topographic features indicative of a meandering channel are largely absent suggesting the channel form of the predevelopment river was anastomosing and not a single-threaded meandering channel. In these reaches, the Cedar River was variously confined by valley walls, alluvial terraces, and alluvial fans built by small tributary streams entering the geomorphic floodplain from adjacent plateaus.

5. Discussion

The interaction between sediment supply, discharge, and large wood in determining a river's channel form and processes is complex and occurs over timescales ranging from decades to centuries (e.g., O'Connor et al., 2003; Konrad et al., 2011). Anthropogenic changes to the Cedar River and its floodplain, including flow regulation and bank stabilization, have contributed to decreases in sediment supply, reduced wood, lower peak discharges, and lower frequency of peak discharge events. Collectively, these changes have contributed to channel narrowing, lower channel migration rates, and the predominance of a single-threaded channel on the Cedar River.

5.1. Alteration of Cedar River channel dynamics and processes

Prior to anthropogenic alterations, the Cedar River had a wider and predominantly anastomosing channel (Perkins, 1994) similar to other western Washington rivers like the nearby Nisqually River (Collins et al., 2012), which serves as a control site for analysis of anthropogenic changes to the Cedar River. Along the lower Nisqually River, where federal and tribal land ownership has preserved much of the riparian corridor, large wood recruited from the floodplain acts as 'key' stabilization points upon which log jams and forested islands form helping to maintain an anastomosing channel pattern (Collins et al., 2012). In addition to promoting multiple channels, wood assemblages in the low-flow channel of a river increase pool depth and frequency, which is beneficial to fish. On the Cedar River, much of the wood in the riparian corridor was removed with development. Also, revetments have mostly isolated the river from its floodplain, reducing the recruitment of new wood. Revetments and a marked decrease in wood availability changed the Cedar River's anastomosed channel pattern to its present single-threaded character.

Revetments along the Cedar River also prevented the recruitment of gravel from the floodplain to the river by limiting channel migration and avulsions. Sediment sources to the lower Cedar River for gravel include alluvium from eroding banks, landslides of unconsolidated Pleistocene sediment of glacial and glaciofluvial origin, and minor tributary inputs (Perkins, 1994). In recent years, removal of revetments in the vicinity of Cedar Rapids (Rkm 11.5–12.5) has facilitated local channel migration and the formation of side channels resulting in sediment recruitment from the floodplain.

Landslides along the valley walls of the Cedar River are evident throughout much of the twentieth century orthoimagery. The largest and most geomorphically significant landslide occurred in 2001 at Rkm 7.5–8.5. Subsequent high-flow events transported and reworked this landslide sediment, but much of the Pleistocene glacial sediment released by the landslide was smaller than existing gravel in the river, and the landslide provided little additional sediment available for salmonid spawning. The significant accumulation of sediment from the landslide and its subsequent reworking resulted locally in a wide, braided channel at Rkm 7.5–8.5 that migrated into the adjacent floodplain.

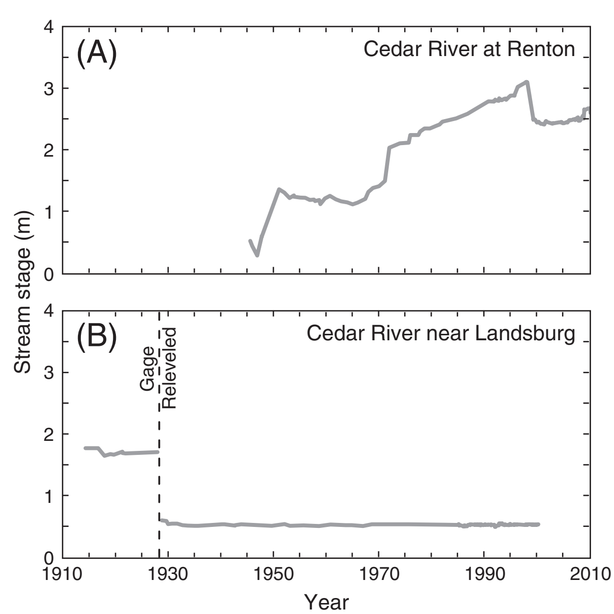

Fig. 9. Temporal variations in stream stage for the median streamflow at USGS streamflow gaging stations at (A) Renton (12119000) and near (B) Landsburg (12117500) on the Cedar River.

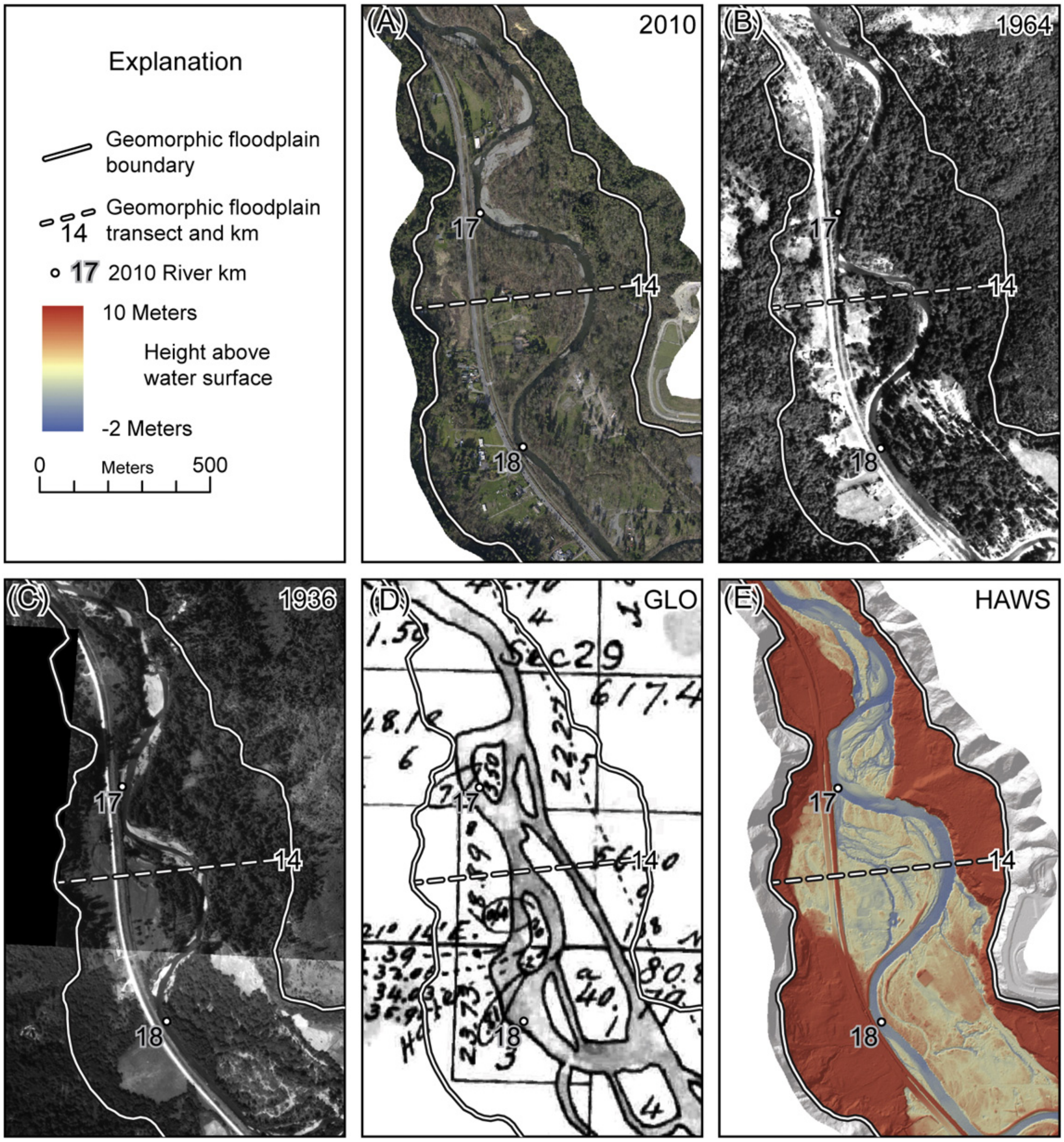

Fig. 10. Progression of planform geomorphic features in the vicinity of GFPkm 14: (A) 2010 orthoimagery, (B) 1964 orthoimagery, (C) 1936 orthoimagery, (D) 1865–1880 General Land Office (GLO) survey, and (E) height above water surface (HAWS).

5.2. Channel-forming flows

The frequency of channel-forming flows capable of reestablishing channel and floodplain features of the Cedar River by entraining sediment and recruiting large wood decreased following flow regulation (Fig. 2). Furthermore, bank stabilization, designed to restrict channel migration, limited the formation of new morphological features that channel-forming flows would have otherwise produced. Notably, overall channel width of the Cedar River did not increase coincident with the December 1975 and December 1977 high-flow events with 20- and 10-year recurrence intervals, respectively. Between 1989 and 2011, the 10-year recurrence interval was exceeded four times, including the post-regulation peak of record in November 1990 (50-year recurrence interval), and the average width of the Cedar River increased only slightly. Also, negligible planform and streambed changes were observed to most confined sections of the river following the high-flow event of January 2009 (30-year recurrence interval).

In reaches not confined by revetments, geomorphic function of the river is still present to some degree. During the twentieth century, channel avulsions and bank erosion occurred periodically in the three wide unconfined reaches (Fig. 5A) where the river was unimpeded by revetments. New pools and bars formed within these unconfined reaches during high-flow events, but overall pool frequency remained largely unchanged throughout the Cedar River (Fig. 6). Most of the pools that formed near bedrock or armored banks were stable and recorded during both the 2010 and 2011 longitudinal profile. Mean residual pool depth was similar between the 2010 (1.6 ± 0.6 m) and 2011 (1.7 ± 0.5 m) longitudinal depth profiles suggesting no substantial net change to the depth structure of the Cedar River during the January 2011 high-flow event.

Small-scale geomorphic changes, including the distribution of sediment and wood, are evident from field observations and orthoimagery analysis before and after the January 2009 and January 2011 high-flow events. These observations suggest a general decrease in areal extent of gravel available for spawning salmonids within 8 km of Landsburg. Those gravels were readily transported and deposited downstream by the high flow, but because gravel bars were deposited at an elevation above the low-flow channel, there was little increase in available spawning habitat downstream of Landsburg. Net gravel scour from the wetted channel and deposition on elevated gravel bars resulted in a decrease in available spawning habitat. Also, many side channels, important to salmonid rearing and spawning, were isolated by fresh gravel deposits. Other side channels were filled by gravel such that depth decreased, which discouraged spawning. In addition, the general redistribution of wood from small- and medium-sized assemblages near the low-flow channel to larger, elevated jams above and away from the low-flow channel resulted in a net decrease of submerged wood available to fish.

While less confined rivers benefit from the 10- to 20-year recurrence-interval channel-forming flows (e.g., Poff, et al., 1997; Wald, 2009), it qualitatively appears that similarly sized floods on the Cedar River result in a net decrease of beneficial ecological function. These observed responses, however, were not measured quantitatively. Presumably, heavy bank armoring of the Cedar River increases flow depth and flow velocity for channel-forming flows compared to other river system that migrate, avulse, or widen when subjected to such flows. Associated larger flow velocities also efficiently remove comparatively more sediment within a bank-armored river corridor. The higher stage associated with widespread revetments promotes sediment deposition on topographically higher bars where gravel cannot be used by spawning salmonids during low-flow periods. In the geomorphic and ecological context, quantifying and monitoring the availability of spawning gravels in the low-flow channel can improve management decisions focused on fish productivity.

It is likely that removal of revetments in key ecological reaches would increase river function and response to channel-forming flows. River management actions, such as setback levees or levee removal, help alleviate issues with flooding primarily by reducing the water-surface elevation of peak flows in flood-prone reaches (e.g., Singer and Dunne, 2006; Konrad et al., 2008; Czuba et al., 2010). For the Cedar River, in addition to beneficial effects of reducing flood stage, setback levees would also decrease water velocity, helping to preserve spawning gravels, and reconnect the primary channel to ecologically important side channels (e.g., Jones, 2006). For example, the HAWS maps from the Cedar River showed relic side channels in the inside bend of the Cedar River meander at GFPkm 14 (Fig. 10E) that, if reconnected to the main stem, would improve ecologic function of the river.

6. Conclusions

Anthropogenic changes to fluvial systems including flow regulation and floodplain alteration establish new geomorphic conditions that affect aquatic ecosystems. The geomorphic data presented here show that revetments and other bank stabilization structures influence channel migration rates, promote channel narrowing, reduce recruitment of wood to the river corridor, and reduce gravel supply to the channel. Analysis of historical orthoimagery showed that the overall mean width of the Cedar River decreased from a 47-m maximum in 1936 to a 23-m minimum in 1989. In this altered fluvial system, the effectiveness of channel forming flows with ~10- and 20-year recurrence intervals in performing geomorphic work that benefits aquatic ecosystems has been reduced. During the 1990s, increased magnitude and frequency of floods widened the overall mean width of the channel to 34 m by 2011 and increased channel migration rates in unconfined reaches. Increased geomorphic function of reaches unconfined by revetments, including the mobilization of bed material and maintenance of channel morphologic features such as pools and riffles, suggests that preserving and restoring a channel-floodplain connection is important for maintaining aquatic ecosystems.

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