Cedar River
Channel Migration Study

April 2015

King County

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EXECUTIVE SUMMARY

The Cedar River moves, or migrates, across its floodplain. This "channel migration" can occur gradually as the river erodes one bank and deposits sediment along the other, and it can also occur suddenly when a channel shifts abruptly to a new location. Channel migration represents a different type of flood hazard than inundation by overbank flow. The area subject to channel migration hazard within a given timeframe is referred to as the channel migration zone (CMZ).

The purpose of this study is to delineate a Cedar River CMZ and identify channel migration hazard areas in the study area extending from Lake Washington to Cedar River Mile (RM) 22. The results of the study will directly inform the planning and development of capital flood risk reduction projects. The CMZ map also will inform regulation of land use within channel migration hazard areas.

Study area characteristics

The CMZ study area includes the mainstem Cedar River from Landsburg Bridge at RM 22 downstream to the mouth of the river (RM 0) in the City of Renton, plus adjacent valley bottom floor and valley walls. Both the natural geologic setting and constructed structures strongly influence study area characteristics.

The Cedar River within the study area is a post-glacial valley that has incised through glacial and non-glacial deposits since the last glaciation some 13,000 years ago. Bedrock exposures are rare but locally exert significant control on channel migration. More commonly, the Cedar River valley walls are composed of sedimentary formations that range from erosion-resistant to erodible. The valley bottom is composed mainly of alluvium, which typically is loose sand and gravel deposited by the river or its tributaries, through which the channel will migrate readily if unimpeded.

Operation of the Masonry Dam and associated waterworks upstream of the study area since circa 1914 has altered Cedar River flows and thereby influenced channel conditions and migration characteristics for about a century. Widespread construction in the 1960s of levees (raised earthen berms, typically with rock armor on the river side) and revetments (rock armor intended to prevent erosion), along with other infrastructure such as the Cedar River Trail, SR169, and several other bridges, have resulted in armored riverbanks along much of the study area. The effects of flow regulation and bank armoring plus naturally erosion-resistant geology combine to constrain the potential for channel migration in many areas. However, there continues to be active channel migration along unarmored alluvial riverbanks.

Methods

This CMZ study and resultant map uses historical channel migration patterns and rates to predict future channel migration hazard. Cedar River channel migration was evaluated and mapped using information from existing studies, field observations, and analyses conducted in a Geographic Information System (GIS). Historical aerial photographs dating from 1936 through 2011, historical maps, and present-day aerial imagery, including topography shown by LiDAR, were evaluated in GIS to map historical channels and calculate channel migration rates.

Channel migration hazards in the Cedar River were mapped by identifying the component parts of a CMZ as specified by the King County Channel Migration Public Rule and consistent with Washington State Department of Ecology guidance. CMZ components are defined in the following equation and described below.

CMZ = HMZ + AHZ + EHA – DMA
where
HMZ = Historical Migration Zone
AHZ = Avulsion Hazard Zone
EHA = Erosion Hazard Area = Erosion Setback (ES) + Geotechnical Setback (GS)
DMA = Disconnected Migration Area

The Cedar River HMZ includes the area occupied by channels from 1936 to present. The AHZ includes areas subject to a rapid shift of channel location. The ES width was calculated as a time period ranging from 50 years to 100 years multiplied by an average annual channel lateral migration rate calculated individually for each study reach. A GS was mapped where EHA/ES encounters certain erosion-resistant landforms at a 1H:1V slope landward into that landform. The DMA was mapped to exclude areas landward of publicly maintained artificial structures that (in incorporated areas) limit channel migration or (in unincorporated areas) are likely to restrain channel migration and are built to an elevation that is greater than that of the annual 1 percent flood.

Once the CMZ components were mapped and combined to delineate the outer edge of the CMZ, severe and moderate hazard areas were identified within the overall CMZ.

This study considers the effect of channel migration on slope stability when mapping the CMZ, but it does not consider the process by which a landslide blocks and redirects the channel. As information is compiled and mapping methodologies defined with regard to landslide hazard areas, CMZ mapping will be evaluated to consider necessary revisions.

Characteristics of channel migration in the study area

Channel migration occurs mainly by three processes in the Cedar River:

- Lateral migration: progressive movement of the channel across floodplain resulting from erosion along one riverbank and deposition along the other.
- Channel expansion: channel widening resulting from erosion along both banks.
- Avulsion: an abrupt shift of the channel to new location.

The channel gradient, channel confinement, channel pattern, and riverbank materials directly influence the type and extent of channel migration that is likely to occur. Channel migration in the Cedar River typically is more active in a channel with moderate gradient, unconfined conditions and unarmored banks than in a steeper, confined channel with armored banks. Channel conditions through much of the study area are confined and armored.

Average annual lateral migration rates vary from 1 foot/year to 5 feet/year in most reaches, with the highest rates in the range of 8 feet/year. In addition to spatial variation in channel migration resulting from factors described above, the channel pattern has simplified and channel migration rates have decreased through time because of flow regulation since 1914 and widespread installation of bank armoring in the 1960s.

Delineation of the CMZ and channel migration hazard areas within the CMZ

An unconstrained CMZ was mapped as the combination of the HMZ + AHZ + EHA (including EHA/ES and EHA/GS). The unconstrained CMZ does not recognize artificial constraints and therefore predicts channel migration in the absence of levees, revetments, and infrastructure. In a majority of study reaches, the width of the HMZ constitutes most of the width of the unconstrained CMZ.

The unconstrained CMZ was modified in two ways to produce the CMZ map. First, the DMA was mapped to recognize that certain artificial structures can restrain channel migration. All publicly maintained structures in the City of Renton were mapped as barriers to migration, as were SR 169 and sole-access roads within King County. The majority of levees and revetments maintained by King County within unincorporated King County were not mapped as barriers to channel migration because they were not built higher than the elevation of the annual 1 percent chance flood and were not likely to restrain channel migration. No privately maintained structures were mapped as barriers to channel migration.

A second modification to the unconstrained CMZ was that severe and moderate hazard areas were mapped within the overall CMZ. Severe hazard areas are composed of the entire HMZ, severe AHZs, and typically half of the EHA. The present-day active channel always is mapped as a severe hazard area. With these components mapped as severe hazards, the severe hazard area occupies most of the width of the CMZ throughout the study area. The moderate hazard area lies between the severe hazard area and the outer boundary of the unconstrained CMZ. The result of these two modifications to the unconstrained CMZ completes the Cedar River CMZ map.

Key findings and conclusions

Modifications to the Cedar River flow regime since circa 1914, coupled with widespread bank armoring since the 1960s, combine to simplify channel pattern, confine channel conditions, and decrease channel migration rates. With flow regulation assumed to continue as it has for the past century, channel confinement and bank armoring emerge as the prominent variables presently affecting channel migration in this study area. Channel migration does occur in confined and armored areas, though at lower rates than in unconfined or unarmored areas. However, the potential for active channel migration remains high should bank armoring fail or be removed.

In the few areas that are naturally unconfined or recently have had bank armoring removed, lateral migration rates typically are higher than in confined or armored areas. A multiple-channel pattern prevails and gravel bars are bare and active, all of which suggest sediment deposition. Greater numbers of large wood exist in unconfined areas than in confined areas and conditions that favor avulsion may be present. Channel expansion typically occurs after a triggering event such as avulsion or levee removal.

The Cedar River CMZ includes most of the valley floor in the naturally confined upstream part of this study area (Reaches 20 through 18). Further downstream, the CMZ includes most of the valley floor where it is not cut off by major infrastructure (e.g., SR 169) in reaches that exhibit historically active channel migration or are subject to avulsion hazards, or both (Reaches 15, 12, 10, 9, 8, 6 and 4). The CMZ along most of the length of other reaches covers a relatively narrow portion of the valley floor.

In addition to using the Cedar River CMZ map to regulate land use in affected channel migration hazard areas, the CMZ map and findings of this study will inform planning and development of capital flood risk reduction projects via the Cedar River Corridor process. There is potential to decrease flood risk and increase floodplain connectivity in mapped channel migration hazard areas by acquiring at-risk properties, removing constructed bank armoring and allowing channel migration to proceed in a less constrained condition than currently exists. This potential would be greatest in areas where channel gradient is moderate and naturally erosion-resistant riverbanks are absent or do not dominate. Such conditions exist in Reaches 16, 15, 12, 11, 10, 7, 6, 5 and 4 of this study area.

This study is based on the use of historical information to predict future hazard; these methods are consistent with accepted practices and guidance from the Washington State Department of Ecology. Because some factors affecting channel migration are stochastic in nature, the channel may not occupy all parts of the mapped CMZ within the next 100 years. Furthermore, the channel could occupy portions of the valley floor beyond the limits of the mapped CMZ within the next 100 years. To recognize the need to have hazard mapping reflect more near-term, expected conditions, it is intended that a CMZ map be updated every 20 years. Also, portions of a CMZ map may be revised at timeframes shorter than 20 years if local changed conditions warrant.

1.0 INTRODUCTION

The Cedar River moves, or migrates, across its floodplain. This "channel migration" can occur gradually as the river erodes one bank and deposits sediment along the other, and it can also occur suddenly when a channel shifts abruptly to a new location. Abrupt channel changes may happen during a single flood event.

Channel migration represents a different type of flood hazard than inundation by overbank flow. It can endanger properties located outside of the regulatory floodplain shown on flood hazard and flood insurance maps. Although both channel migration and flood inundation are hazards that may result from flooding, there is no specific correlation between the mapped boundaries of these two distinct hazard areas. The area subject to channel migration hazard within a given timeframe is referred to as the channel migration zone (CMZ). There is a potential hazard to permanent structures anywhere within a CMZ.

The historical approach to addressing potential damage from bank erosion and channel migration has been to armor the riverbanks with levees or revetments. However, such bank armoring can be expensive to construct and is subject to ongoing flood damage, which requires costly recurring maintenance work. Bank armoring can aggravate flooding or erosion problems upstream or downstream of the armored location and degrade aquatic habitat. In order to prevent future development in areas subject to channel migration, the King County Flood Hazard Management Plan Update ("Flood Plan") (King County 2013) states in Policy FP-2:

> King County should identify channel migration hazard areas through geomorphic analyses and review of historical channel migration patterns and rates. Land-use regulations shall restrict unsafe development in identified channel migration hazard areas.

The Flood Plan and its policies are incorporated into the King County Comprehensive Plan (King County 2012). These King County policies and their implementation are consistent with State Shoreline provisions, which require the mapping of CMZs (WAC 173-26-221) and State Department of Ecology guidance on CMZ mapping (Department of Ecology Shorelands and Environmental Assistance Program 1994-2014; referred to herein as "Ecology 1994-2014").

This study constitutes the geomorphic analyses recommended in King County Flood Plan Policy FP-2. The Cedar River CMZ map produced by this study will be provided to King County Department of Permitting and Environmental Review (DPER) for adoption via the 2014 Revised King County Channel Migration Public Rule (King County 2014) to use in regulating land use within channel migration hazard areas.

1.1 Statement of purpose

The purpose of this study is to delineate a Cedar River CMZ and identify channel migration hazard areas in the study area extending from Lake Washington to River Mile (RM) 22.

The Cedar River CMZ map and study utilizes historic channel information, and the resultant hazard mapping portrays expected channel movement over time. The results of the study will directly inform the planning and development of capital flood risk reduction projects. For the Cedar River, this study is particularly timely for corridor planning now underway. River corridor planning and the development of capital projects serve to implement the policies and recommendations of the King County Flood Plan. The CMZ map also will inform regulation of land use within channel migration hazard areas. These uses of the Cedar CMZ map and study are consistent with county and state policies and regulations cited on page 1.

1.2 Report Layout

This Cedar River channel migration study provides an overview of geomorphic, geologic, physical, and structural factors affecting channel migration in the study area. Mapping methods and criteria are described in detail. Historical channel migration patterns and rates are evaluated as the basis of predicting future channel migration hazard. Finally, channel migration hazard areas are identified in a channel migration zone map.

1.3 Timeframes relevant to this study

A CMZ is defined as the area through which channel migration is predicted to occur within a given timeframe (Ecology 1994-2013; Rapp and Abbe 2003). The timeframe used in this study to map channel migration hazard is 100 years. That timeframe is consistent with planning timeframes used in Federal Emergency Management Agency (2013) and National Marine Fishery Service (2008) and the adopted policies of the King County 2006 Flood Plan and 2013 Update and Progress Report.

Although the information and methods used in this study constitute the best available science, channel migration is a dynamic process, and the CMZ maps now prepared may become less informative or obsolete in the distant future (i.e., 100 years). To recognize the need to have hazard mapping reflect more near-term, expected conditions, the King County Channel Migration Public Rule (King County 2014) requires that a CMZ map should be updated every 20 years. As such, 20 years can be considered the planning horizon for this CMZ study. Also, the Public Rule provides that portions of a CMZ map may be revised at a shorter timeframe than 20 years if locally changed conditions affect channel migration, such as construction of a levee setback project.

1.4 Effect of landslides on channel migration

The process by which a landslide blocks and redirects the channel is not addressed in this study or CMZ maps, and CMZ mapping methods do not include technical methods to account for landslide processes that may block or redirect the channel. As information is compiled and mapping methodologies defined with regard to landslide hazard areas, CMZ mapping will be evaluated to consider necessary revisions.

2.0 STUDY AREA CHARACTERISTICS

The Cedar River flows from headwaters in the Cascade Mountains to its mouth at the south end of Lake Washington, as shown in Figure 1. The CMZ study area includes the length of mainstem Cedar River from Landsburg Bridge at River Mile (RM) 22.1 downstream to the mouth of the river (RM 0) in the City of Renton. The width of the study area includes the valley bottom floor and valley walls along the length of the study area.

2.1 General basin characteristics

The crest of the Cascade Mountains forms the eastern border of the Cedar River basin at elevations in excess of 5,000 feet. The Cedar River flows west for 45 miles from its headwaters to its mouth and drains about 196 square miles. From its headwaters, it descends through the steep, heavily forested City of Seattle's Cedar River Municipal Watershed for over half its length. Masonry Dam impounds flow at RM 37 in Chester Morse Lake (Figure 1). The City of Seattle operates the dam primarily for water supply and power generation. The river flows through a steep and confined reach between Chester Morse Lake and Landsburg. Flow is diverted at the Landsburg Diversion Dam at RM 22.6 for water supply.

Unincorporated King County areas downstream of Landsburg through Maple Valley to the City of Renton boundary are typified by rural residential and suburban land use of varying densities. The lowest five miles of the river and its floodplain are almost entirely within the City of Renton and its urban growth boundary. This area contains parks, single- and multi-family residential development, several major subdivisions, significant commercial/ industrial development, and portions of the downtown business core. Much of the area is developed area and supports infrastructure in close proximity to the Cedar River.

The location of this study area within the Puget Sound lowland area affected by multiple glaciations and the geomorphic response since retreat of glaciation strongly influence basin characteristics relevant to channel migration, as described in Section 2.3.1.

2.2 Human activity and built features

Early land uses in the Cedar River valley included the extraction industries of coal mining and timber harvesting. Construction of a railroad up the valley in the late 19th century spurred those activities. Masonry Dam and associated waterworks were constructed by City of Seattle for water and power supply in the early 20th century. The entire basin upstream of Landsburg was preserved in the City of Seattle's municipal watershed.

The Cedar River valley downstream of Landsburg within the study area remained largely rural through the first half of the last century. Subsequently, low-density rural land use transitioned to areas of moderate or higher density residential use resulting in greater numbers of structures built in areas subject to flooding and channel migration. With the increase of population and structures in flood hazard areas, levees and revetments were

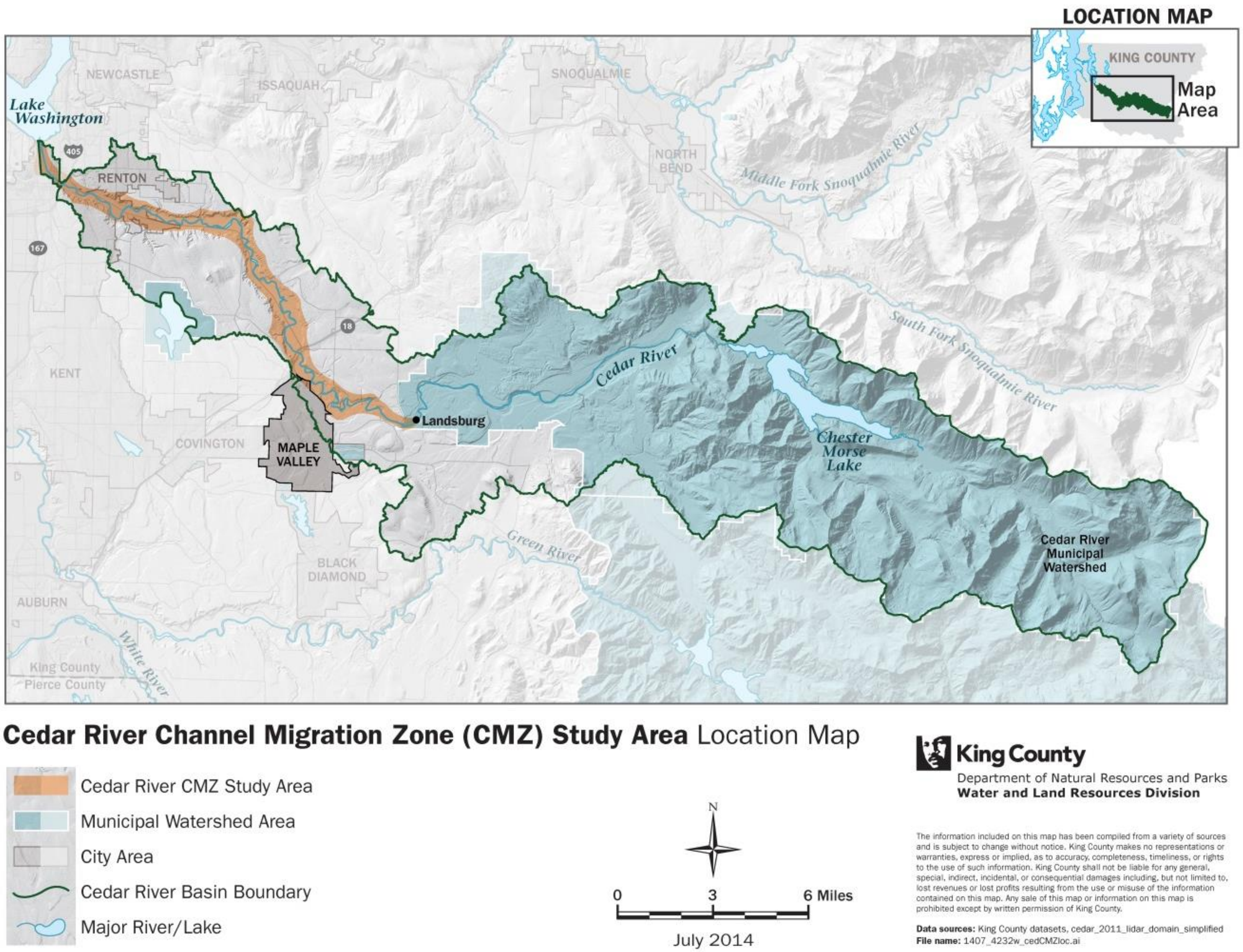

Figure 1. Cedar River CMZ study area location map.

constructed along the river channel. In addition to inhibiting flooding, levees and revetments also constrain channel migration.

Levees (raised earthen berms, typically with rock armor on the river side) and revetments (rock armor intended to prevent erosion) can inhibit or constrain channel migration. There are approximately 70 publicly maintained levees and revetments, built as flood protection facilities, along the Cedar River's banks within the study area. King County maintains facilities upstream of I-405 (RM 1.63); the City of Renton maintains the system of levees and floodwalls downstream of I-405. The locations and approximate construction dates of these facilities are shown in Map 1, Appendix A.

The majority of the publicly constructed and maintained flood protection facilities within the study area were built in the 1960s with public funds raised by two King County bond issues (Figure 2). No new bank armoring facilities have been constructed within the King County part of the study area in the last few decades, although maintenance and repairs of existing facilities is ongoing. Most facilities are either revetments or "training levees," the latter of which typically do not contain large flood flows but instead train or direct the flow of the river.

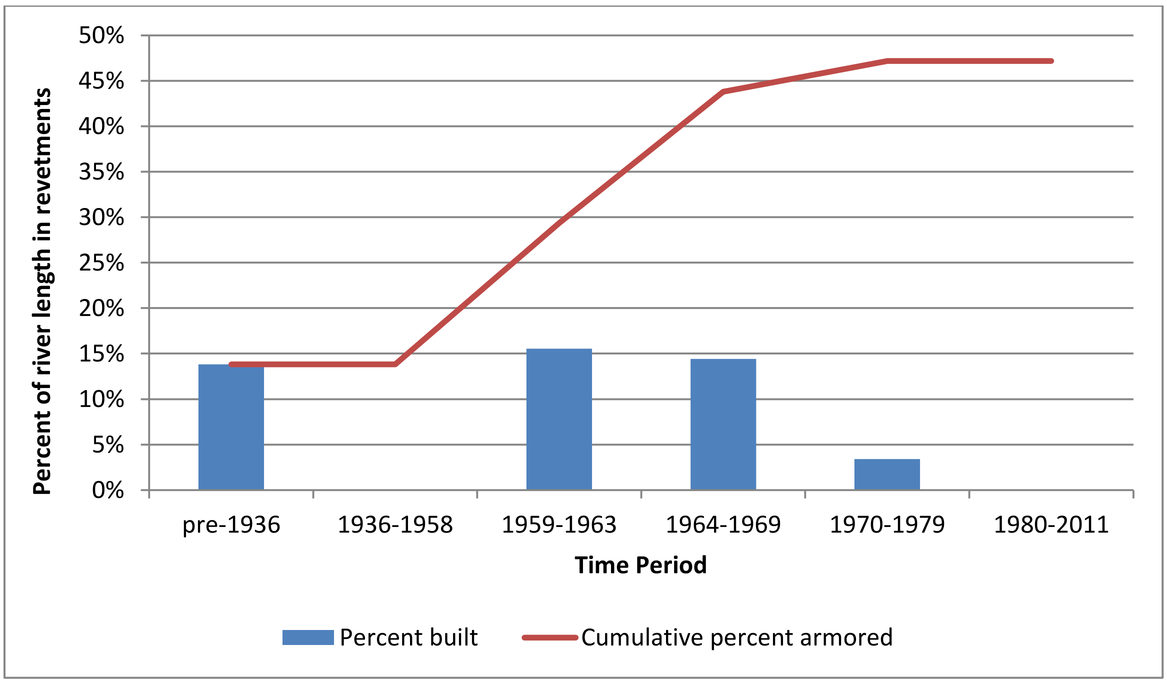

Figure 2. Cedar River construction history of publicly maintained bank armoring.

The lowest mile of the Cedar River was rerouted to its current location and both riverbanks were lined by armored levees in 1914. Presently, a combination of floodwalls and armored levees, termed the Cedar River 205 Flood Control Project, provide containment of 12,000 cubic feet per second (cfs) (the annual 1 percent flood) from I-405 to the mouth. The 205 Flood Control Project also prevents channel migration of the Cedar River through the same area.

The fill prism and bridges of a former railroad line dating from the late 1800s extend through almost the entire length of the study area and now serve as the Cedar River Trail (CRT). Separate CRT bridges cross the river at three locations upstream of Maple Valley (RM 15) and three locations downstream of Maple Valley in tandem with SR169 bridges (Map 1, Appendix A). In all, there are 18 bridges that span the Cedar River from I-405 upstream with abutments that, to some extent, fix the river channel in place. From Landsburg to I-405, either the CRT alone or the CRT and SR169 disconnect the Cedar River from its floodplain in several locations.

Considerable amounts of infrastructure (i.e., roads, bridges, utilities, and bank armoring) exist in close proximity to the Cedar River through much of this study area. Some individual segments of the Cedar River are armored extensively, and publicly maintained levees or revetments line the majority of the length of at least one bank in about half of the reaches of the study area (Figure 3). This percentage is higher when privately constructed bank armoring and infrastructure are included. Almost every outside bend of the Cedar River from Landsburg to the mouth is either armored by levees or revetments or bounded by an erosion-resistant geologic feature (Section 2.3). Together, constructed roads, bank armoring, and bridges plus naturally erosion-resistant geology combine to constrain the potential for channel migration in many parts of this study reach.

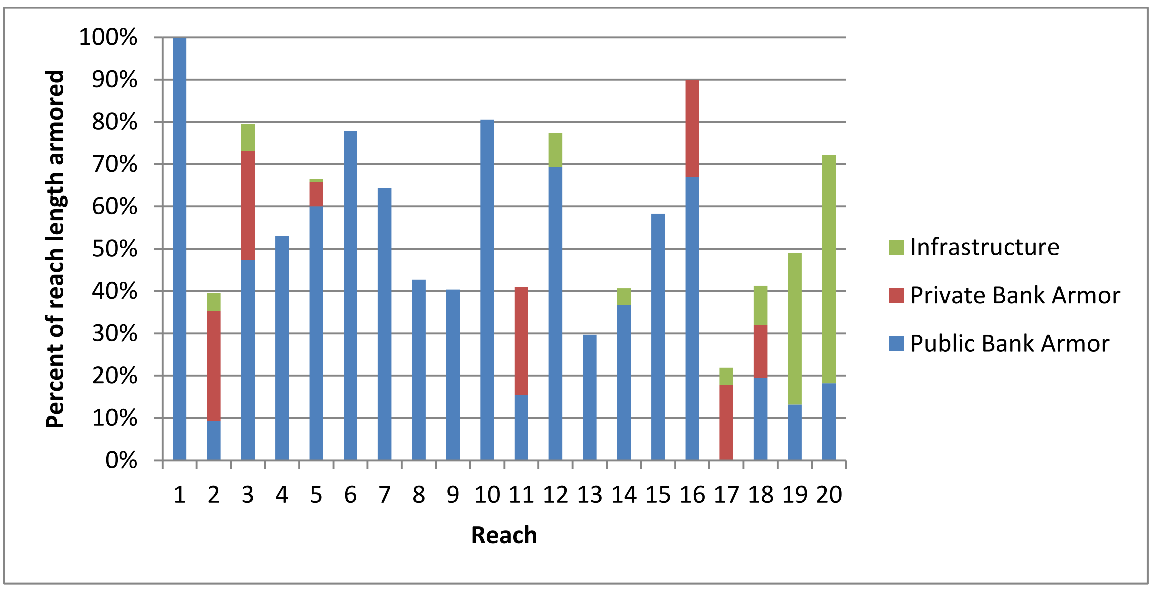

Figure 3. **Percent of Cedar River riverbank length with bank armoring.**

2.3 Geology and sediment

The Cedar River basin is underlain by Tertiary volcanic and sedimentary bedrock that is exposed rarely in the study area and exerts little influence on fluvial processes relevant to channel migration on the basin scale. Locally, bedrock walls exert significant control on channel migration. Multiple episodes of continental glaciation extending down from British Columbia covered the Puget Lowland over the past 2.5 million years and shaped the landscape of today. Today, most of the Cedar River basin from Landsburg to the mouth has valley walls composed of glacial and non-glacial sediments and a valley bottom of young alluvium. A generalized geologic map of the study area is shown in Map 2, Appendix A (after Mullineaux 1970 and Booth 1995).

The Cedar River within the study area has incised through glacial and non-glacial deposits since the last glaciation some 13,000 years ago. The Cedar River in the study area is an east-west trending, post-glacial, Holocene valley that joins a north-south trending glacial trough, now occupied by Lake Washington, carved by direct glacial contact (Collins and Montgomery 2011).

As a result of its geologic past, the river flows through a floodplain of erodible alluvial materials composed primarily of sediments eroded from glacial and non-glacial deposits. If unconstrained, the river typically will migrate laterally through young alluvium of the modern floodplain, older alluvium of abandoned flood terrace deposits, as well as exposed colluvium, alluvial fans, and modified fill. The river more slowly erodes relatively erosion-resistant cliffs by undermining and cliff retreat processes, as is evident in several locations in this study area (Perkins et al. 2002). In the few places where Tertiary bedrock forms the valley walls, no bank erosion or channel migration is evident during timeframes relevant to this study.

2.3.1 Geology

The following paragraphs describe geologic formations observed in river banks and valley walls of the study area, in order from oldest to youngest.

Tertiary bedrock in the Puget Group (map unit Tp) is exposed near the middle of the study reach and again along the south valley wall near the downstream end of the valley. This sedimentary rock dates from the upper Eocene (some 38 million years ago) and consists of sandstone with interbedded shale and coal. Members of the Puget Group within the study area are the Renton Formation (Tpr) and Tertiary sedimentary (Ts) rock. The Renton Formation outcrops on both sides of the river from RM 9 to RM 10. This outcrop along both valley walls likely results in the narrowness of the floodplain in that area. The south valley wall from about RM 3.9 to RM 2.2 consists of Tertiary sedimentary rock.

Quaternary glacial and non-glacial deposits are sediments deposited by glaciers and rivers, respectively, during and between glacial advances of the last 2.5 million years. They comprise most of the Cedar River valley walls and are exposed extensively within the study area. The sequence of glacial sediments deposited during the most recent glaciation of 15,000 to 13,000 years ago include Vashon advance outwash (Qva), Vashon Till (QVt), and Vashon recessional outwash (QVr) sediments. These Vashon glacial sediments constitute the vast majority of the surficial geology of the plateaus adjacent to the Cedar River valley.

Glacial sedimentary deposits of the pre-Fraser (Qpf) glaciation age include at least two till layers older than Vashon glaciation. Greater age and the pressures of multiple glaciations make the pre-Fraser a more consolidated, more erosion-resistant sedimentary unit than the most recent glacial sediments. This unit forms near-vertical bluffs along both valley walls through much of the study area, and resists the rapid erosion that can affect looser alluvium. Still, the pre-Fraser bluffs adjacent to the river are subject to cliff retreat due to undermining by the river and to episodic landsliding.

The one outcrop of ice contact (Qvi) deposit found at the downstream end of the south valley wall, near I-405, may have been deposited as a glacial moraine. This deposit would be similar to, but contain a higher percentage of silt than, a recessional outwash.

Recent deposits were formed in the Holocene period during the last 13,000 years and are still being formed by ongoing processes. Recent deposits include colluvium (landslides and mass wasting material), alluvium (typically valley bottom river sediment) and modified surfaces (contemporary fill material).

The modern, post-glacial Cedar River has incised through a complex sequence of glacial and non-glacial deposits, leaving high and steep valley walls along both sides of the river for much of the length of this study area. Following initial downcutting, the Cedar River has filled most of its present-day valley with thick deposits of sand and gravel (King County 1993).

With geologically recent incision into glacial and non-glacial sediments, the steep Cedar River valley walls exhibit widespread and locally severe landsliding. Landslides (Qls) and mass-wastage colluvial deposits (Qmw) are prevalent along both valley walls, often draped upon the older pre-Fraser unit. Where in contact with the river, landslides provide sediment directly to the channel. In this setting, channel migration maintains steep sideslopes (Booth 1995) as the river erodes and redistributes the colluvial sediment.

The entire Cedar River valley floor is composed of alluvium sediment (typically sand and gravel) deposited by the river or its tributaries. Younger alluvium (Qyal) is moderately sorted sediment, largely composed of reworked glacial sediments in this basin. Older alluvium (Qoal) is texturally equivalent to the younger alluvium but lies at a higher elevation as a terrace no longer flooded by the river. Such elevated terraces may resist channel migration more than younger, frequently flooded alluvium. There is a terrace of older alluvium along the northeast side of the valley adjacent to the river near RM 11.8 to RM 12.4.

2.3.2 Sediment characteristics

As channel gradient and confinement decrease, so does sediment transport capacity, and this reduced capacity for the river to transport sediment typically results in sediment deposition. Accumulations of large wood debris can also force the local deposition of sediment. Depositional river reaches with unarmored alluvial banks are likely to experience bank erosion and channel migration, as flow is deflected by deposited material. The deposited sediment of primary interest in this study includes coarse sand, gravel, and larger particles. These sediment fractions are often referred to collectively as gravel.

Perkins et al. (2002) estimated the total gravel supply to the mainstem Cedar River within this same study area at 11,000 to 12,000 cubic yards per year (cy/yr), most of which comes from upstream of Landsburg and cliff erosion a few miles downstream of Landsburg. This annual gravel influx volume is consistent with the 11,000 to 15,000 cy/yr estimated by King County (1993) and regional sediment yields for basins of this size (Nelson 1977).

Most of the gravel entering Reaches 20 through 18 does not deposit there because of the steep channel gradient and natural confinement in those reaches. Continuing downstream, the sediment transport capacity of the Cedar River is adequate to move incoming sediment through most of the study area (King County 1993; Perkins et al. 2002). Indeed, sediment transport modeling indicates that sediment transport capacity exceeds sediment supply between Landsburg and about RM 2, making sediment transport in the Cedar River sediment-supply limited through most of the study area (King County 1993).

The flat channel gradient in the lower approximately two river miles and backwater from Lake Washington upstream of the river mouth decrease transport capacity in that area, resulting in ongoing aggradation. Dredging in this portion of the channel has been conducted periodically to maintain channel flood capacity; the most recent dredging activity was in 1998. The average annual sediment deposition volume in the channel from RM 1.3 to the river mouth between 1998 and 2011 is 9,700 cy/yr (Northwest Hydraulic Consultants 2011), which is about 70 to 90 percent of the estimated average annual coarse sediment influx to the entire study area (Perkins et al. 2002). The similarity of the upstream influx and downstream deposition volumes is consistent with sediment transport conditions that are sediment-supply limited.

The change in stage elevation through time at U.S. Geological Survey (USGS) gage 12119000 (Cedar River at Renton) reflects ongoing aggradation at RM 1.4 (Figure 4A), which also is typical of conditions from I-405 to the mouth. A similar plot at USGS gage 12117500 (Cedar River near Landsburg) indicates no long-term aggradation at RM 23.4 (Figure 4B).

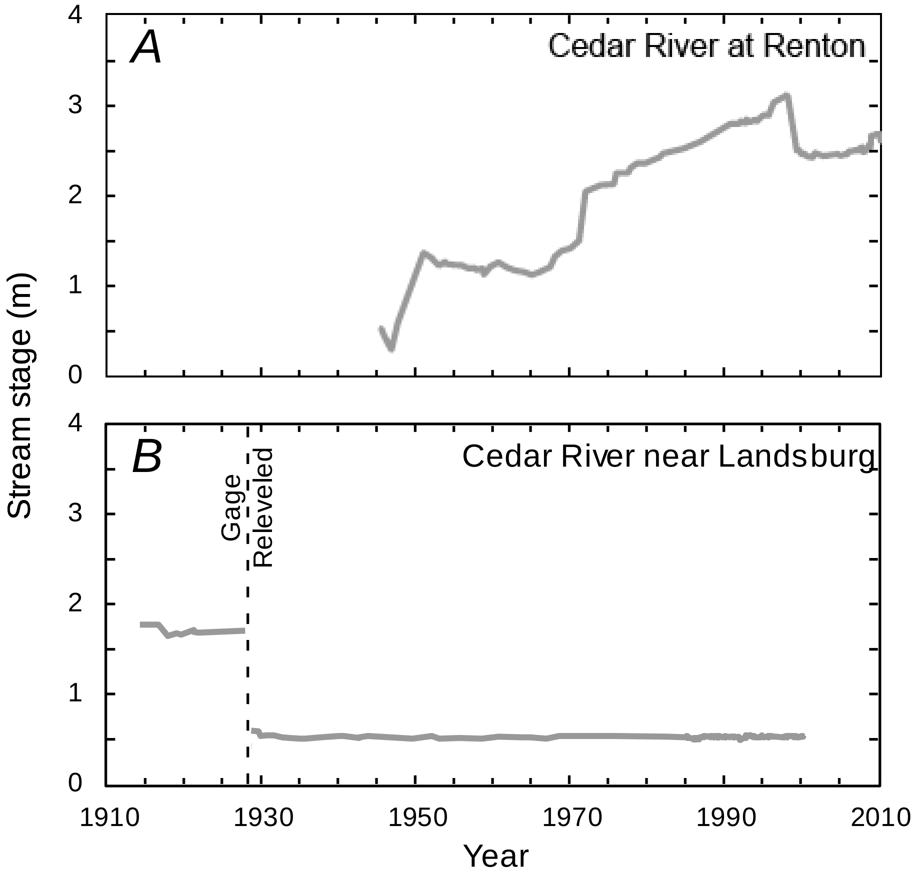

Figure 4. Temporal changes in stage at (A) USGS gage 12119000, Cedar River at Renton, and (B) USGS gage 12117500, Cedar River near Landsburg (from Gendaszek et al. 2012).

Approximately 200 channel cross sections from Landsburg to I-405 that were surveyed in 2000 or 2003 were resurveyed in 2012 to evaluate change in average riverbed elevations through the study area. Comparison of the two datasets reveals wide variability in riverbed elevation changes through the period between surveys (Figure 5). Annual monitoring of average bed elevation within the City of Renton documents increases in sediment levels from RM 1.3 (Wells Ave) downstream to the mouth that range from 1 feet to 8 feet (average is approximately 3 feet) from 1998 to 2011 (Northwest Hydraulic Consultants 2011). In all, available information suggests a general efficiency in transporting coarse sediment and no systemic recent changes in in-channel sediment levels from Landsburg to I-405 (RM 1.7). Monitoring data document ongoing aggradation from RM 1.7 downstream to the mouth.

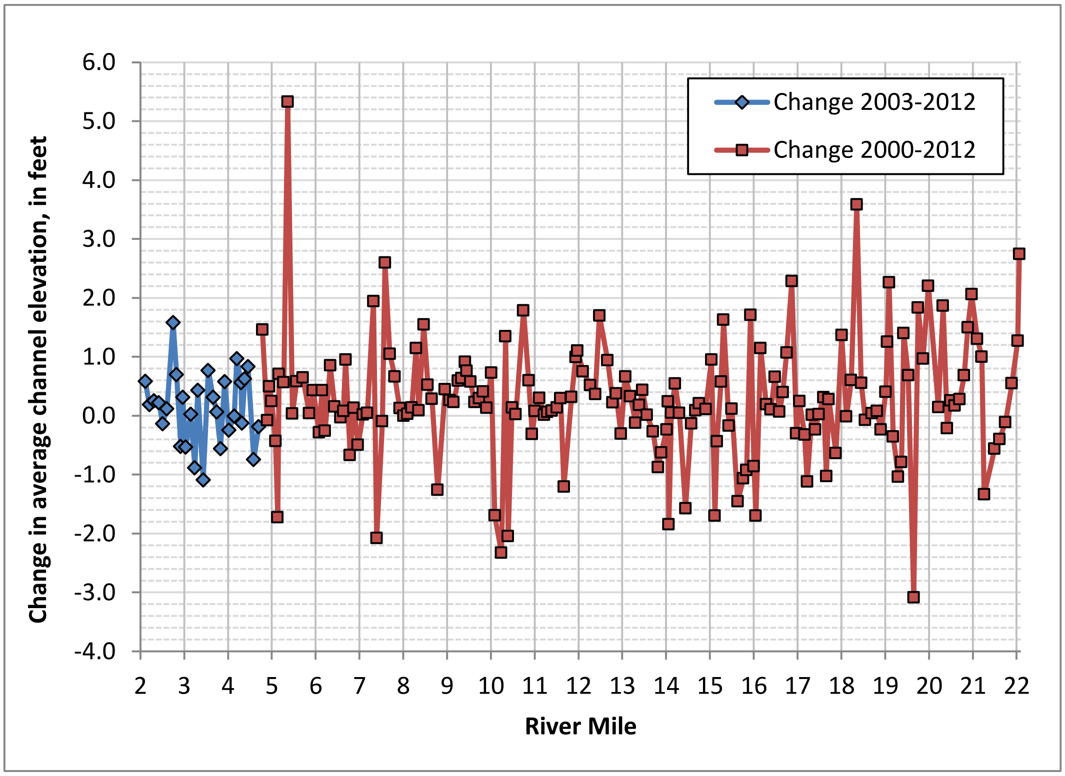

Figure 5. Change in average bed elevations, 2000 or 2003 to 2012.

The competence of a river, or its ability to transport a given sediment particle size, typically decreases with channel gradient in the downstream direction. Figure 6 plots reach-averaged channel gradient, based on water surface gradient at 1,800 cfs flow (Section 2.4) with the median surface sediment size through the study area. The riverbed is predominantly coarse material (e.g., boulder, cobble) in the steep (0.6 percent) channel gradient of Reaches 20 to 18. From Reach 17 (RM 17.5) downstream to Reach 2 (RM 3), substrate particle size generally decreases with channel gradient, with some notable local variability (Figure 6). In parts of the study area there is no apparent trend in substrate size in the downstream direction, and sampling results can vary widely within a short river distance because of local morphology and hydraulics (Perkins et al. 2002). The Cedar River remains a gravel-bedded channel to well downstream of RM 1 even as channel gradient becomes very flat (<0.2 percent). Finer gravel transitions to mainly sand within 1,000 feet of the river mouth (Northwest Hydraulic Consultants 2001; U.S. Army Corps of Engineers 1997).

Sediment transport varies as a function of channel gradient, water depth, and riverbed particle size. Based on these factors, initial movement of riverbed sediment was calculated to occur at about 2,000 cfs near Landsburg and 2,700 cfs in Renton (Perkins et al. 2003), both calculations of which are consistent with the empirical observation that significant sediment movement and deposition begins to occur at about 2,500 cfs in Renton (Northwest Hydraulic Consultants 2001).

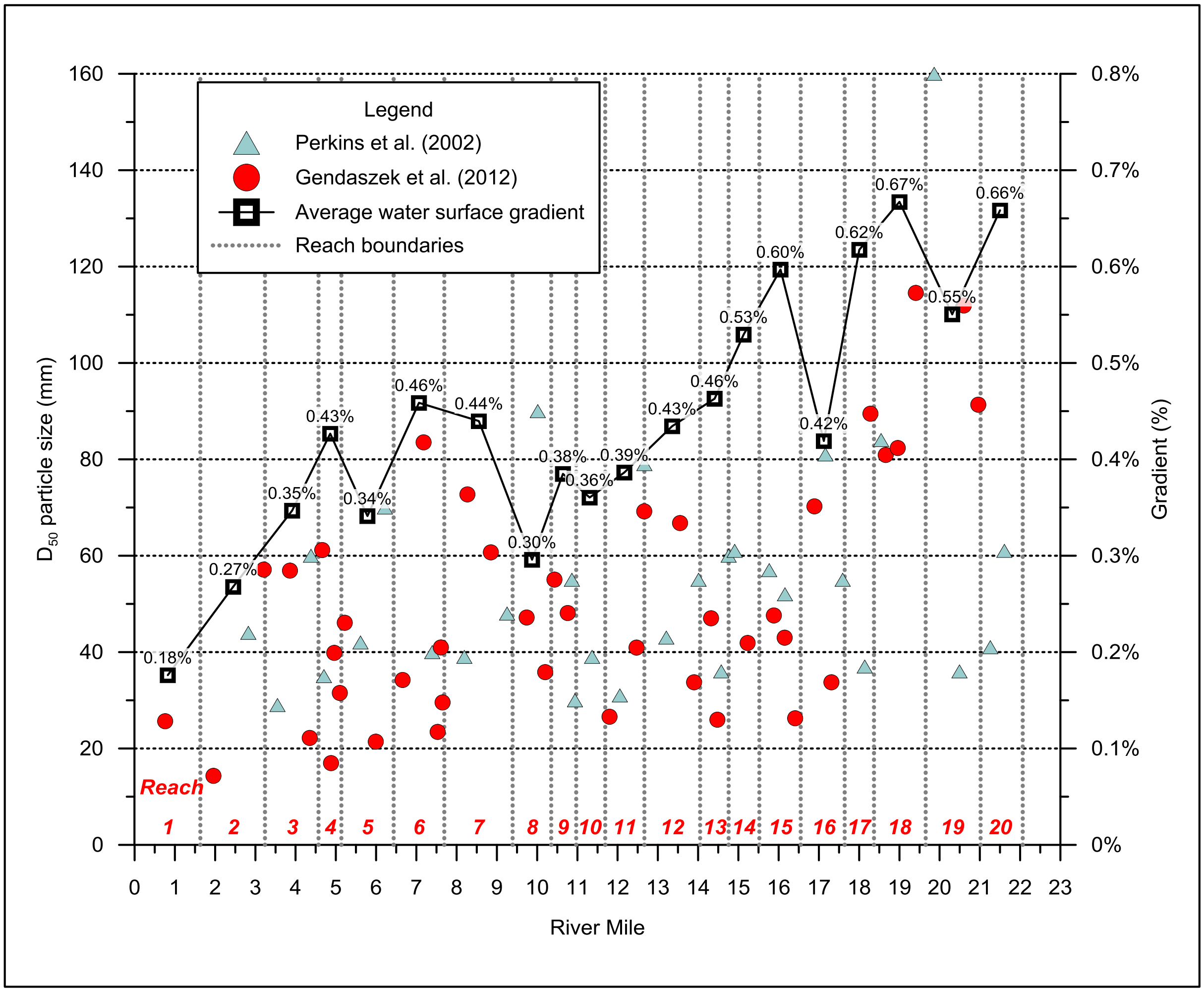

Figure 6. Reach-averaged channel gradient and channel substrate particle size (substrate data from Perkins et al. 2002 and Gendaszek et al. 2012).

2.4 Flood hydrology

Floods along the Cedar River occur primarily during the winter months of November through February, and each event typically lasts a few days. Annual peak flows at USGS gage 12117500, the Cedar River near Landsburg, at RM 23.4 are shown in Figure 7 for the period of record through water year 2011. Peak flows after 2011 are not shown because 2011 is the most recent aerial photo used in Geographic Information System (GIS) analyses in this study. Selected recurrence interval flood magnitudes from the Cedar River Flood Insurance Study (Federal Emergency Management Agency 2005) and other flows of interest are listed in Table 1 and shown in Figure 7 for context. Three floods between 1900 and 1912 equaled or exceeded the current-day annual 1 percent flood of 10,300 cfs at Landsburg. Masonry Dam and associated waterworks were under construction from 1902 to 1914. Since 1914, only the November 1990 flood has exceeded 10,300 cfs at Landsburg.

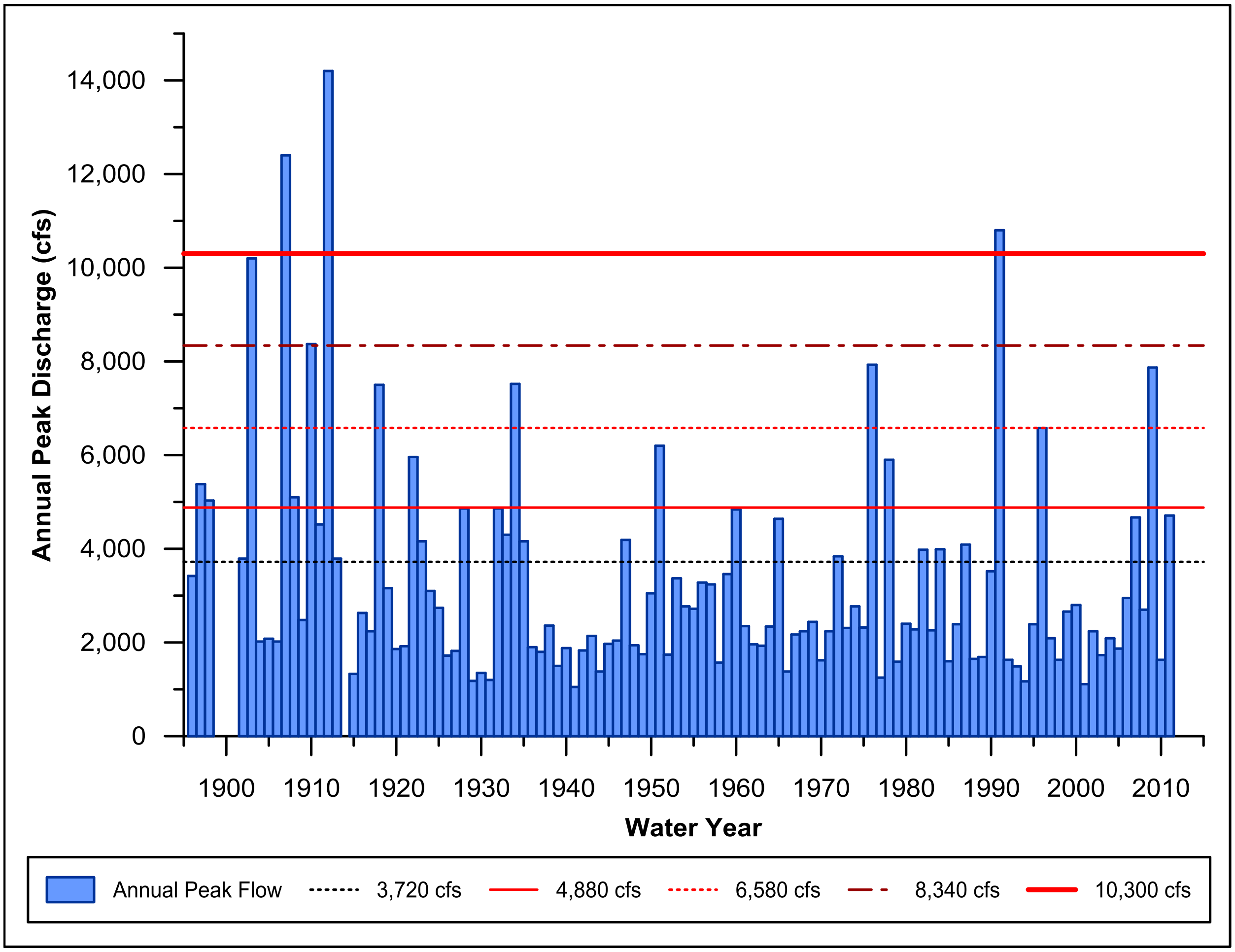

Figure 7. Annual peak flows at USGS gage 12117500 Cedar River near Landsburg.

Table 1. Flow discharge magnitudes, annual percent chance and recurrence intervals.

Discharge at Cedar River near Landsburg (cfs)	Discharge at Cedar River at Renton (cfs)	Annual Percent Chance	Recurrence Interval (Years)	King County Flood Phase or Example Flood	Source: Landsburg, Renton*
1800	2305	Approx. 74	Approx. 1.4	Phase 1	1,4
2800	3510	Approx. 42	Approx. 2.3	Phase 2	1,4
3720	4600	20	5		2,2
4200	5155	Approx. 15	Approx. 6.8	Phase 3	1,4
5000	6080	10	10	Phase 4	1,4
6580	7650	Approx. 4.1	Approx. 24	November 1995	3,3
7870	9390	Approx. 3.3	Approx. 30	January 2009	3,3
8340	9860	2	50	November 1909	2,2
10,300	12,000	1	100	November 1990	2,2

*Source of data in last column of table:

1. King County Flood Warning Phases
2. Federal Emergency Management Agency (2005)
3. USGS flow records
4. Watershed Sciences and Engineering 2013

The Masonry Dam has a primary purpose of water supply and power generation, so its flood control benefits are only opportunistic. However, the presence of this dam appears to have decreased flood peaks since 1914, as suggested by the four large flood events in the dozen years prior to 1914 and only one event of similar magnitude in the century since 1914 (Figure 7). The post-dam 2-year, 10-year, and 100-year recurrence intervals have been reduced by 47, 54, and 56 percent, respectively, relative to pre-dam conditions (Gendaszek et al. 2012). Water diversion or withdrawal for water supply and power generation may alter lower flows, but have little impact on flood peaks.

With a decrease in peak flows since 1914 and widespread increases in channel confinement due to bank armoring since the 1960s, less frequent and larger discharges remain within the riverbanks through much of the study area. A comparison of inundated width to bankfull channel width[1], averaged by reach for various flows, gives an indication of channel confinement (Figure 8; this is the "flood confinement ratio" of Perkins et al. 2002). A ratio of 1 indicates that the flow is entirely contained in the channel. The 5,000 cfs flow (annual 10 percent flood) is entirely contained in several reaches, and in some reaches a discharge of 10,300 cfs (annual 1 percent flood) is contained (Figure 8).

A decrease in the peak magnitude of large floods by necessity results in longer durations of moderate and lower flows than would occur in unaltered conditions, because the total volume of water that flows into the reservoir in a given flood event is unchanged but that water volume is released more slowly by the dam. Much of the longer-duration flows likely exceed the threshold at which sediment movement begins (approx. 2,000 cfs near Landsburg).

[1] Bankfull width was represented by the distance between bank stations identified at every cross section in the Cedar River HEC-RAS hydraulic model (WSE 2013). Bank stations in HEC-RAS mark the transition in hydraulic conditions from the channel to overbank areas and typically are located at or near the top of bank. Visual inspection of bank station locations at each cross section in the HEC-RAS hydraulic model indicated that this was an acceptably accurate representation of the bankfull location. Inundated width, provided directly by the HEC-RAS model at each cross section, includes the full width of the channel and floodplain that is equal to or lower than the water surface elevation of interest, and as such, may overstate the width of floodplain that is inundated by continuous overbank flow.

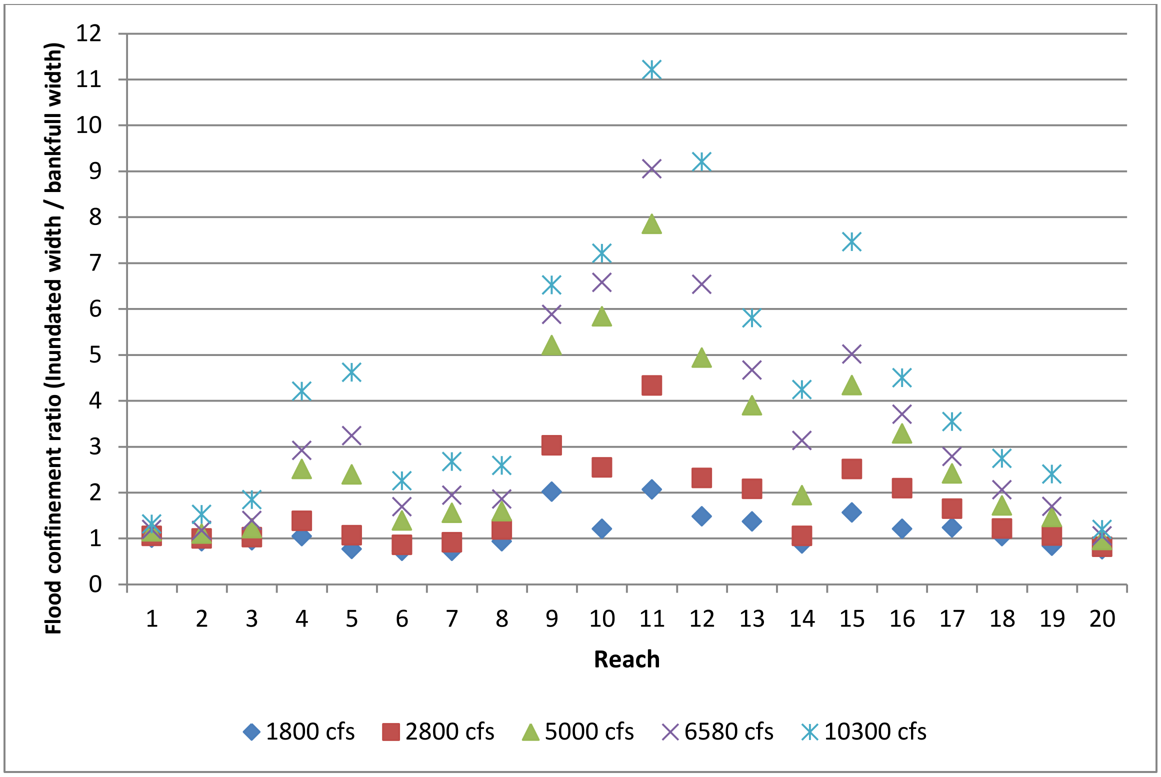

Figure 8. Cedar River flood confinement ratio, by reach, at various flow events.

2.5 Large wood

The presence of large wood has the potential to increase water surface elevations through vertical changes in the elevation of the river bed resulting from sediment deposition upstream of large wood accumulations. The increase in water surface elevation caused by large wood can increase the frequency and extent that flood flows access adjacent floodplain areas, and consequently have an influence on the likelihood of avulsion and channel migration (Brummer et al. 2006). The presence of large wood accumulations is relevant to mapping Cedar River channel migration by avulsion because this study evaluates the frequency and depth of inundation in low lying areas as a criterion for mapping avulsion hazards under current conditions. The management of riparian forests to allow more and larger trees means that the volume of large wood in rivers is likely to increase through the 100-year timeframe relevant to CMZ mapping. See also Section 4.4 for more discussion of the effect of large wood on channel migration.

A study in progress by King County at the time of writing is evaluating the presence and distribution of large wood in the Cedar River (K. Akyuz, pers. comm. 2014). Preliminary data from the study indicate that there were an estimated 11,500 total pieces of large wood on the Cedar River in 2010, and the vast majority of the pieces of wood were categorized as small logs and branches. There were 145 key pieces (wood pieces large enough to act as key member in the formation of a log jam) at an average of 6.5 per river mile. Higher densities of total wood counted and key pieces occurred in unconfined reaches than in confined reaches. These values for large wood metrics on the Cedar River are low relative to large wood in natural conditions on other Pacific Northwest river channels (Fox and Bolton 2007). The potential effect of large wood accumulations on channel migration is discussed in Section 4.4.

3.0 METHODS

Channel migration on the Cedar River was evaluated and mapped using information from existing studies, field observations, and analyses conducted in GIS Esri ArcMap 10.0.

Information from several existing studies of the geology, geomorphology, hydrology, hydraulics, land use, and other factors relevant to Cedar River channel migration forms the foundation of this study. These studies include Cedar River Current and Future Conditions Report (King County 1993), Geologic map of Maple Valley (Booth 1995), Cedar River gravel study (Perkins et al. 2002), Cedar River Flood Insurance Study (Federal Emergency Management Agency 2005) and associated hydraulic model (Harper, Houf, Righellis 2002), historical river channel data for the Cedar River (Collins et al. 2003), and an article titled "Geomorphic response to flow regulation and channel and floodplain alterations in the gravel-bedded Cedar River, Washington, USA" by Gendaszek et al. (2012).

The river channel and other parts of the study area were accessed by raft or on foot. Field observations were made of river bed and bank materials, evidence of erosion, location and condition of bank armoring, general channel pattern, and the presence and nature of hydraulic or geomorphic controls. Channel substrate data were not collected because they are available from Perkins et al. (2002) and Gendaszek et al. (2012).

Historical and current channel locations were documented in GIS from historical information described in Section 3.1. Lateral channel migration rates and the potential for abrupt channel shifting by avulsion were evaluated in GIS, as described in Section 4.3. In Section 5.2, calculated channel migration rates and mapped avulsion potential were used in combination with information from field observations and other relevant resources, such as hydraulic models, geologic maps, and other geomorphic studies, to map channel migration hazards throughout the study area.

3.1 Historical and current information used in report

Historical channel locations were digitized in GIS at a scale of 1:1,000 by Collins et al. (2003) from orthorectified aerial photos dated 1936 through 2000 (Table 2). The digitization process included mapping the active channel for each photo year as the composite of low flow channel, bare gravel bars, and vegetated patches on alluvial surfaces (Collins et al. 2003; O'Connor et al. 2003). King County digitized historical channel locations for 2005 and 2011 using the same methods as Collins et al. (2003).

The horizontal accuracy of the digitized historical channel locations is estimated to be within 25 to 40 feet of actual location (Collins et al. 2003). There are two main sources of inaccuracy: the orthorectification process and the digitization process. Channel locations digitized from 1944 and 1985 were not used in this analysis because of inaccuracies exceeding 60 feet. The high level of inaccuracy in 1944 and 1985 resulted mainly from poor image quality in those two years.

Digital aerial photos and LiDAR coverage from 2013 also are available for the study area. Because there were relatively minor flood events and negligible channel changes between 2011 and 2013, the 2013 channel was not digitized and the 2011 channel is taken to represent present-day conditions for this analysis. LiDAR imagery from 2011 was consulted for this study.

Table 2. Aerial orthophotos used or consulted in this report.

Year	Scale	Estimated Horizontal Accuracy†	Source
1936	1:10,500	10.3 meters (33.8 ft)	King County
1948	1:21,000	16.3 meters (53.5 ft)	King County Conservation District/USDA-NRCS
1959	1: 7,800	5.9‡ meters (19.4 ft)	King County
1964	1:21,000	9.0 meters (29.5 ft)	King County Conservation District/USDA-NRCS
1970	1:12,000	5.0 meters (16.4 ft)	King County
1980	1:58,000	10.0 meters (32.8 ft)	University of Washington Libraries
1989	1:13,500	7.2 meters (23.6 ft)	King County
1995	1:12,000	6.0 meters (19.7 ft)	University of Washington Libraries
2000	2 ft pixel	4.0 meters (13.1 ft)	King County
2005	1 ft pixel	2.0 meters (6.6 ft)	King County
2011	1:1,200	0.3 meters (1.0 ft)	King County
2013	0.5 ft pixel	0.1 meters (0.3 ft)	King County

† National Standard for Spatial Data Accuracy (NSSDA) 95% statistic indicates the horizontal distance over which the user can be confident that the horizontal position of a feature on the image will be within its true location 95% of the time (Collins et al. 2003).
‡ Photo set does not encompass entire study area and contained 10 of 20 field-verifiable locations that the NSSDA 95% statistic requires. Of those 10, horizontal accuracy is 5.9 m (Collins et al. 2003).

A circa 1920 USGS topographic map also was consulted but not used quantitatively due to its small scale (1:125,000).

Historical plat maps surveyed by the General Land Office (GLO) between 1865 and 1880 were reviewed but were not included quantitatively in this analysis because of inherent inaccuracies, as described by Collins et al. (2003). Further, operation of Masonry Dam and associated waterworks since 1914 (described in Section 2.4) has reduced the size of major flood flows; these reduced flows have resulted in long-term alteration of channel conditions throughout the Cedar River (Perkins 1994). With such systemic changes after 1914, the channel locations and conditions shown in the circa 1865 GLO maps are not directly applicable to an analysis of present-day channel migration hazard.

3.2 Channel Migration Zone Components

Channel migration hazards in the Cedar River were mapped by identifying the component parts of a CMZ, as specified by King County (2014) and consistent with Ecology (1994-2014). CMZ components are described in the equation below and illustrated schematically in Figure 9.

CMZ = HMZ + AHZ + EHA – DMA
where
HMZ = Historical Migration Zone
AHZ = Avulsion Hazard Zone
EHA = Erosion Hazard Area. = Erosion Setback (ES) + Geotechnical Setback (GS)
DMA = Disconnected Migration Area

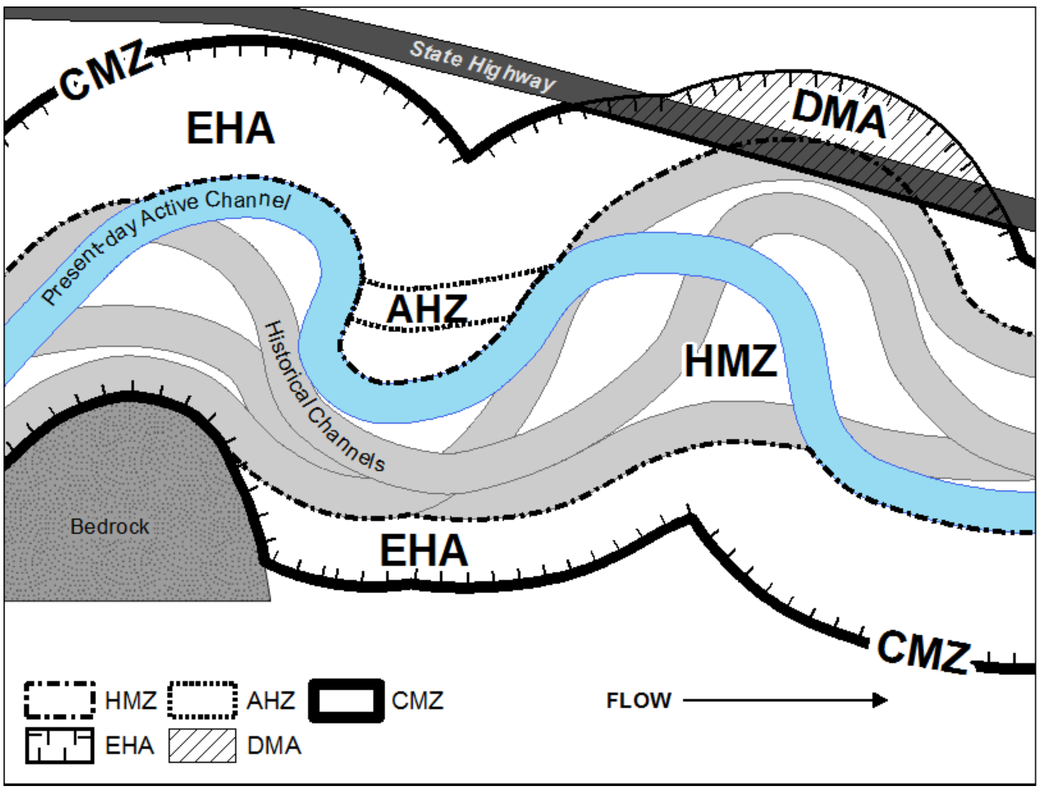

Figure 9. Plan view schematic of Channel Migration Zone (CMZ) components. Modified from Rapp and Abbe (2003).

Each CMZ component is defined and its mapping methods are described in Section 3.3.

3.3 Mapping criteria and methods

This section defines each CMZ component and hazard area and describes mapping criteria and methods. As described in Section 3.2, the combination of the following components constitutes the CMZ: CMZ = HMZ + AHZ + EHA – DMA.

Once the CMZ was delineated, severe and moderate hazard areas were identified within it so as to recognize that channel migration hazard is not equal throughout the CMZ. In general, any part of the CMZ that is not mapped as a severe hazard area is mapped as a moderate hazard area. The criteria by which parts of the CMZ components are mapped as a severe or moderate hazard area are included with the description of each CMZ component.

3.3.1 Historical Migration Zone

The Historical Migration Zone (HMZ) is the portion of a CMZ study area that the channel has occupied during the historical record (King County 2014). The HMZ is mapped as a composite footprint of historical active channel locations from 1936 to 2011, as listed in Table 2. The HMZ typically is a fundamental component of the CMZ.

The entire HMZ was mapped as severe hazard area.

3.3.2 Avulsion Hazard Zone

The Avulsion Hazard Zone (AHZ) is the area outside of the HMZ that is subject to avulsion hazard (King County 2014). To map the AHZ, low-lying areas were identified from the 5,000 cfs (annual 10 percent flood) inundation map. Low-lying areas inundated by 5,000 cfs that occupy a shorter distance in the down-valley direction than the adjacent mainstem channel were evaluated in the field. Other pertinent information was considered in evaluating avulsion hazard, such as whether there was a history of avulsions in the immediate area or if there were discernable trends in the accumulation of wood or sediment in the main channel near the potential avulsion site.

Potential avulsion pathways were included in the AHZ if they met all four of the following criteria (King County 2014):

1. Low-lying ground or channel that is equal to or lower than the water surface elevation of frequent flooding in the current main channel.
2. The length of the potential avulsion pathway follows a shorter distance (and steeper gradient) than the main channel.
3. The substrate in the banks and bed or floodplain of the potential avulsion pathway is erodible material.
4. The potential avulsion pathway is a likely avulsion route based on consideration of Quaternary history, avulsion history in the basin, flow regulation, channel alteration, sediment trends, and large woody debris loading.

An Avulsion Hazard Zone was mapped as a severe hazard area if it met any of the following criteria:

1. Potential avulsion pathways have little or no vegetation, or show evidence of fresh scour, channel widening or oversteepening, consistent with erosion from recent flood events, or
2. Potential avulsion pathways have a direct low-elevation surface connection to the main channel such that it is flooded deeply and frequently (which may be indicated by surface flow through the pathway even during periods of low river flow), or
3. Indicators of avulsion hazard regarding accumulation of sediment or large wood in the main channel, or changes to main channel meander geometry, exist in close proximity to a potential avulsion pathway.

Severe AHZs were mapped as wide as the 2011 average Active Channel of the reach in which the avulsion pathway is located. The AHZ typically was centered along the centerline of avulsion pathway unless site-specific conditions such as variability of substrate indicated it was appropriate to map the AHZ otherwise.

An AHZ that did not meet any of the three criteria listed above for the severe hazard AHZ was mapped as a moderate hazard AHZ. As with a severe AHZ, a moderate AHZ was mapped to a width equal to the average Active Channel width of the present river channel reach in which the avulsion pathway is located and along the centerline of the avulsion pathway unless conditions indicated otherwise.

Where an artificial structure such as a levee blocks a potential avulsion pathway that otherwise meets the criteria to be mapped as an AHZ except for the blockage, that pathway was mapped as an AHZ if the top elevation of the blocking structure is lower than the water surface elevation of the 1 percent annual chance flood and the blocking structure is not likely to restrain channel migration. The AHZ behind the blockage was mapped as a severe hazard area if the severe hazard mapping criteria, listed above, were met, or it was mapped as a moderate hazard area if the criteria were not met.

3.3.3 Erosion Hazard Area/Erosion Setback

The Erosion Setback is that part of the EHA within the CMZ that is susceptible to lateral channel migration due to stream or river erosion (King County 2014). The width of the Erosion Setback (referred to as EHA/ES) was calculated as a lateral channel migration rate times a given time period.

To calculate lateral channel migration rates, channel centerlines were digitized along the mid-line of the active channel in each year of aerial photos and lateral channel migration distances were measured between channel centerlines in sequential aerial photos (Table 2). These distances between channel centerlines were measured along transects spaced 400 feet apart, down-valley, and oriented perpendicular to the centerline of the Historical Migration Zone.

Average annual lateral channel migration rates were calculated as the lateral migration distance measured between sequential aerial photos divided by the time elapsed between the photos. The rate used in this study is the time-weighted average of the absolute value of the migration distance measurements described above. Using the absolute value calculates channel migration as if it occurred in one direction between every pair of photos.

Channel migration was measured at sites where channel migration occurred as channel expansion. The channel expansion distance was calculated as the difference in active channel widths as measured at HMZ transects in sequential aerial photos. That distance was divided by 2 to indicate the extent of expansion that had occurred on each side of the active channel in the first photo. The resulting distance was divided by the number of years between aerial photos to calculate the migration rate at that location.

Channel migration rates were calculated for each reach using aerial photos from between 1964 and 2011 and for Reach 1 through Reach 11 using aerial photos from between 1936 and 2011 (Table 2). Migration rates between 1936 and 1964 could not be calculated upstream of Reach 11 either because of a lack of photo coverage or the inferior accuracy of existing photos. Collins et al. (2003) describe lesser accuracy of photo orthorectification in these earlier photos resulting from fewer observable landmarks in the eastern portions of the study area.

Channel migration rates were calculated in two ways: first, rates were calculated using all measurements taken, and second, rates were calculated using only those measurements where erosion occurred. For erosion to have occurred, not only must there be a movement of the channel centerline at an HMZ transect, but the channel edge in a given photo-year must have moved outside the channel edge of the previous photo-year. This measurement method captured lateral channel migration and channel expansion but excluded channel contraction and locations of no erosion. If the channel remained entirely within the boundaries of the channel from the previous aerial photo, no erosion was assumed to have occurred even if the channel centerline had moved.

3.3.3.1 Erosion Hazard Area/Erosion Setback applied to the Historical Migration Zone or to the Active Channel

The width of the Erosion Setback was calculated using the eroding-only channel migration rates. For each reach, the width of the EHA/ES for lateral migration in Holocene valley-bottom alluvium was calculated as the greater of the following two distances (Figure 10).

1. 50 years of lateral migration times the channel migration rate, applied to each side of the HMZ, or
2. 100 years of lateral migration times the channel migration rate, applied to each side of the most recent active channel (2011).

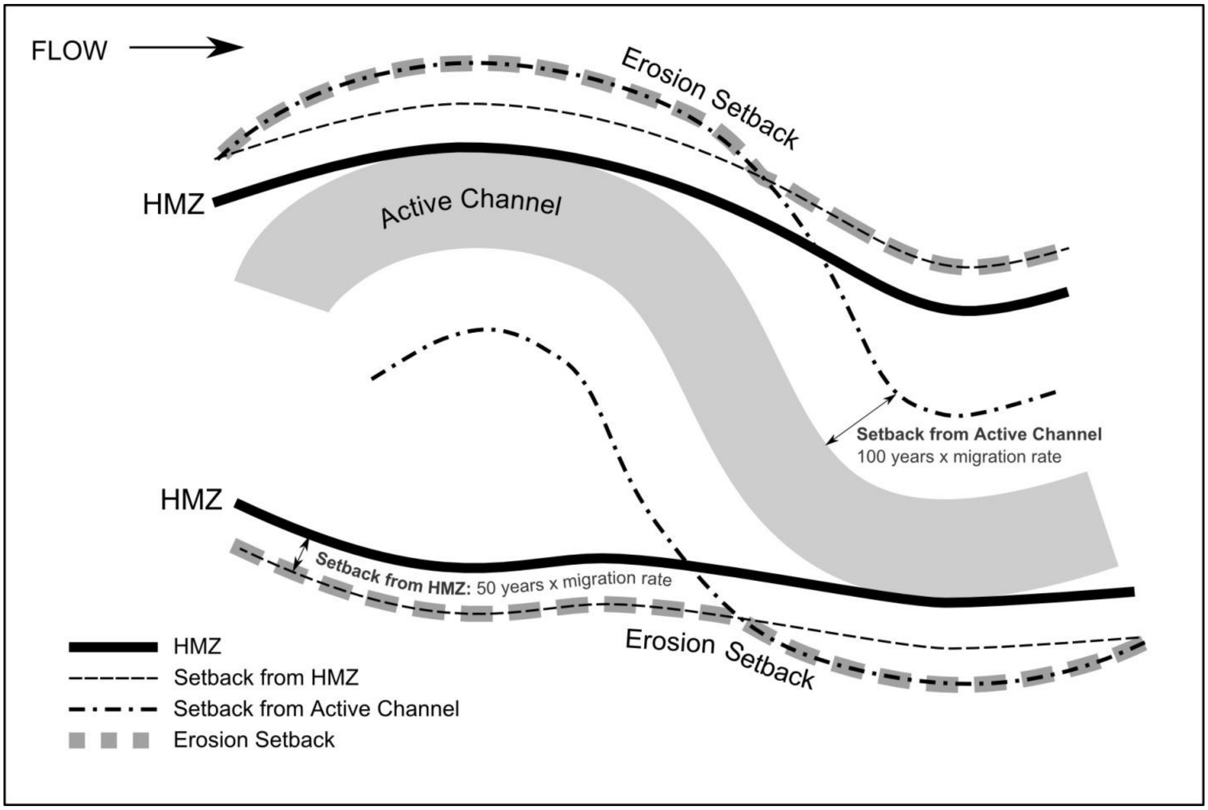

Figure 10. Plan view schematic of the Erosion Hazard Area/Erosion Setback.

The EHA/ES can be further broken down into moderate and severe hazard areas. The width of the severe hazard area within the Erosion Setback was delineated as the greater of the following two distances.

1. 25 years times the representative channel migration rate of this reach applied to each side of the HMZ, or
2. 50 years times the representative channel migration rate of this reach applied to each side of the most recent active channel (2011).

The area that lies between the severe channel migration hazard area and the outer edge of the Erosion Setback was mapped as moderate hazard area.

Where historical channel locations indicated that there was a measureable, consistent down-valley component to lateral channel migration, the EHA/ES was adjusted based on down-valley migration rates measured at the affected sites.

Erosion-resistant landforms that the EHA/ES intersected included tall bluffs composed of the Pre-Frasier glacial formation and Vashon-age glacial drift at several locations in the study area (Map 2, Appendix A). In these locations, the width of the portion of the EHA/ES within the more-resistant landform was calculated using an appropriately lower channel migration rate. The lower channel migration rate was based on lateral retreat rates observed in the same or similar tall bluffs that the active channel encountered and during that part of the historical record of the study during which the active channel eroded that landform. The resulting EHA/ES width is likely to be narrower than it would be in Holocene alluvium in the same river reach (Figure 11).

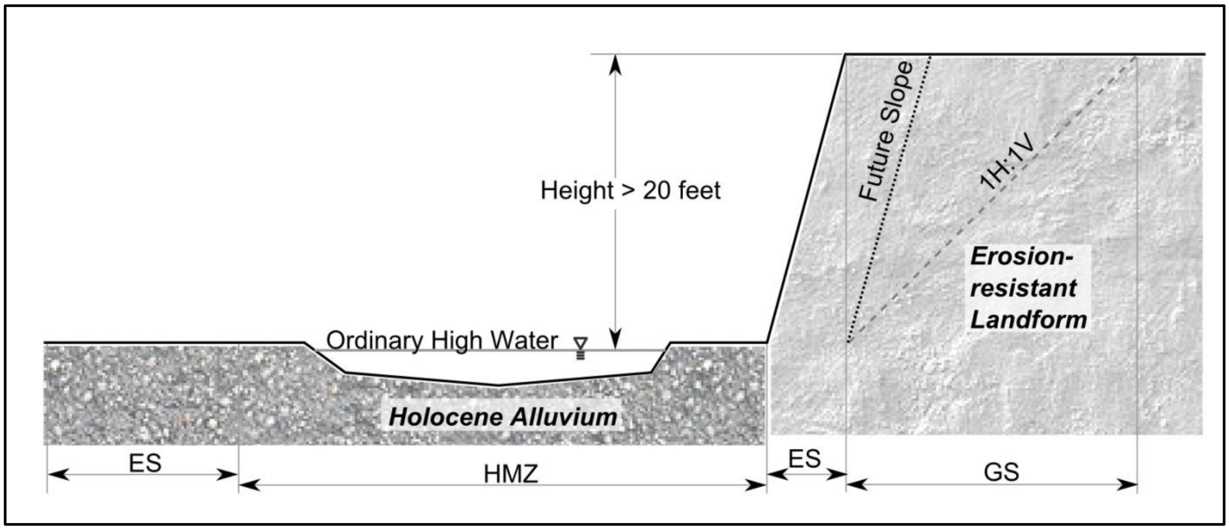

Figure 11. Cross-section schematic of Erosion Hazard Area/Geotechnical Setback.

3.3.3.2 Erosion Hazard Area/Erosion Setback applied to Avulsion Hazard Zone

Once an avulsion occurs, lateral migration is assumed to proceed from the new channel location. The width of that lateral migration is calculated as an EHA/ES added to the AHZ. An EHA/ES applied to either a severe AHZ or moderate AHZ was mapped as a moderate hazard area. The widths of this EHA/ES applied to an AHZ may vary as follows:

1. Erosion Hazard Area/Erosion Setback applied to a severe AHZ: This Erosion Setback distance was added to each side of a severe AHZ to a width equal to a range of 25 years to 50 years times the representative channel migration rate for that study reach. The number of years is based on the extent to which AHZ mapping criteria in Section 3.3.2 were met.
2. Erosion Hazard Area/Erosion Setback applied to a moderate AHZ: This Erosion Setback distance was added to each side of a moderate AHZ to a width equal to 25 years times the representative channel migration rate for that the study reach.

3.3.4 Erosion Hazard Area/Geotechnical Setback

Where the outer edge of the EHA/ES encountered an erodible land surface that is greater than 20 feet in height above Ordinary High Water, a Geotechnical Setback, referred to as EHA/GS, was applied to the outer edge of the EHA/ES (King County 2014). The EHA/GS was delineated at a 1H:1V slope measured from the predicted toe of slope after applying the EHA/ES (Figure 11). No EHA/GS or EHA/ES was applied to sound bedrock showing no signs of erosion.

The entire EHA/GS was mapped as moderate hazard.

3.3.5 Disconnected Migration Area

A Disconnected Migration Area (DMA) is the area located landward of an artificial structure that is likely to restrain channel migration and that meets criteria in Washington Administrative Code 173-26-221(3)(b) and King County (2014). In other words, the DMA is an area that would be subject to channel migration were it not for the presence of the artificial structure.

Areas landward of the legally existing, publicly maintained artificial structures (e.g., revetments, levees) that met the following criteria were mapped as a DMA:

1. Within incorporated areas and urban growth areas, an artificial structure that limits channel migration.
2. In all areas, an artificial structure that is likely to restrain channel migration and is built above the one hundred-year (100-year) flood elevation.
3. State highways and sole-access major county roads.
4. Legally existing active railroads.

An artificial structure was considered likely to restrain channel migration if its construction, condition, and configuration are consistent with current relevant design and construction standards and if the present channel is unlikely to migrate landward of the structure (King County 2014). Levees and revetments maintained by King County within unincorporated King County were evaluated for their likelihood to restrain channel migration. Information on construction date and methods, damage, and repair history was consulted from King County files. Available project repair design plans were reviewed regarding construction standards. Levees and revetments maintained by King County or the City of Renton within the City of Renton were evaluated as to the structure's ability to limit channel migration.

Whether an artificial structure was built above the elevation of the 10,300 cfs discharge (annual 1 percent flood[2]) was determined from the hydraulic model prepared for the Cedar River flood study (Harper, Houf, Righellis, Inc. 2002) and inundation maps based on the flood study hydraulic model (Watershed Science and Engineering 2013). Relevant empirical evidence also was considered regarding structure elevations relative to the water surface elevation of the 10,300 cfs discharge.

If an artificial structure did not meet all criteria necessary to map a DMA, then the severe and moderate hazard area delineations were not revised. This approach was taken so as recognize the channel migration hazard landward of that structure.

[2] Referred to as the 100-year flood in relevant WAC and KCC sections cited above.

4.0 CHARACTERISTICS OF CHANNEL MIGRATION IN THE STUDY AREA

4.1 Channel migration processes

Channel migration occurs by three processes in the Cedar River study area: lateral migration, channel expansion, and avulsion. Lateral channel migration occurs as a combination of bank erosion along one riverbank coupled with sediment deposition along the opposite bank. The result is a progressive net movement, or migration, of the channel across the valley bottom. A comparison of the 1964 and 2011 channel locations near RM 15.5 on the Cedar River illustrates lateral migration (Figure 12). There also may be a down-valley component to the lateral migration. Through time, the down-valley component would result in an area downstream and between river meanders being affected by channel migration, not just an area laterally landward from the channel. Lateral migration is the main type of channel migration affecting the Cedar River in the study area.

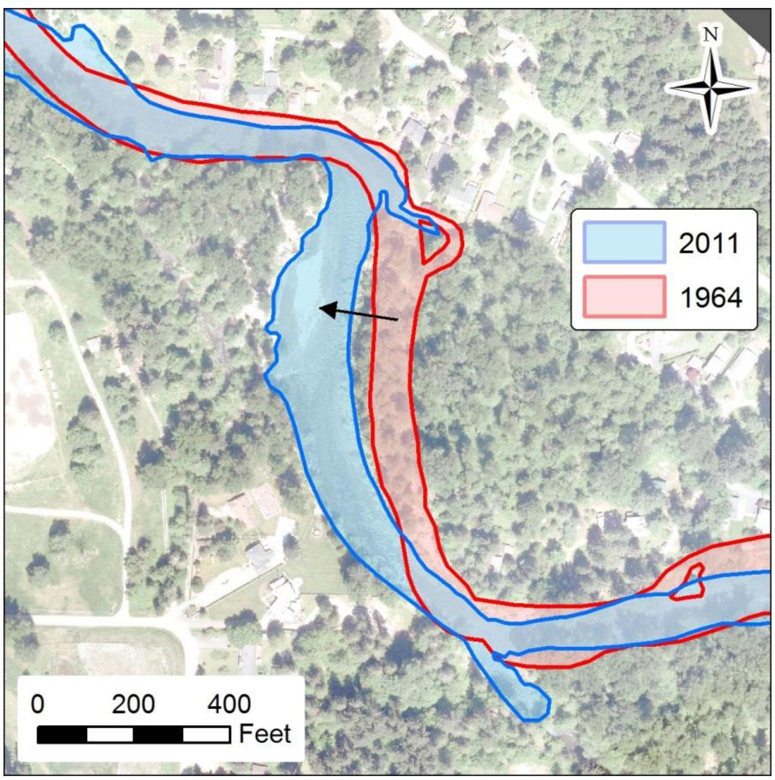

Figure 12. Example of lateral migation on the Cedar River near RM 15.5.

Channel expansion is a widening of the channel, which manifests as an increase of the channel width toward both riverbanks. Conditions that cause this type of channel migration include an increase in sediment influx or the eroding effects of a large flood flow. Channel expansion also can result from channel incision if the lowering of the riverbed undercuts and destabilizes the riverbanks (Simon 1989). Channel expansion on the Cedar River occurred near RM 5 after a 2001 landslide from the right (north) bank deposited a large volume of sediment directly in the river channel (Figure 13).

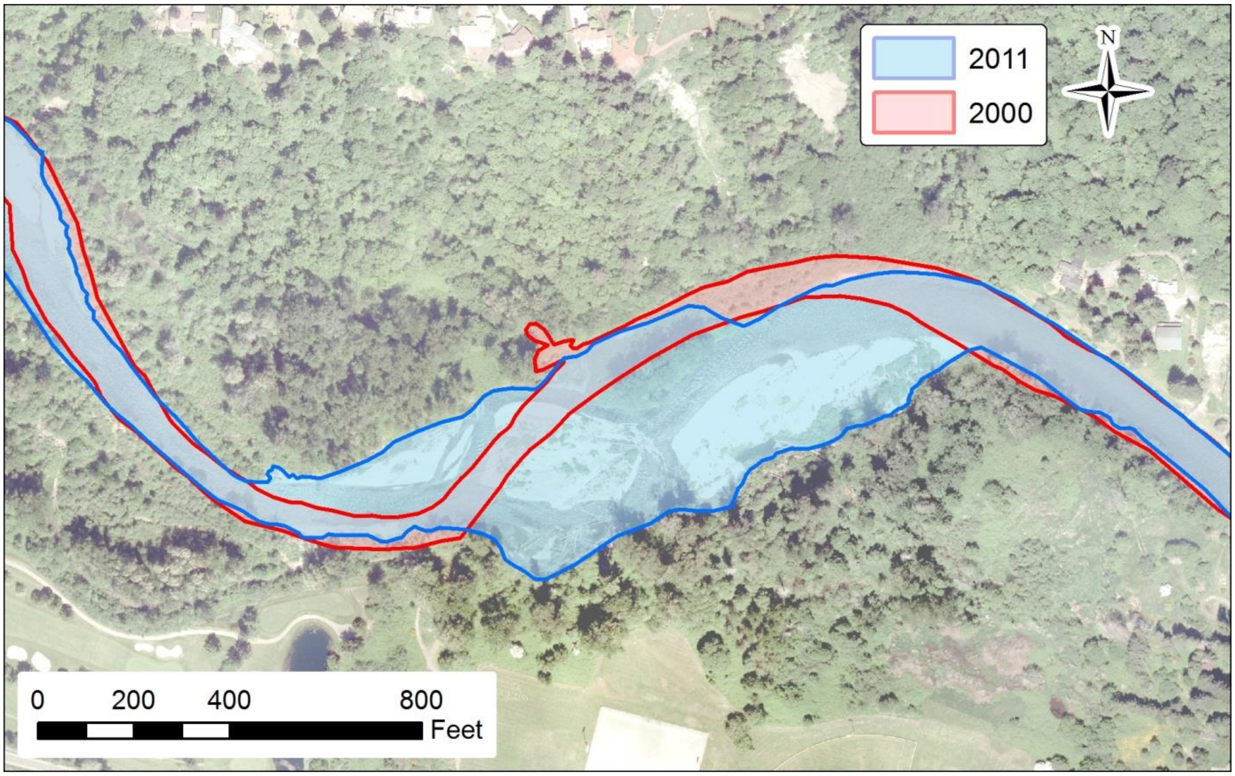

Figure 13. Example of channel expansion on the Cedar River at RM 5.

In a channel migration process called an avulsion, the channel shifts abruptly to a different location without laterally eroding through the land between the two channel locations. The channel may shift by avulsion rapidly, such as during a single flood event. Avulsions also may occur more gradually, as the majority of flow shifts from one channel to another. Avulsions may be triggered by the onset of unpredictable conditions such as a landside or log jam. Though avulsion triggers may be unpredictable, certain conditions favor the occurrence of avulsions, as described in Section 3.3.2. Avulsions have occurred in the Cedar River, for example, near RM 10.5 where the split flow conditions in 1989 shifted to a single channel in 1995 without eroding the forested island between channel locations (Figure 14). Conditions that favor avulsion (Section 3.3.2) exist within the study area.

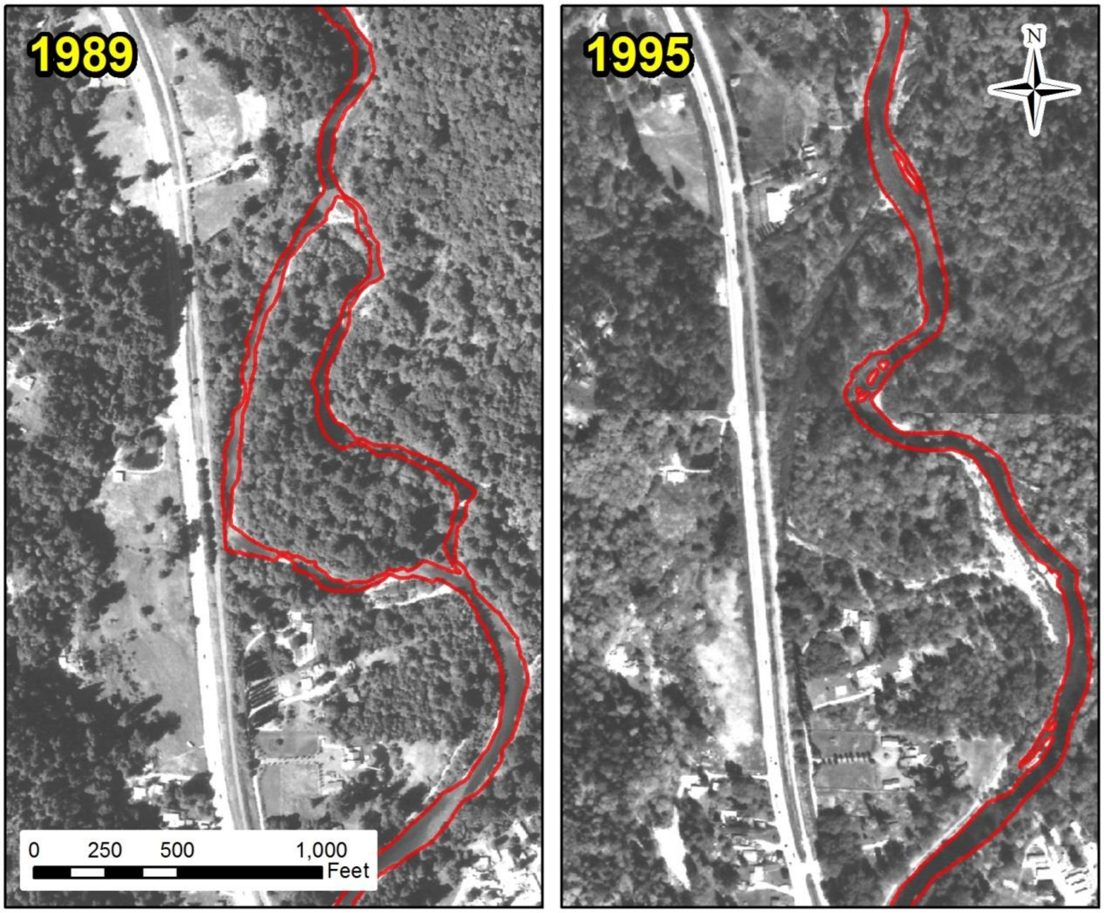

Figure 14. Example of avulsion on the Cedar River near RM 10.5.

Comparison of channel locations evident in historical maps and aerial photos reveals the location, type, and extent of past channel migration. Information about past channel migration is used to predict future channel migration and map channel migration hazard areas. Comparison of channel locations in sequential aerial photos in a GIS format informs the evaluation of lateral channel migration, channel expansion and avulsion, as does the compilation of all digitized historical channel locations. The composite map of historic channel locations becomes the HMZ shown in Map 3, Appendix A.

Water surface elevations of selected flows in the mainstem channel were compared to the topographic elevations of adjacent valley-bottom surfaces and secondary channels using existing Cedar River hydraulic model results (Harper, Houf, Righellis, Inc. 2002 and Watershed Sciences and Engineering 2013) and LiDAR digital surfaces. The elevation difference between the water surface at 5,000 cfs (annual 10 percent chance flood) and the valley-bottom surface topography is shown in Map 4, Appendix A. Map 4 is equivalent to a "Height Above Water Surface" map produced by Jones (2006) except that Map 4 shows color only in the areas of the valley bottom that are below the 5,000 cfs water surface elevation, not above it. A 5,000 cfs flood is equivalent to a Phase 4 event in King County flood warning phase system (Table 1). The 5,000 cfs flood event was selected for Map 4 because it is a relatively frequent flood that may access low-lying areas of the valley bottom and so is relevant to mapping avulsion hazard. Map 4 is not an inundation map because it does include consideration of the hydraulic connectivity of the colored valley-bottom areas to the main channel at a discharge of 5,000 cfs.

Dark blue in Map 4 indicates valley-bottom areas that are as much as 5 feet lower in elevation than the water surface at 5,000 cfs and yellow to green indicates valley-bottom areas that are as much as 1 foot lower in elevation than the water surface at 5,000 cfs. Along the river channel, this map illustrates the difference in elevation between the water surface at 5,000 cfs and the water surface at the time that LiDAR was flown. Therefore, the water depth within the channel is illustrated generally in Map 4 and does not represent specific localized conditions in the channel.

4.2 Morphology of the study reaches

A river reach is a length of channel that exhibits consistent physical conditions. River reaches in the study area were identified based primarily on channel gradient, channel confinement, channel pattern, and riverbank material. Channel sinuosity (ratio of channel length to valley length), confluence with tributaries, and the presence of infrastructure were considered secondarily.

Twenty reaches were identified, numbered in upstream direction through the study area; many of the reaches correspond closely to the river segments used by Perkins et al. (2002). Reach characteristics are summarized in Table 3 and described below in the downstream direction.

The State Department of Ecology defines channel confinement based on the ratio of active channel width to valley bottom width. A ratio of less than 2 is confined; a ratio of greater than 4 is unconfined; and a ratio between 2 and 4 is moderately confined (Ecology 1994-2014). The only place where the ratio is less than 4 on the Cedar River in this study area is at Landsburg Bridge and a few hundred feet downstream. In this report, the term confinement does not refer to the active channel/valley bottom ratio defined by Ecology, but is used to generally describe the relative level of constraint placed on the channel by the proximity of the valley walls, terraces, or constructed features.

Channel patterns are described in the study reach as two types. A single-channel pattern, or single channel, conveys flow up to and including bankfull flow entirely in one main channel. A multi-channel pattern, or multiple-channel pattern, consists of more than one channel separated by islands that may be stable and vegetated. An anabranching channel (see footnote 3) is an example of multi-channel pattern.

Reaches 20 through 18 are among the steepest in the study area, with channel gradients ranging from 0.67 to 0.55 percent. The single channel in these reaches generally is confined and often in contact with high banks or bluffs. Channel substrate is a coarse gravel/cobble/

boulder mix. With most gravel influx being routed through these reaches (Section 3.2.3), gravel bars are infrequent and narrow.

The river in Reach 17 is single channel with a 0.62 percent gradient and increasing channel width in the downstream direction. This reach has erosion-resistant banks at its upstream end and a right bank composed of colluvium along its downstream end. Coarse channel substrate, some of which appears to have come from a right bank landslide, is evident in the mid-channel bar just upstream of the CRT Bridge at the downstream end of Reach 17 (RM 17.6).

Reaches 16 and 15 have a single channel, a widening floodplain and decreasing channel gradient (ranging from 42 to 60 percent). Bank materials alternate between continuous lengths of armoring and unarmored alluvium. Bare gravel bars suggest increased in-channel sediment deposition. Side channels or floodplain channels are present across the interior of every meander bend in Reach 15.

The river in Reaches 14 and 13, between the SR 18 (RM15.3) and SR 169 (RM 14.1) bridges, is a single, relatively straight channel. Alluvial banks are armored in much of Reach 14 or confined by bridge abutments. The channel in Reach 13 runs contiguous to an erosion-resistant bluff and the alluvial fan of Peterson Creek along its left (west) bank. In March 2014, a relatively small landslide from the left bank bluff briefly blocked the mainstem channel in the Royal Arch neighborhood area at approximate RM 14.5, but the channel quickly incised through the landslide debris and remained in the same location.

In Reach 12, the single channel is bounded by SR169 and CRT bridge abutments at its upstream end and bank armoring at every outside bend as well as some interior bends. Landward and between bank armoring segments, floodplain channels show bare gravel or surface water, or both, evidence of frequent flow. Taylor Creek and associated floodplain channels flow and coalesce behind the Getchman levee before joining the river just upstream of Jan Road levee (RM 13.4). Unarmored alluvial river banks exhibit active erosion along both left and right banks between revetments. The channel gradient in Reach 12 is 0.43 percent.

In Reach 11, the single channel is in contact with a right bank terrace and glacial bluffs through the entire reach. Ongoing bank erosion and channel migration into the terrace of old alluvium is evident in a very tight curve at the Rawson bend (RM 12.5). The channel flows along the right bank base of tall glacial bluffs from RM 12.1 to RM 11.8 (across from the Lions Club area).

In Reach 10, the single channel flows under Cedar Grove Bridge near its upstream end, curves along the Rainbow Bend levee removal site, and then flows in a straight line adjacent to the CRT for almost 2,000 feet. Even with the Rainbow Bend levee removal, the channel has armoring or abutments on at least one of its banks through almost 90 percent of this reach. The levee removal project excavated two floodplain channels that are readily accessed by flow from the main channel.

Table 3. Cedar River reach characteristics.

Reach	River Mile[€] D/S* end	U/S* end	Length (miles)	Average Gradient (%)[†]	Armored Length (%)[‡]	Channel pattern, river banks, geology, constraints**	General location - infrastructure, King County facilities, tributaries, etc.
1	0	1.633	1.6	0.18	100	Single channel, nearly straight, flat gradient.	Leveed channel within City of Renton
2	1.633	3.241	1.6	0.27	9	Single incised and confined channel, mild meanders. Narrow valley.	Along SR 169 U/S of I-405
3	3.241	4.57	1.3	0.35	47	Single channel, one meander; 1980s landslide on LB; armored spots on alluvial banks.	Maplewood subdivision on RB
4	4.57	5.135	0.6	0.43	53	Multiple channels; 2001 RB landslide.	Ron Regis Park area
5	5.135	6.435	1.3	0.34	60	Single channel, flatter gradient, mild meanders; armored spots on alluvial banks.	Elliott Bridge and lower Jones Road area
6	6.435	7.695	1.3	0.46	78	D/S part has single channel, mostly armored banks. U/S is multi-channel, unconfined.	Riverbend and Cedar Rapids area
7	7.695	9.39	1.7	0.44	64	Single channel, large meander; moderately confined by relatively high alluvial RB.	Upper Jones Road area
8	9.39	10.35	1.0	0.30	43	Single channel; narrow valley; bedrock walls.	Bedrock area
9	10.35	10.97	0.6	0.38	40	Multiple accessible channels. Valley narrows.	Belmondo area
10	10.97	11.69	0.7	0.36	81	Single channel; mostly armored alluvial bank, until 2013.	Cedar Grove; RB Rainbow Bend levee removed 2013
11	11.69	12.666	1.0	0.39	15	Single channel; RB old alluvium terrace, bluff.	Rawson curve to Lions Club area
12	12.666	14.05	1.4	0.43	69	Single channel; armored alluvial bends; side channels or creek landward of armoring.	Getchman, Rhode, Rutledge-Johnson Jan Rd facilities; Taylor Creek joins RB
13	14.05	14.757	0.7	0.46	30	Single channel; mild meander; tall LB bluffs, the site of 2014 landslide.	Royal Arch area
14	14.757	15.52	0.8	0.53	37	Relatively straight single channel; alluvial banks w/armor.	SR 169 and SR 18 Bridges
15	15.52	16.55	1.0	0.60	58	Single channel with accessible side channels; armored spots on alluvial banks.	Doris Creek, Dorre Don Road; Lower Don area
16	16.55	17.64	1.1	0.42	67	Single channel; armored lengths of alluvial banks; erosion resistant bends.	Upper Dorre Don area to Orchard Grove
17	17.64	18.37	0.7	0.62	0	Single channel; one meander along colluvial material on RB.	Isolated residential areas on both banks, upstream of Cedar River Trail
18	18.37	19.654	1.3	0.67	19	Single channel in tortuous bends; tall bluffs both banks are sediment sources.	Arcadia-Nobel area
19	19.654	21.02	1.4	0.55	13	Single channel; relatively straight; tall bluffs are sediment source.	Isolated residential areas on both banks
20	21.02	22.063	1.0	0.66	18	Steep single channel; glacial material banks.	Landsburg Bridge at U/S end of study

Table 3 footnotes:
€ River Miles with 3 decimal places are located at cross sections surveyed for the Cedar River Flood Insurance Study (FEMA 2005) and hydraulic model (Harper, Houf, Righellis (2002). River Miles with 2 decimal places are located between surveyed cross sections.
* D/S = downstream; U/S= upstream.
† Average gradient measured from the water surface elevation at the 1,800 cfs flow.
‡ Armored length is the channel length armored by King County or Renton flood protection facilities on either one or both banks. Total cannot exceed 100%.
** LB= left bank and RB = right bank when viewed downstream.

The river in Reach 9 is a single channel with a valley bottom that narrows in downstream direction. The channel has shifted by avulsion and also eroded the alluvial floodplain by lateral migration. Channel migration is active in Reach 9. The downstream end of Reach 9 and upstream part of Reach 8 are referred to as the Belmondo area.

The river in the upstream part of Reach 8 has a multi-channel pattern, with a left bank side channel that is actively connected to the mainstem throughout the year. Mid-channel gravel bars downstream of a circa 2009, relatively small right bank landslide split the mainstem channel into multiple flow paths. The valley bottom continues to narrow going downstream through Reach 8, with bedrock walls on outside bends. The downstream end of Reach 8 is at upper Jones Road Bridge.

In Reach 7, the floodplain broadens as the channel exits the area of bedrock walls. The single channel remains moderately confined as it flows through the largest amplitude meander bend of the study area and is bounded by a high right bank alluvial surface. More than half of the downstream part of this reach has armored banks. The unarmored alluvial banks show active erosion.

In the upstream 1,200 feet of Reach 6, the river has a multi-channel pattern that is wide and unconfined, with active bare gravel bars and recently shifting channel locations along the Cedar Rapids levee setback project. This part of Reach 6 exhibited dynamic channel migration from 2009 to 2011. Through almost all of the remainder of Reach 6, the river flows in a single channel and is armored on one or both banks.

The river in Reach 5 flows in a single channel through more than a mile of low-amplitude meanders that are armored on most outside bends. Alluvial banks show erosion between armored bends. Channel gradient decreases to 0.34 percent.

Reach 4 is the site of a 2001 landslide from the right bank that blocked the main channel and induced its rerouting. Similar slide activity and channel responses are evident in historical aerial photos. Episodic infusion of sediment over several decades causes this reach to have a multi-channel pattern and an average active channel width about four times that along most other parts of the river. Although most of the 2001 slide material appears to have been evacuated by channel erosion, channel expansion has occurred since 2001 and adjustments are ongoing in this unconfined reach.

In Reach 3, the river flows in a single channel under SR 169/CRT bridges and around one relatively large-amplitude meander bend. Left bank substrate is composed of discontinuous bank armoring, colluvial material (at the site of a 1980s landslide), and a short stretch of bedrock. Between the non-alluvial left bank substrate and a right bank subdivision, the channel is confined and relatively narrow in this reach. The channel begins to exhibit incised conditions in the downstream 1,000 feet of Reach 3.

Through Reach 2, the river flows in a single channel through low-amplitude meanders as gradient drops to less than 0.3 percent. The narrowing valley bottom and SR 169 confine the channel in place. The channel is incised through Reach 2.

The Cedar River in Reach 1 flows under I-405 at RM 1.63 and between continuous levees on both river banks through the center of Renton to the mouth. Channel gradient is less than 0.2 percent. Channel substrate is gravel through most of this reach and transitions to sand near the river mouth.

Sinuosity, S, was calculated as the ratio of active channel centerline length to valley bottom centerline length, for each reach in each photo-year from 1936 to 2011 (Figure 15). Channels are considered sinuous with S values less than 1.5 and meandering with S values greater than 1.5 (Leopold et al. 1964). A sinuosity of 1.0 indicates a straight channel, and examples of straight-channel sinuosity are the channelized Reach 1 within the City of Renton and the very straight Reach 20. The largest S values are for Reaches 3, 12 and 17, which all approach or equal the meandering category (S=1.5). These larger S values result from one or a few meander wavelengths occupying a relatively short valley distance. The majority of study reaches are in the sinuous category and their sinuosity has not varied greatly through time. Increases in the calculated sinuosity in some reaches may result from a narrowing of the active channel with an associated minor increase in active channel centerline length.

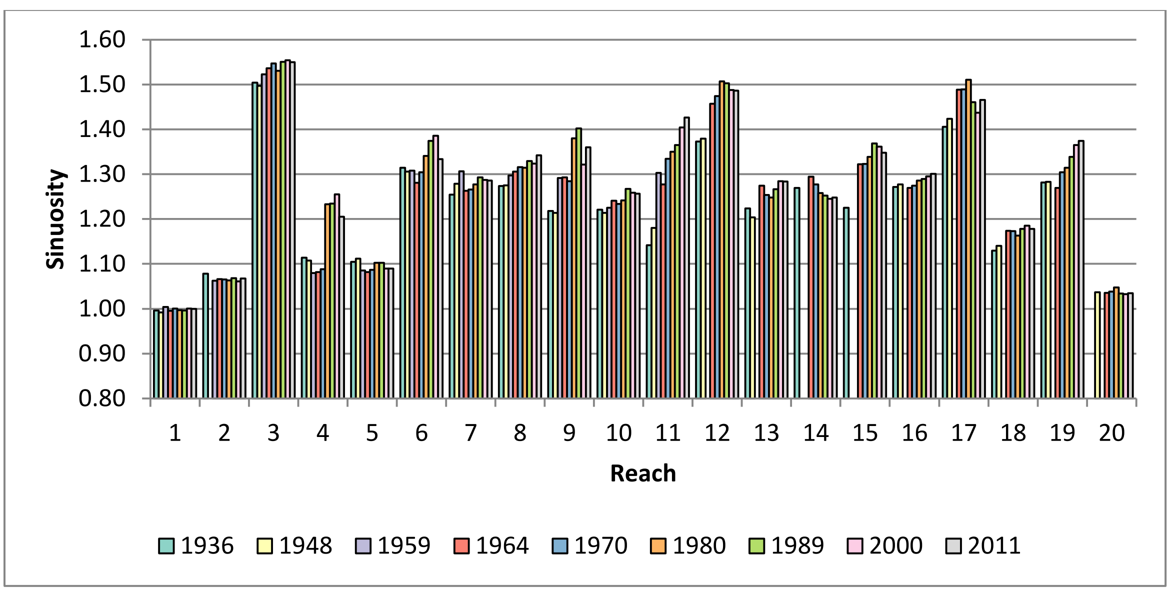

Figure 15. Channel sinuosity by reach.

4.3 Lateral channel migration rates

As noted in Section 3.3.3, lateral channel migration rates were calculated as the distance between channel locations in successive aerial photos divided by the time between photos. Channel migration rates were calculated throughout each reach for time intervals between successive aerial photos from 1936 to 2011 (Table 2) in two ways: using all measurements and using eroding-only measurements. Channel migration rates calculated throughout each reach are summarized for all measurements in Table 4 and for eroding-only measurements in Table 5. The last two columns of each table report a time-weighted average value of migration rates for 1936 to 1964 and for 1964 to 2011.

Table 4. Cedar River channel migration rates using all measurements.

Reach	1936 to 1948	1948 to 1959	1959 to 1964	1964 to 1970	1970 to 1980	1980 to 1989	1989 to 2000	2000 to 2011	1936 to 1964	1964 to 2011
1	1.0	1.0	1.9	2.1	0.9	1.2	0.8	0.5	1.1	1.0
2	0.9	1.8	3.8	3.3	1.5	1.0	2.0	0.6	2.4	1.6
3	1.3	2.6	6.2	3.8	2.0	1.9	1.8	0.7	2.7	1.9
4	2.0	4.8	5.3	5.3	8.5	3.0	4.3	2.0	3.7	4.7
5	2.8	3.5	3.2	2.7	2.9	2.7	2.5	1.0	3.2	2.3
6	2.6	8.4	7.1	5.4	2.3	3.2	1.8	2.8	5.7	2.9
7	4.9	5.5	7.0	3.9	2.0	3.1	1.8	0.6	6.1	2.1
8	1.5	2.0	5.8	3.5	2.5	1.7	2.1	2.7	2.5	2.4
9	2.0	3.8	2.9	4.6	2.8	1.8	1.5	2.5	2.9	2.8
10	3.1	4.0	2.8	2.7	1.8	2.3	1.1	0.8	3.4	1.6
11	4.5	4.9	3.7	4.1	2.3	2.3	1.9	1.0	4.5	2.1
12				3.3	3.1	2.2	2.2	0.6		2.2
13				3.6	2.4	2.7	1.9	0.9		2.1
14				2.7	2.6	2.2	0.8	0.6		1.6
15				1.9	3.5	3.8	2.2	1.0		2.4
16				1.7	1.5	1.9	1.6	0.8		1.5
17				3.0	1.8	3.2	2.8	1.4		2.4
18				2.0	2.6	2.3	1.6	0.9		1.8
19				2.7	1.7	2.2	1.3	0.8		1.6
20				2.1	1.4	2.0	0.7	0.7		1.3

Migration rates from each of the eight time periods calculated using all measurements (Table 4) have varied through the study area and through time (Figure 16). The highest migration rates are approximately 8 feet/year. These higher rates are common to reaches or areas with less confinement or bank armoring (e.g., Reach 4 and part of Reach 6). Migration rates through all reaches typically have declined through the period of this study. Typical migration rates range from 2 feet/year to 7 feet/year during 1936 to 1964 and range from 1 foot/year to about 5 feet/year during 1964 to 2011.

Table 5. Cedar River channel migration rates using eroding-only measurements.

Reach	1936 to 1948	1948 to 1959	1959 to 1964	1964 to 1970	1970 to 1980	1980 to 1989	1989 to 2000	2000 to 2011	1936 to 1964	1964 to 2011
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	1.0	1.5	4.8	3.8	1.8	1.2	2.2	0.7	2.8	1.9
3	1.4	3.1	6.2	4.9	2.2	1.9	2.1	0.9	3.2	2.2
4	2.6	5.4	5.7	5.9	11.7	2.8	4.9	2.2	4.5	6.4
5	1.8	4.4	3.3	2.8	3.8	2.7	2.6	1.1	3.5	2.5
6	3.1	8.5	7.6	7.6	3.1	4.9	1.8	3.6	6.2	3.3
7	1.8	4.7	7.3	5.1	2.2	3.7	2.2	0.8	6.7	2.2
8	1.7	2.5	5.8	3.9	3.1	2.3	2.4	2.6	2.9	2.7
9	2.0	8.6	3.7	4.1	2.8	1.3	1.6	2.9	4.6	2.9
10	3.3	4.0	3.2	2.7	2.4	2.9	1.7	1.0	3.9	2.0
11	4.4	5.5	3.0	4.6	2.4	2.9	2.5	1.2	5.3	2.6
12				3.0	3.1	2.5	2.4	1.0		2.3
13				3.6	2.6	3.6	2.2	1.7		2.5
14				2.9	3.2	4.1	1.2	1.1		2.0
15				2.5	3.5	3.8	2.2	1.5		2.7
16				2.3	1.7	2.2	1.8	1.1		1.7
17				3.2	2.5	3.9	2.7	1.3		2.6
18				2.8	2.8	2.6	2.1	1.1		2.2
19				3.6	1.9	2.8	2.0	1.1		2.0
20				2.8	1.9	2.4	0.9	1.1		1.6

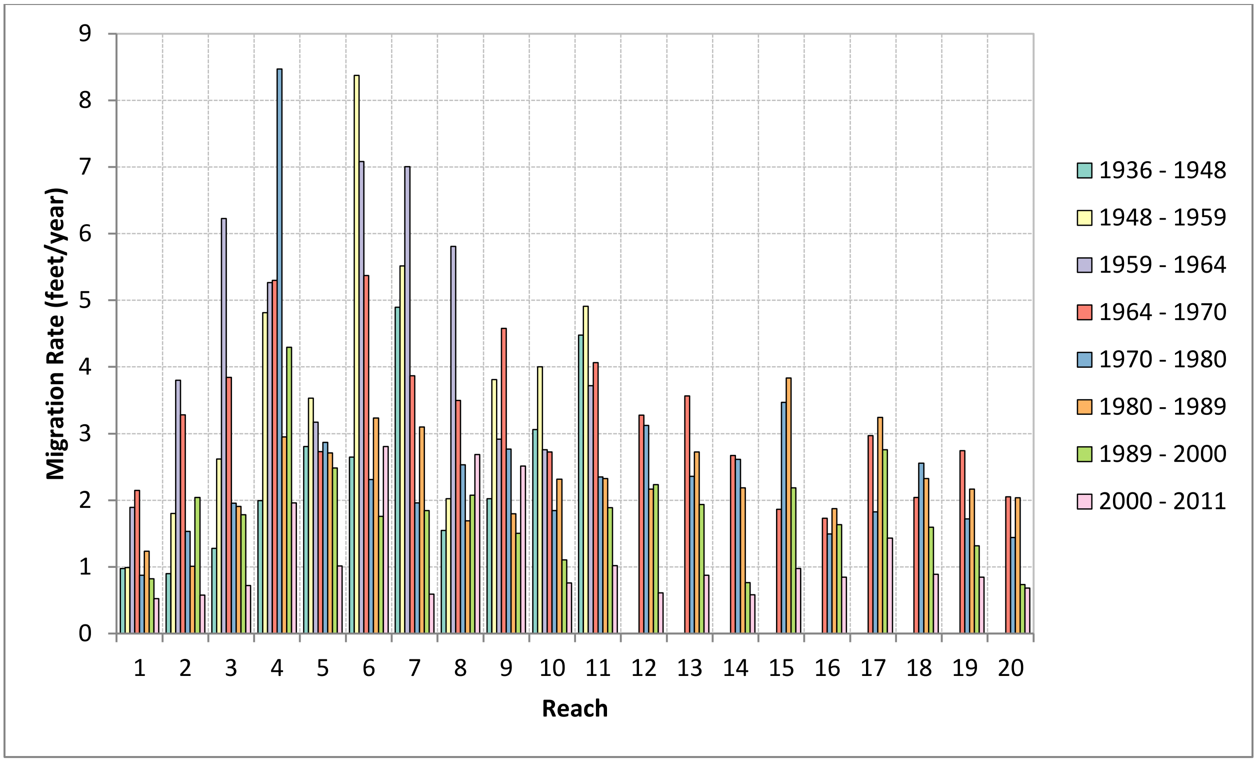

Figure 16. **Cedar River channel migration rates using all measurements.**

Time-weighted average migration rates (Table 5, Figure 17) moderate the variability in migration rates evident through the eight time periods (Figure 16). However, overall spatial and temporal trends in migration remain similar whether calculated in each time period or as a time-weighted average. Migration rates based on eroding-only measurements are consistently greater than rates based on all measurements, typically by about 5 to 10 percent (Figure 17). The migration rates during 1964 to 2011 are lower than those during 1936 to 1964.

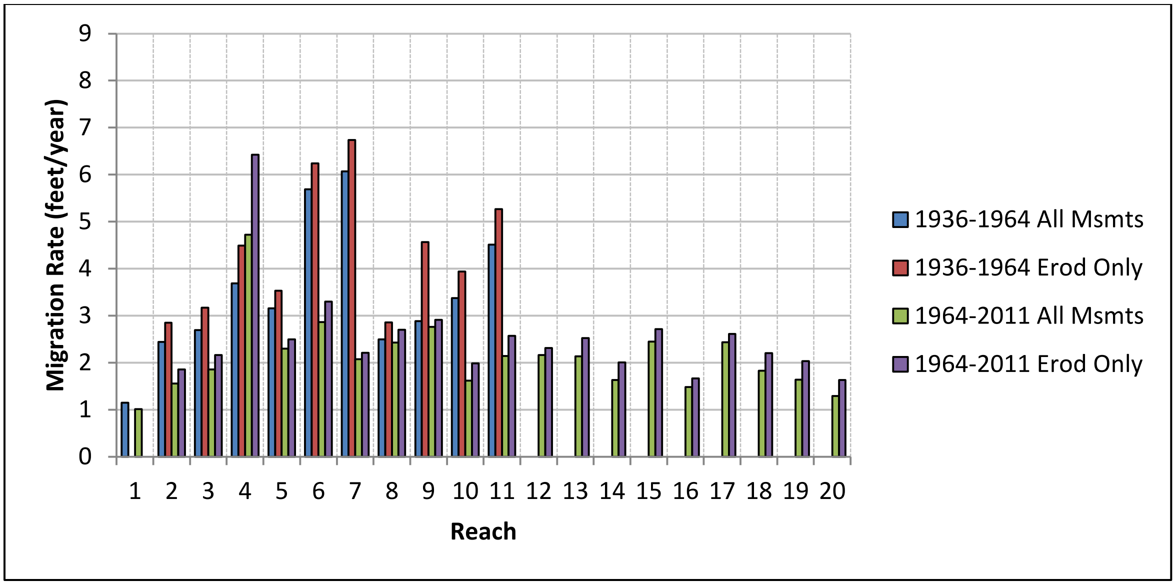

Figure 17. Cedar River weighted-average channel migration rates, using all measurements and eroding-only measurements.

Migration rates also were calculated based on measurements taken only in unarmored areas to evaluate the effect of bank armoring on channel migration (Appendix B). The migration rates in unarmored areas based on all measurements (Appendix B, Table B-1 and Figure B-1) have varied through the study area and through the eight time periods similarly to channel migration rates in all areas (Table 4, Figure 16). The magnitudes of channel migration rates in unarmored areas typically are greater than migration rates in all areas (e.g., by 10 to 50 percent), although there is much variability in the differences in migration rates in unarmored compared to all areas. In most reaches, the time-weighted average rates in unarmored areas (Appendix B, Table B-1, Table B-2, and Figure B-2) are within 10 percent of the time-weighted average rate based on measurements in all areas. The few locations where migration rates in unarmored areas are notably greater than those in all areas are in Reach 6, where rapid and expansive migration followed levee removal at the Cedar Rapids site (RM 7.4), and in the largely unconfined and unarmored Reach 9.

The general similarity between migration rates in unarmored areas and in all areas results from different reasons during the 1936 to 1964 and the 1964-2011 periods. Bank conditions in all areas and in unarmored areas were very similar during the 1936 to 1964 period because relatively little bank armoring had been constructed at that time (Figure 2). Similarities of migration rates in all areas and in unarmored areas during the 1964 to 2011 period likely result because widespread bank armoring can reduce channel migration along adjacent unprotected banks as well as at armored sites.

Eroding-only channel migration rates, both in all areas and in unarmored areas, have been used in previous CMZ mapping studies on local rivers. Channel migration rates calculated on the Tolt River (Shannon & Wilson 1991) and the Middle Green River (King County 1993) provide local context for Cedar River channel migration rates. Both the Tolt River and the

Middle Green River have migrating channels in post-glacial valleys, and both are affected by the presence of dams. Both studies calculated migration rates using eroding-only measurements; the Tolt River from all areas and the Middle Green River from unarmored areas. Eroding-only channel migration rates on the Tolt River ranged from 2 feet/year to 10 feet/year and on the Middle Green River ranged from about 1 foot/year to 11 feet/year. River channels in both the Tolt River and Green River study areas have less bank armoring than the Cedar River study area. Typical eroding-only channel migration rates from all areas on the Cedar River throughout the timeframe of 1964 to 2011 range from 2 feet/year to about 6 feet/year. Migration rates on the Cedar River are comparable to these two local examples.

4.4 Spatial variation in channel migration

Much of the study area exhibits confined channel conditions, as indicated by widespread containment of the 1,800 cfs (annual 74 percent) and 2,800 cfs (annual 42 percent) flood events. Containment of these frequent flows, and, in some locations, the 5,000 cfs (annual 10 percent) and larger floods, results in a decreased frequency and extent of overbank flows, recruitment of gravel and large wood, bank erosion, and channel migration. These conditions are typical throughout the study reaches except in unconfined areas such as within Reach 4 (RM 5; 2011 landslide) and Reach 6 (RM 7.4; Cedar Rapids area).

The Cedar River appears to be generally efficient at moving coarse sediment from Landsburg to I-405. In Reach 20 (RM 22) through Reach 18 (RM 17), the naturally steep channel gradient and narrow valley bottom confinement combine to keep incoming sediment in transport. In Reach 17 and downstream as well, pervasive bank armoring or erosion-resistant geology plus containment of flows well above the threshold of coarse sediment movement generally maintain conditions that favor coarse sediment transport. From Reach 17 (RM 17) to Reach 2 (RM 3), the lack of a clear correlation between channel gradient and sediment characteristics (Figure 5 and Figure 6) suggests that local variations in factors such as channel confinement have a stronger influence than channel gradient on sediment transport and deposition, and by extension, on bank erosion and channel migration. The areas noted in the previous paragraph are example locations where unconfined channels exhibit sediment deposition and active channel migration.

Large wood accumulations have the potential to influence and increase channel migration activity (Brummer et al. 2006). However, the current amounts, densities, and distribution of large wood (K. Akyuz, pers. comm. 2014) suggest that large wood presently is not a significant factor regarding channel migration, at least not systemically. Large wood accumulations within a reach typically increase local water surface elevations, and these increases cause increased potential for avulsion and channel migration, depending on the proximity of the large wood feature to a potential avulsion pathway. The location, presence, and size of present-day large wood accumulations were considered when evaluating potential avulsion sites for avulsion hazard in this study (Section 5.1.2).

Habitat restoration plans for endangered species recovery and other purposes have the goal of increasing the number and size of large wood over time within the Cedar River. It is assumed that, as riparian reforestation projects mature, the amount of wood in the river will increase. Potential future increases in in-channel large wood accumulations likely will result in increased water surface elevations and the extent of potential channel migration, locally at first and more systemically over longer periods.

4.5 Temporal changes in channel migration

The combination of flow regulation since 1914 and the widespread presence of bank armoring since the 1960s has resulted in a narrowing of the average active channel width by approximately 50 percent and a simplification of the channel pattern from anabranching[3] to single channel in most of the study area (Perkins 1994). With simplification of channel pattern, channel migration by avulsion likely decreased through time because of less opportunity for flows to access the multiple flow paths present in anabranching channels.

The decrease in channel migration rates seen after 1964 (Figure 17) likely also results from the proliferation of bank armoring in the 1960s. The effects of bank armoring on channel migration rates persist to present day, with relatively minor lateral channel migration observed after the January 2009 flow of 7,870 cfs (approximately an annual 3.3 percent flood event) (Gendaszek at al. 2012).

[3] Anabranching channel: A channel pattern that consists of multiple channels separated by stable islands which are large relative to the size of the channels and which divide the flow up to and including bankfull (Knighton 1998).

5.0 CHANNEL MIGRATION HAZARDS ON THE CEDAR RIVER

The findings from Section 4 are used in this chapter to predict future limits of channel migration within the study area. The resulting identified channel migration hazard areas are shown in the Cedar River CMZ map in Section 5.2.

5.1 Delineation of channel migration hazard areas

Channel migration hazards associated with each CMZ component are described in the following subsections.

5.1.1 Historical Migration Zone

Historical active channels and the HMZ boundary are shown in Map 3. The HMZ is mapped as a severe hazard area.

5.1.2 Avulsion Hazard Zone

Low-lying, frequently flooded areas evident in the elevation difference map (Map 4) that met AHZ mapping criteria (Section 3.3.2) are listed in Table 6 and shown in Map 5, Appendix A. Mapped AHZs are described in this section.

Table 6. Areas mapped within the Avulsion Hazard Zone.

				Mapping criteria[†]: ALL must be met in order to map as AHZ					Criteria[†] for Severe: must meet ANY			
D/S RM*	U/S RM*	Bank**	Location Description	Low-lying	Shorter	Erodible substrate	Likely route	Map as AHZ?	Unvegetated/ scour	Low Connection	Indicators	Map as Severe?
6.80	6.95	LB	Riverbend Lower	Yes, behind facility	Yes	Yes: Facility not DMA[‡] and is <1 percent flood elevation[Θ]	Yes	Yes	Yes	No	No	Yes
8.95	9.25	LB	Large meander, floodplain channel	Yes	Yes	Yes	Yes	Yes	No	No	No	No
9.85	10.00	RB	Near CRT[€] 5B	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
10.87	11.47	RB	Rainbow Bend; existing low area	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
10.87	11.16	RB	Rainbow Bend; side channel to d/s backwater area	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
11.15	11.44	RB	Rainbow Bend; side channel to river	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
11.21	11.41	RB	Rainbow bend; cut off channel to river	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
13.16	13.44	LB	Rutledge Johnson	Yes, behind facility	Yes	Yes: Facility not DMA[‡] and is <1 percent flood elevation[Θ]	Yes	Yes	Yes	No	Yes	Yes
13.37	13.65	RB	13.65 to Taylor Crk	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
13.37	13.89	RB	Behind Getchman	Yes, behind facility	Yes	Yes: Facility not DMA[‡] and is <1 percent flood elevation[Θ]	Yes	Yes	Yes			Yes
15.74	15.91	LB	U/S Colemn-Lotto	Yes	Yes	Yes	Yes	Yes		Yes	Yes	Yes
15.83	16.2	RB	Doris Creek	Yes	Yes	Yes	Yes	Yes	Yes	Yes		Yes
16.00	16.5	LB	D/S of CRT Bridge	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
16.95	17.09	LB	U/S Youngs	Yes	Yes	Yes	Yes	Yes		Yes		Yes
17.28	17.38	RB	Behind Orchard Grove	Yes, behind facility	Yes	Yes: Facility not DMA[‡] and is <1 percent flood elevation[Θ]	Yes	Yes	No	No	No	No
17.84	18.04	LB	U/S of CRT Bridge	Yes	Yes	Yes	Yes	Yes		Yes		Yes

Table 6 footnotes:
* D/S = downstream; U/S= upstream.
** LB= left bank and RB = right bank when viewed downstream.
† See Section 3.3.2 for full description of mapping criteria.
‡ "Facility not DMA" = Facility does not meet Disconnected Migration Area mapping criteria.
Θ "<1 percent flood elevation" = Top of facility is lower than the 1 percent flood water surface elevation
€ CRT = Cedar River Trail.

An AHZ is mapped along the left bank near RM 7 (Map 5A, Appendix A). The top elevation of the Riverbend Levee at this site is lower in elevation than the water surface elevation of the 10,300 cfs (annual 1 percent) flood, and this levee is not likely to restrain channel migration. This severe AHZ is mapped through Cavanaugh Pond.

A low-lying area that runs generally parallel to the main channel along the left bank near RM 9 is mapped as a moderate AHZ (Map 5B, Appendix A). A present-day side channel that was occupied by the mainstem as recently as the 1970s is mapped as a severe AHZ along the right bank near RM 10 (Map 5B, Appendix A). Although this former channel is within the HMZ, the delineated severe AHZ extends landward of the HMZ.

There are two floodplain channels that were excavated along the right bank near RM 11 as part of the Rainbow Bend levee removal project. These two excavated channels plus two existing low-lying areas onsite are mapped as severe AHZs (Map 5C, Appendix A).

Existing floodplain channels and the downstream end of Taylor Creek located landward of the right bank Getchman levee and the left bank Rutledge-Johnson levee (RM 13 to RM 14) are mapped as severe AHZs (Map 5D, Appendix A). The top elevation of both levees is lower than the water surface elevation of the 10,300 cfs (annual 1 percent) flood, and neither levee is likely to restrain channel migration. An existing right bank floodplain channel located between the Getchman and Jan Road levees near RM 13.6 has a direct, low-elevation surface connection to the Cedar River and is mapped as severe hazard (Map 5D, Appendix A).

There is a low-lying floodplain channel along the left bank near RM 15.8 and more than one such floodplain channels near RM 16.5 that have a direct, low-elevation connection to the mainstem. All are mapped as severe AHZs (Map 5E, Appendix A). A right bank side channel named Doris Creek located between RM 16.2 and RM 15.9 maintains a direct low-elevation surface connection to the mainstem with year-round flow; it is mapped as a severe AHZ (Map 5E, Appendix A).

There are two low-lying floodplain channels along the left bank that have a direct, low-elevation connection to the mainstem channel; one is near RM 17 and one is near RM 18 (Map 5F, Appendix A); both areas are mapped as severe AHZs. A low-lying area landward of the right bank Orchard Grove levee near RM 17.4 is an AHZ because the top elevation of this levee is lower than the water surface elevation of the 10,300 cfs and this levee is not likely to restrain channel migration (Map 5F, Appendix A). This AHZ is a moderate hazard area because the landward area does not meet any of the criteria to be mapped as a severe AHZ.

5.1.3 Erosion Hazard Area/Erosion Setback

The 1964-2011 weighted average channel migration rate calculated using eroding-only measurements (Table 5) is taken to be the representative lateral migration rate for the reach in which it was calculated. The 1964-2011 timeframe was used because it produces long-term average migration rates, which are appropriate to the prediction of channel migration hazard over multiple decades. It also encompasses the period through which bank armoring and flow regulation, representative of current conditions, have been in place. The migration rates using eroding-only measurements also are representative because they use measurements along both armored and unarmored locations, which reflect present channel conditions. Channel migration rates calculated in unarmored areas were not used because they do not include armored locations, which are pervasive under present conditions.

EHA/ES widths calculated for moderate hazard areas and severe hazard areas in valley-bottom alluvium using eroding-only migration rates are summarized in Table 7. The severe hazard ES width is delineated as either 25 years times the channel migration rate in column 2 of this table applied to the HMZ or 50 years times the same migration rate applied to the 2011 Active Channel, whichever distance is more landward. The moderate hazard area ES width is delineated in the same way as the severe hazard area ES using 50 years and 100 years. In addition to applying these setback widths to the HMZ and the 2011 Active Channel, an ES also was applied to the delineated AHZ to a width based on 25 to 50 years of lateral migration (as described in Section 3.3.3.2).

Table 7. Erosion Hazard Area/Erosion Setback widths.

Reach	Channel Migration Rate (ft/year)	EROSION SETBACK WIDTHS (feet)			
		SEVERE HAZARD AREA		MODERATE HAZARD AREA	
		Feet from HMZ	Feet from 2011 Active Channel	Feet from HMZ	Feet from 2011 Active Channel
		25 years	50 years	50 years	100 years
1	0.0	0	0	0	0
2	1.9	46	93	93	185
3	2.2	54	108	108	216
4	6.4	161	321	321	642
5	2.5	62	125	125	250
6	3.3	82	165	165	330
7	2.2	55	111	111	221
8	2.7	68	135	135	270
9	2.9	73	146	146	291
10	2.0	50	99	99	199
11	2.6	64	128	128	257
12	2.3	58	115	115	231
13	2.5	63	126	126	252
14	2.0	50	100	100	200
15	2.7	68	136	136	271
16	1.7	42	83	83	166
17	2.6	65	131	131	261
18	2.2	55	110	110	220
19	2.0	51	102	102	203
20	1.6	41	81	81	163

There was a measureable, consistent, channel migration that progressed in the downstream (down-valley) direction in addition to lateral channel migration at approximate RM 7.4 and RM 9.8. At these locations, a down-valley component was added to the EHA/ES.

The lateral migration rate from Table 5 was not a representative migration rate in some locations because the substrate was not valley-bottom alluvium (i.e., the material in which Table 5 migration rates were calculated), or the land surface elevation at that location was much higher than the valley bottom within which that rate was calculated, or both. Specific locations where these non-representative conditions exist are as follows:

- a left bank landslide site at RM 3;
- the 2001 landslide site on the right bank at approximate RM 5;
- an alluvial fan on the right bank at approximate RM 7.4;
- a terrace mapped as mass-wasting material on the right bank at about RM 10.5;
- a terrace composed of old alluvium on the right bank at about RM 12.5;

- an alluvial terrace on the right bank at RM 15.35; and
- a landslide site on the right bank at RM 17.7.

At these locations, an EHA/ES was mapped using lateral migration rates that were calculated specific to that site. The lateral migration rates at these sites were lower than those in nearby valley-bottom alluvium.

5.1.4 Erosion Hazard Area/Geotechnical Setback

An EHA/GS was added to the outer edge of the EHA/ES at several locations where the EHA/ES encountered a landform that was greater in height than 20 feet above Ordinary High Water, as described in Section3.3.4. The EHA/GS is included in the CMZ delineated in Section 5.2.

5.1.5 Disconnected Migration Area

Legally existing publicly maintained levees, revetments, and other infrastructure within King County or the City of Renton that met the mapping criteria in Section 3.3.5 are summarized in Table 8. Areas landward of such structures are eligible to be mapped as a DMA.

Table 8. Assumed barriers to channel migration.

D/S RM	U/S RM	River Bank	Name of Structure	Type of Structure(s)
0.00	1.66	Both	Cedar River 205 Flood Control Project	Levees and floodwalls within City of Renton
1.99	13.31	Either	SR 169, at several locations	State highway
2.74	2.78	Left	Haddad	Revetment within City of Renton
2.77	2.84	Right	Tabor-Crowall	Revetment within City of Renton
3.33	3.51	Right	Brodell	Revetment within City of Renton
4.11	4.21	Right	Erickson	Revetment within City of Renton
4.26	4.31	Right	Maplewood Golf Course	Revetment within City of Renton
4.27	4.41	Left	Lower Elliott Park	Revetment within City of Renton
4.77	4.89	Left	Upper Elliott Park	Levee within City of Renton
7.36	7.54	Right	Cedar Rapids Right Bank*	Levee
10.32	10.41	Left	Belmondo	Levee
11.47	11.51	Right	Rainbow Bend Upstream	Revetment
11.67	11.94	Left	SE 184th Str	Sole-access county road
12.67	12.82	Left	SE 193rd Str to 216th Ave SE	Sole-access county road
14.04	14.06	Both	SR 169 bridge	State highway bridge abutments
14.97	15.16	Left	SE Bain Rd	Sole-access county road
14.75	14.81	Right	SE 214th Str to 221st Ave SE	Sole-access county road
14.91	15.16	Left	SE Bain Rd	Sole-access county road
15.12	15.16	Both	SR 18 bridges	State highway bridge abutments
15.22	15.26	Both	SR 169 bridge	State highway bridge abutments
15.81	15.89	Right	Dorre Don Way SE	Sole-access county road
15.99	16.34	Right	Dorre Don Way SE	Sole-access county road
16.55	16.58	Left	Elkington Cedar Trail Bridge	Revetment
16.95	17.05	Right	Dorre Don Way SE	Sole-access county road
17.19	17.53	Right	Upper Dorre Don Way SE	Sole-access county road

*Mapped as a barrier to channel migration for Severe Hazard Area only.

5.2 Channel migration hazard maps

Areas within the Historical Migration Zone, Avulsion Hazard Zone, and Erosion Hazard Area (including the Erosion Setback and Geotechnical Setback) were combined to form an unconstrained channel migration zone, as shown in Map 6, Appendix A. The unconstrained CMZ does not recognize artificial constraints and therefore predicts channel migration in the absence of levees, revetments, and structures such as the Cedar River Trail, SR 169, and bridge features.

In a majority of study reaches, the width of the HMZ constitutes most of the width of the unconstrained CMZ. Reaches where this relationship holds true include those that are steep, confined, or both (e.g., Reaches 20-16, 14, 13, 5, 3, 2, and 1). In reaches where the width of the HMZ does not constitute most of the width of the unconstrained CMZ (e.g., Reaches 15, 12, 11, 8, and 6), typically an AHZ is present, or there has been a down-valley component mapped in the EHA/ES, or both. The width of the HMZ may or may not constitute most of the width of the unconstrained CMZ in unconfined reaches with high channel migration rates (e.g., Reach 4 and Reach 6).

A channel migration zone map was prepared by modifying the unconstrained CMZ in two ways. First, the effects of artificially constructed constraints on channel migration were recognized by mapping a Disconnected Migration Area (DMA) based on the information from Table 8. Structures listed in Table 8 were assumed to be barriers to channel migration, and the outer edge of the CMZ was drawn along the boundaries of these structures. Areas landward of these structures were considered DMAs and removed from the unconstrained CMZ, with one exception: the severe hazard area along the right bank at RM 7.4 in Reach 6 landward of the Cedar Rapids Right Bank levee was reduced in width to match the boundary of the bank armoring. The severe hazard width was reduced at this location because this structure met the criteria for top elevation being higher than that of the annual 1 percent flood and for its construction standards but not for the possibility of erosion landward of the structure. The outer extent of the CMZ remains unaltered at this location and is mapped as a moderate hazard area.

In accordance with WAC and King County code provisions (cited in Section 3.3.5), artificial structures in unincorporated King County were mapped as barriers to migration only if they are publicly maintained, built higher than the annual 1 percent flood elevation, meet construction standards, and the channel is unlikely to migrate landward of the structure (Section 3.3.5). The majority of levees and revetments maintained by King County within unincorporated King County were not mapped as barriers to channel migration because they were not built higher than the elevation of the annual 1 percent flood and were not likely to restrain channel migration. All publicly maintained structures in the City of Renton were mapped as barriers to migration. No privately maintained structures were mapped as barriers to channel migration. If an artificial structure did not meet all criteria necessary to map a DMA, the width of both severe and moderate hazard areas were left unrevised in order to recognize the channel migration hazard landward of that structure.

The second modification to the unconstrained CMZ map was to delineate a severe hazard area and moderate hazard area within the CMZ. This delineation recognizes that channel migration hazard is not equal throughout the CMZ. Channel migration hazard is greater for sites that are near the current channel and potential avulsion pathways.

Severe hazard areas are composed of the HMZ, severe AHZs, and portions of the EHA. The 2011 (present-day) active channel is located within the HMZ, and therefore the active channel always is located within the severe hazard area. The severe hazard area occupies most of the width of the CMZ throughout the study area except at RM 14.5 and RM 19.25, where the moderate-hazard EHA/GS is relatively wide (Map 6, Appendix A). Severe hazard area widths upstream of the channelized Reach 1 range from 110 feet at RM 20 where both river banks are bedrock to about 1,000 feet in the naturally unconfined Reach 4. The moderate hazard area lies between the severe hazard area and the outer boundary of the unconstrained CMZ.

The Cedar River channel migration zone is presented in Map 7, Appendix A.

The Cedar River CMZ includes most of the valley floor in the naturally confined upstream part of this study area (Reaches 20 through 18). Further downstream, the CMZ includes most of the valley floor where it is not cut off by major infrastructure (e.g., SR 169) in reaches that exhibit historically active channel migration or are subject to avulsion hazards, or both (Reaches 15, 12, 10, 9, 8, 6 and 4). The CMZ along most of the length of other reaches covers a relatively narrow portion of the valley floor.

5.3 Summary, conclusions

Natural conditions set the stage for channel migration in the study area. Over the past 13,000 years, the Cedar River has incised through glacial and non-glacial sediments, deposited alluvial sediments, and migrated across its alluvial valley bottom. Artificial conditions imposed on the natural setting over the past 50 to 100 years have altered channel conditions and channel migration characteristics through most of the study area. Modifications to the flow regime since circa 1914 have resulted in containment of small to moderate flood events as well as a simplified channel pattern. Widespread bank armoring installed in the 1960s, along with other constraining infrastructure, confine much of the river channel length and have decreased channel migration rates. With flow regulation assumed to continue as it has for the past century, channel confinement and bank armoring emerge as the prominent variables presently affecting channel migration in this study area. The river has a single-channel pattern and lower lateral migration rates in confined and armored areas than in unconfined or unarmored areas. However, the potential for active channel migration remains high should bank armoring fail or be removed.

In the few areas that are naturally unconfined or recently have had bank armoring removed, the following channel conditions have been observed:

- Lateral migration rates typically are higher than in confined areas.
- A multiple-channel pattern prevails and gravel bars are bare and active, all of which suggest sediment deposition.
- Conditions that favor avulsion may be present.
- Channel expansion typically occurs after a triggering event such as avulsion or levee removal.
- Greater numbers of large wood exist than in confined areas.

In addition to using the Cedar River CMZ map to regulate land use in affected channel migration hazard areas, the CMZ map and findings of this study will inform planning and development of capital flood risk reduction projects via the Cedar River Corridor process. There is potential to decrease flood risk and increase floodplain connectivity in mapped channel migration hazard areas by acquiring at-risk properties, removing constructed bank armoring and allowing channel migration to proceed in a less constrained condition than currently exists. This potential would be greatest in areas where channel gradient is moderate and naturally erosion-resistant riverbanks are absent or do not dominate. Such conditions exist in Reaches 16, 15, 12, 11, 10, 7, 6, 5 and 4 of this study area. If channel migration predicted for conditions following a bank-armor removal project is significantly different from present conditions, the relevant portion of the CMZ map may be updated, as described in Section 1.3.

This study's use of historical information to predict existing and future hazard is consistent with accepted practices and guidance (King County 2014; Ecology 1993-2014). Because some factors affecting channel migration are stochastic in nature, the channel may not occupy all parts of the mapped CMZ within the next 100 years. However, there also is a low but real possibility that the channel could occupy portions of the valley floor beyond the limits of the mapped CMZ. As such, all parts of the alluvial valley bottom, excluding high terraces, should be considered to have a low level of channel migration hazard.

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7.0 APPENDIX A

Map 1. Publicly maintained levees and revetments

Map 2. Generalized geologic map of the study area

Map 3. Historical channels and Historical Migration Zone (HMZ)

Map 4. Elevation difference (water surface at 5,000 cfs and surface topography)

Map 5. Avulsion Hazard Zone

Map 6. Unconstrained Channel Migration Zone

Map 7. Cedar River Channel Migration Zone

Maps 1 through 7 are included after Appendix B.

8.0 APPENDIX B

Table B-1. Channel migration rates in unarmored areas using all measurements.

Reach	1936 to 1948	1948 to 1959	1959 to 1964	1964 to 1970	1970 to 1980	1980 to 1989	1989 to 2000	2000 to 2011	1936 to 1964	1964 to 2011
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.9	1.9	3.9	3.4	1.5	1.0	2.1	0.6	2.5	1.6
3	1.3	2.6	6.3	3.8	1.7	1.3	1.8	0.6	2.7	2.3
4	2.0	4.8	5.3	7.0	1.7	3.6	4.6	1.8	3.7	5.1
5	2.9	3.6	2.8	2.9	2.9	3.4	2.1	1.1	3.4	2.6
6	2.8	8.8	8.9	8.6	3.7	5.5	1.7	6.9	6.1	5.0
7	4.4	5.3	4.5	2.7	1.4	1.9	1.4	0.9	5.3	1.6
8	1.6	2.1	6.8	4.4	2.4	1.7	2.4	3.5	2.7	2.8
9	1.7	4.3	2.8	5.5	4.5	2.5	0.9	2.7	3.0	3.6
10	2.1	4.3	3.7	2.3	2.9	4.8	0.1	0.2	3.4	1.9
11	4.5	4.9	4.0	4.4	2.1	2.3	1.8	1.0	4.5	2.1
12				1.5	2.9	2.5	2.2	0.6		1.9
13				2.7	2.5	2.2	2.1	1.0		2.0
14				2.6	2.6	2.5	0.9	0.7		1.7
15				1.8	4.4	5.0	4.0	1.3		3.1
16				2.4	1.8	2.4	1.2	1.3		1.7
17				3.0	1.8	3.2	2.8	1.4		2.4
18				1.7	2.4	2.4	1.6	0.9		1.8
19				3.1	1.6	2.1	1.4	0.9		1.7
20				2.3	1.3	2.1	0.7	0.8		1.3

Table B-2. Channel migration rates in unarmored areas using eroding-only measurements.

Reach	1936 to 1948	1948 to 1959	1959 to 1964	1964 to 1970	1970 to 1980	1980 to 1989	1989 to 2000	2000 to 2011	1936 to 1964	1964 to 2011
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	1.1	1.5	5.0	3.8	1.8	1.2	2.3	0.7	3.0	1.9
3	1.4	3.1	6.3	4.9	2.0	1.4	1.9	0.8	3.1	2.6
4	2.6	5.4	5.7	7.8	3.9	1.4	5.7	1.8	4.5	5.4
5	1.8	4.6	3.4	3.2	3.9	3.4	2.2	1.3	3.9	2.5
6	3.1	9.0	9.3	13.2	4.6	5.5	1.9	9.3	6.6	5.9
7	1.8	5.7	3.8	3.5	2.0	2.5	1.9	1.2	4.8	2.0
8	1.5	2.6	6.8	4.6	2.7	2.1	2.5	2.7	2.9	2.8
9	1.6	8.6	3.7	3.4	4.5		3.6	3.5	4.6	3.6
10	2.6	5.0	3.6	2.3	2.9	4.8	0.7	0.2	4.3	2.3
11	4.4	5.5	3.0	4.9	2.1	2.7	2.5	1.2	5.3	2.6
12				1.8	2.9	3.3	2.5	1.3		2.3
13				2.7	2.7	3.0	2.5	1.8		2.4
14				3.0	2.7	4.1	1.4	1.0		2.1
15				1.8	4.4	4.5	4.0	3.2		3.6
16				3.1	1.8	2.4	1.5	1.6		1.9
17				3.2	2.5	3.9	3.1	1.3		2.6
18				2.5	2.7	2.8	2.1	1.1		2.2
19				4.0	1.7	2.8	2.0	1.2		2.1
20				2.9	1.2	2.1	0.9	1.2		1.7

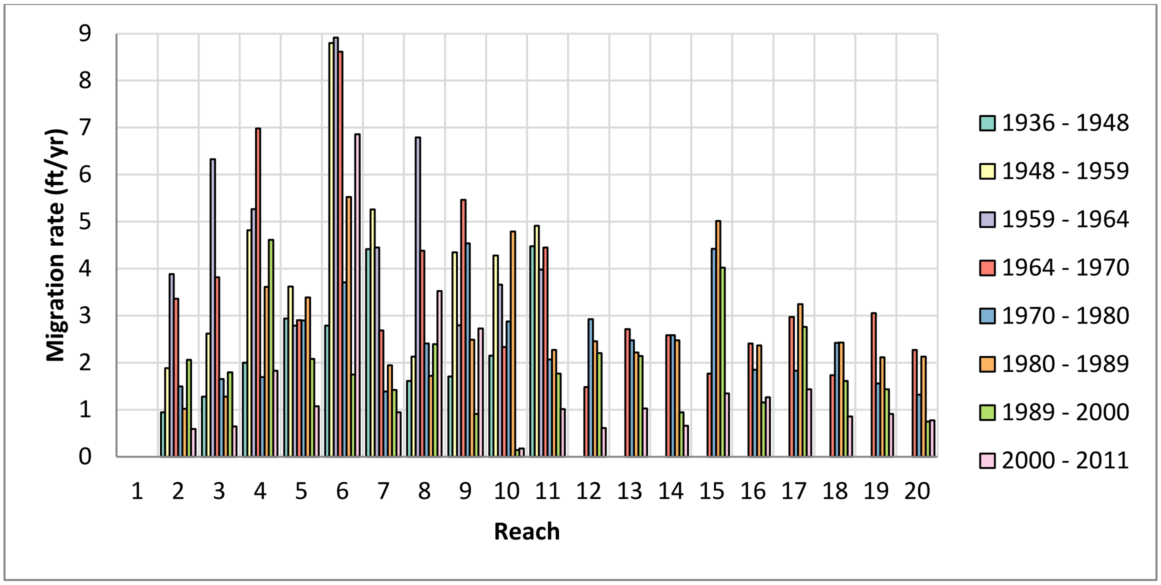


Figure B-1. Cedar River channel migration rates in unarmored areas using all measurements.

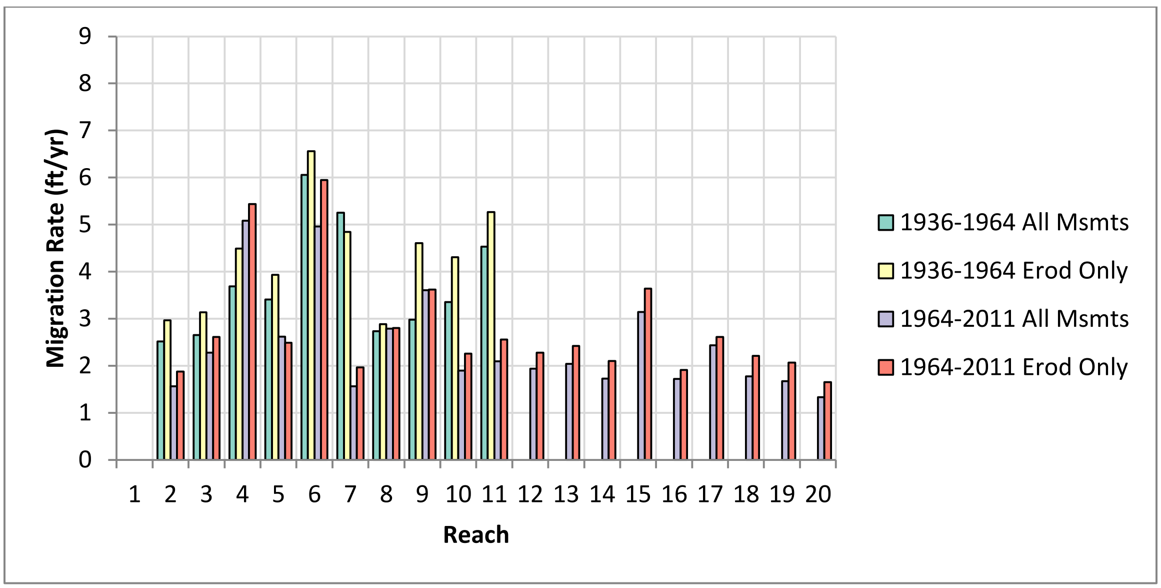
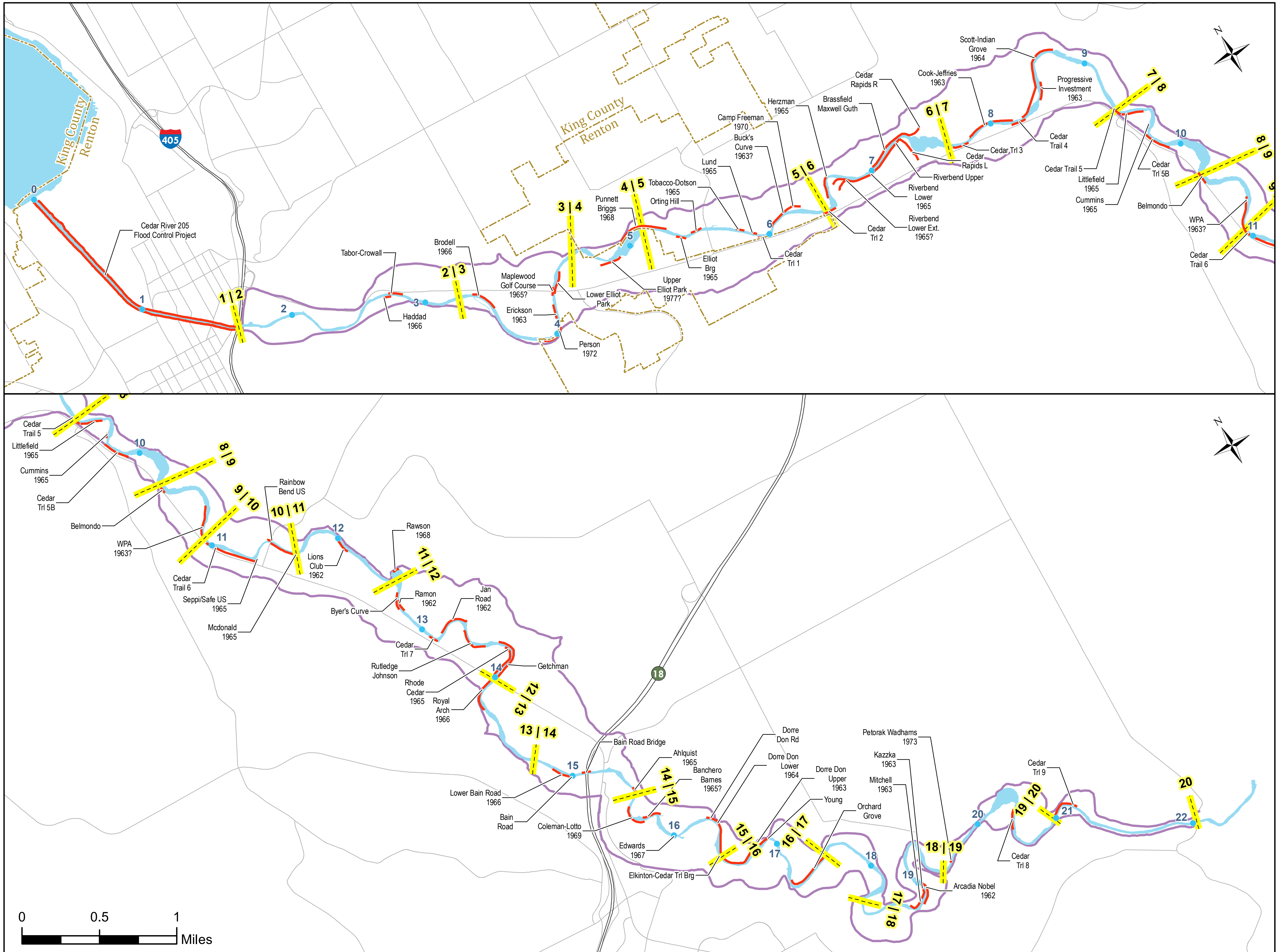


Figure B-2. Cedar River weighted-average channel migration rates in unarmored areas using all measurements and in eroding-only measurements.

Cedar River

Map 1. Publicly maintained levees and revetments



Legend

- River Mile
- City Boundaries
- Levees and Revetments
- Reach Boundaries
- 2011 Active Channel
- Valley Wall
- Streets

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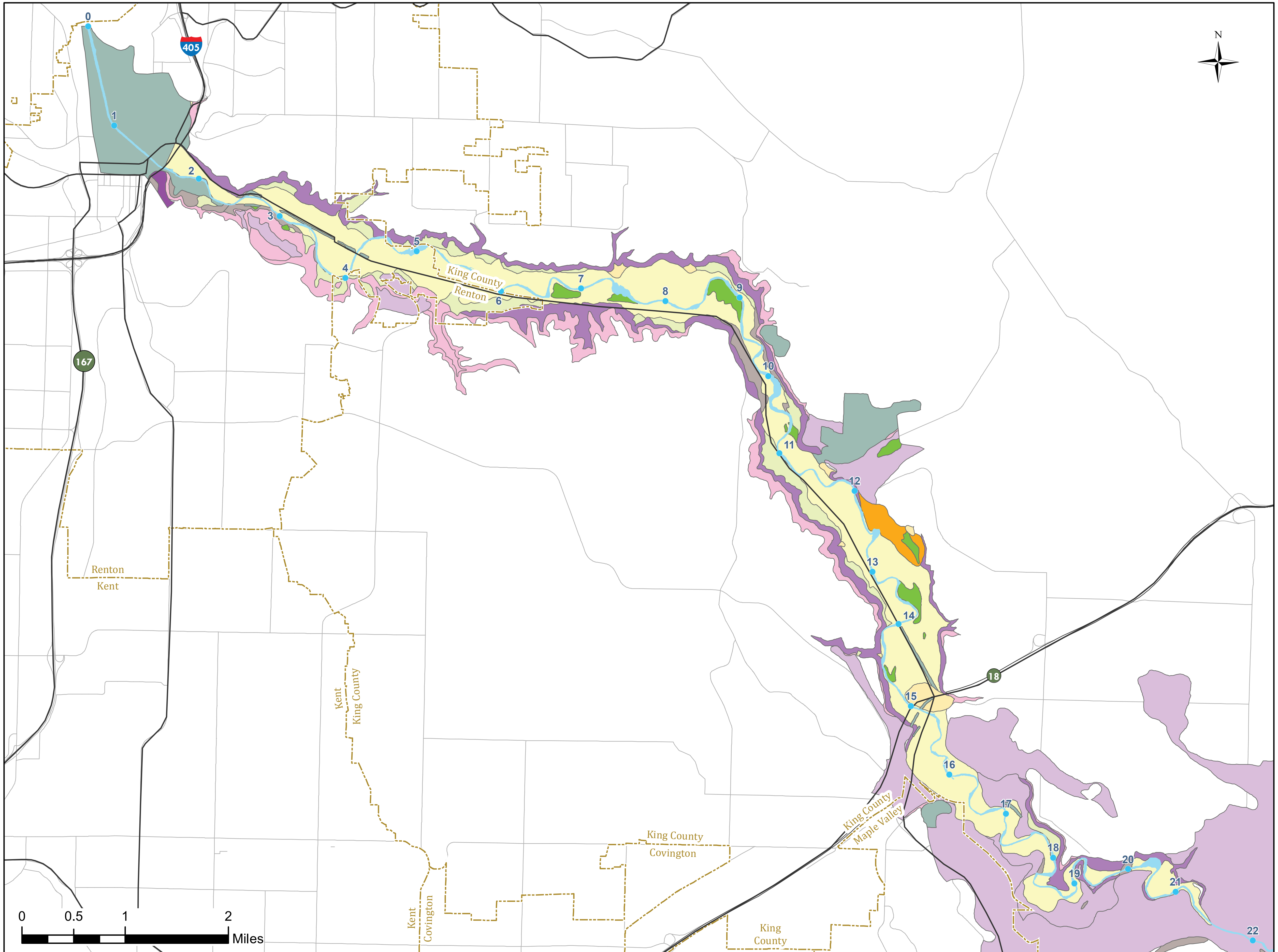
Cedar River

Map 2. Generalized geologic map of the study area



Legend

- River Mile
- City Boundaries
- Streets
- 2011 Active Channel

Study Area Geology

Modern Post Glacial Deposits

- Modified
- Wetland (Qw)
- Landslide (Qls, Qmw)
- Alluvium (Qyal)
- Alluvial Fan (Qf)
- Older Alluvium (Qoal)

Glacial Deposits

- Recessional Outwash (Qvr)
- Ice Contact (Qvi)
- Advance Outwash and other deposits (Qvu, Qva, Qu)
- Till (Qvt)
- Pre-Fraser deposits (Qpf)

Bedrock

- Bedrock (Ts, Tp, Ti, Tpr)

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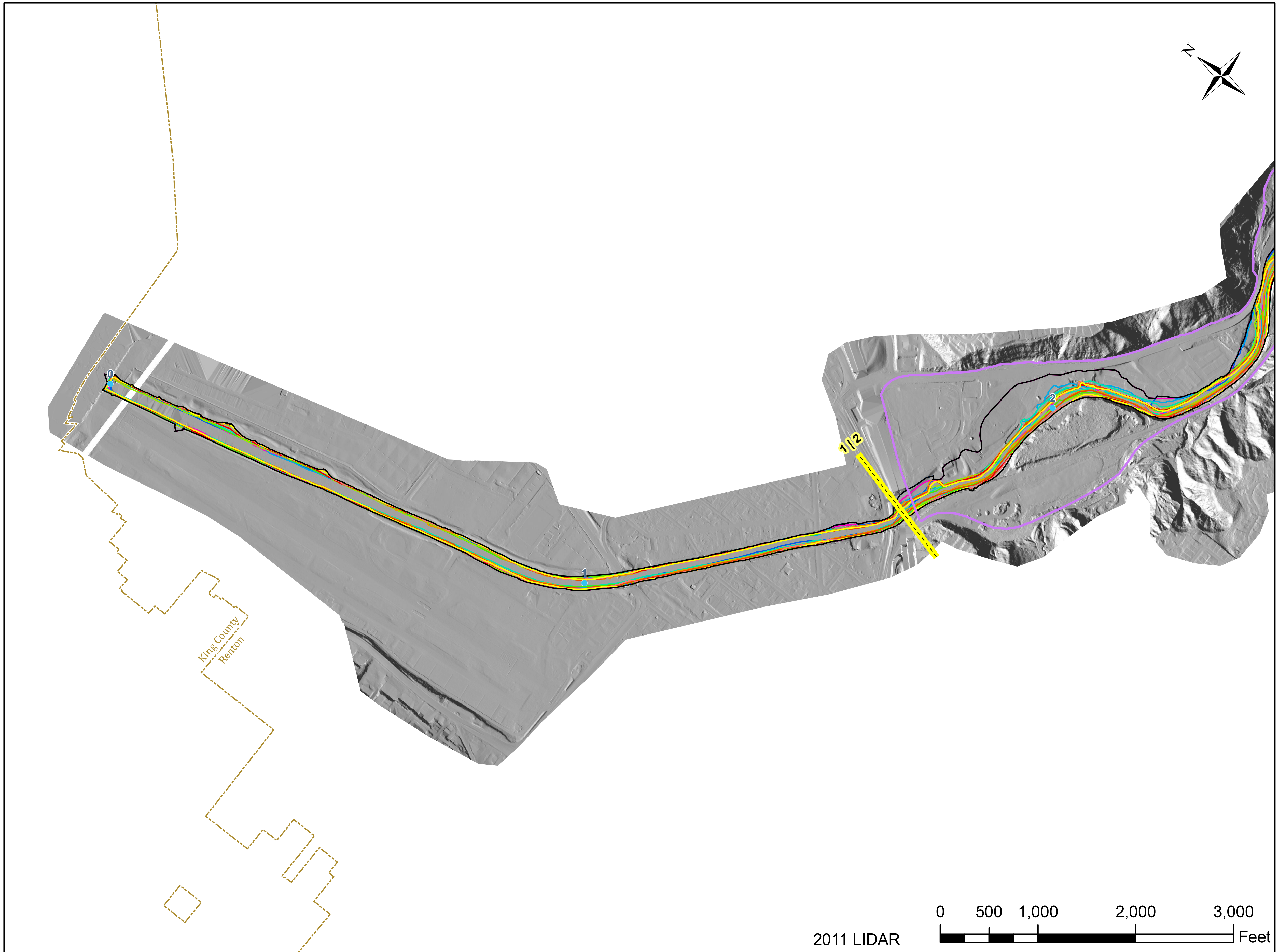

Cedar River

Map 3. Historical active channels and Historical Migration Zone (HMZ)

Panel 1 of 8

Legend

- River Mile
- City Boundaries
- Valley Wall
- Reach Boundaries
- HMZ Boundary

Historical Active Channels

- 2011
- 2005
- 2000
- 1995
- 1989
- 1980
- 1970
- 1964
- 1959
- 1948
- 1936

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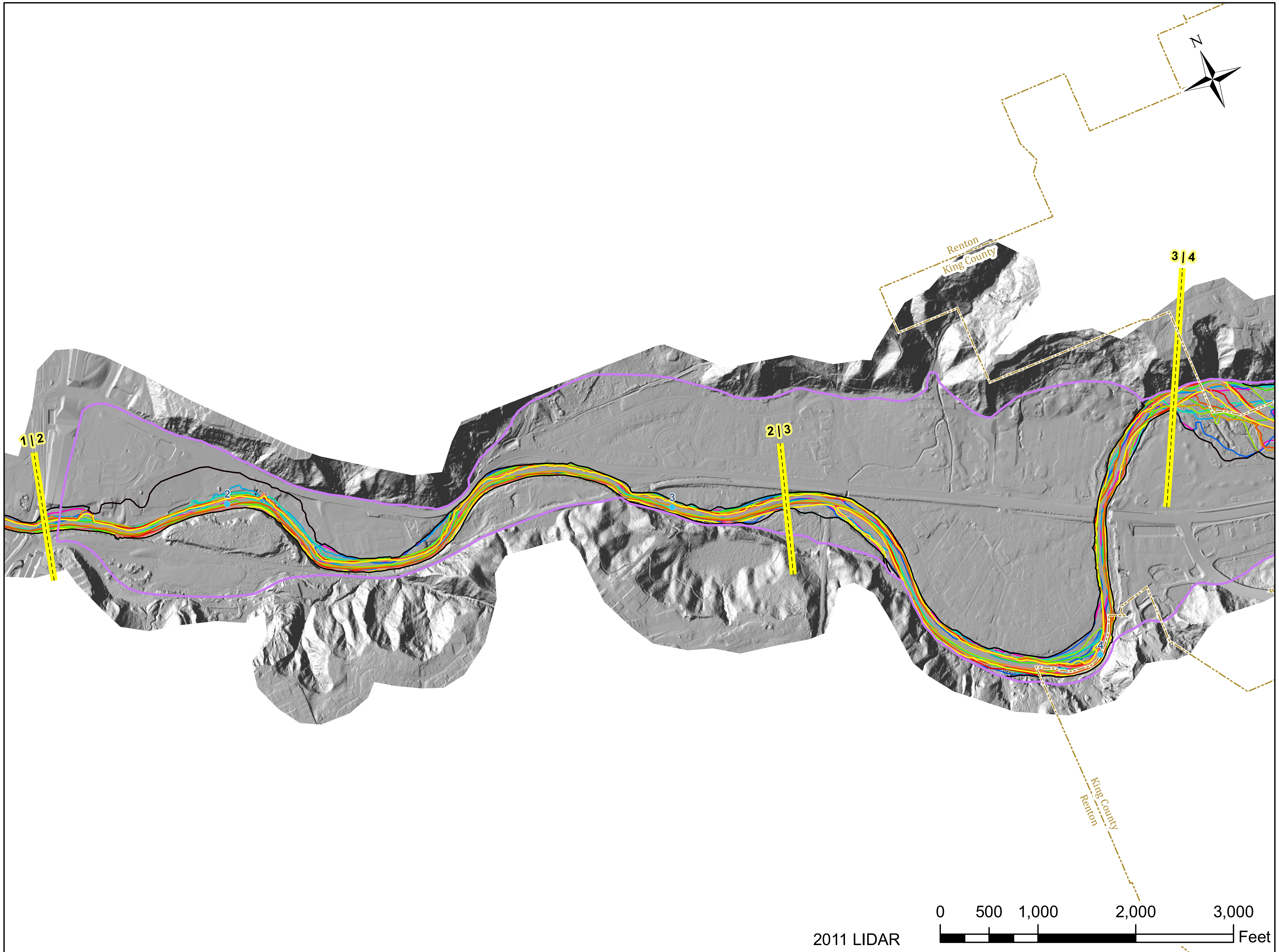

Cedar River

Map 3. Historical active channels and Historical Migration Zone (HMZ)

Panel 2 of 8

Legend

- River Mile
- City Boundaries
- Valley Wall
- Reach Boundaries
- HMZ Boundary

Historical Active Channels

- 2011
- 2005
- 2000
- 1995
- 1989
- 1980
- 1970
- 1964
- 1959
- 1948
- 1936

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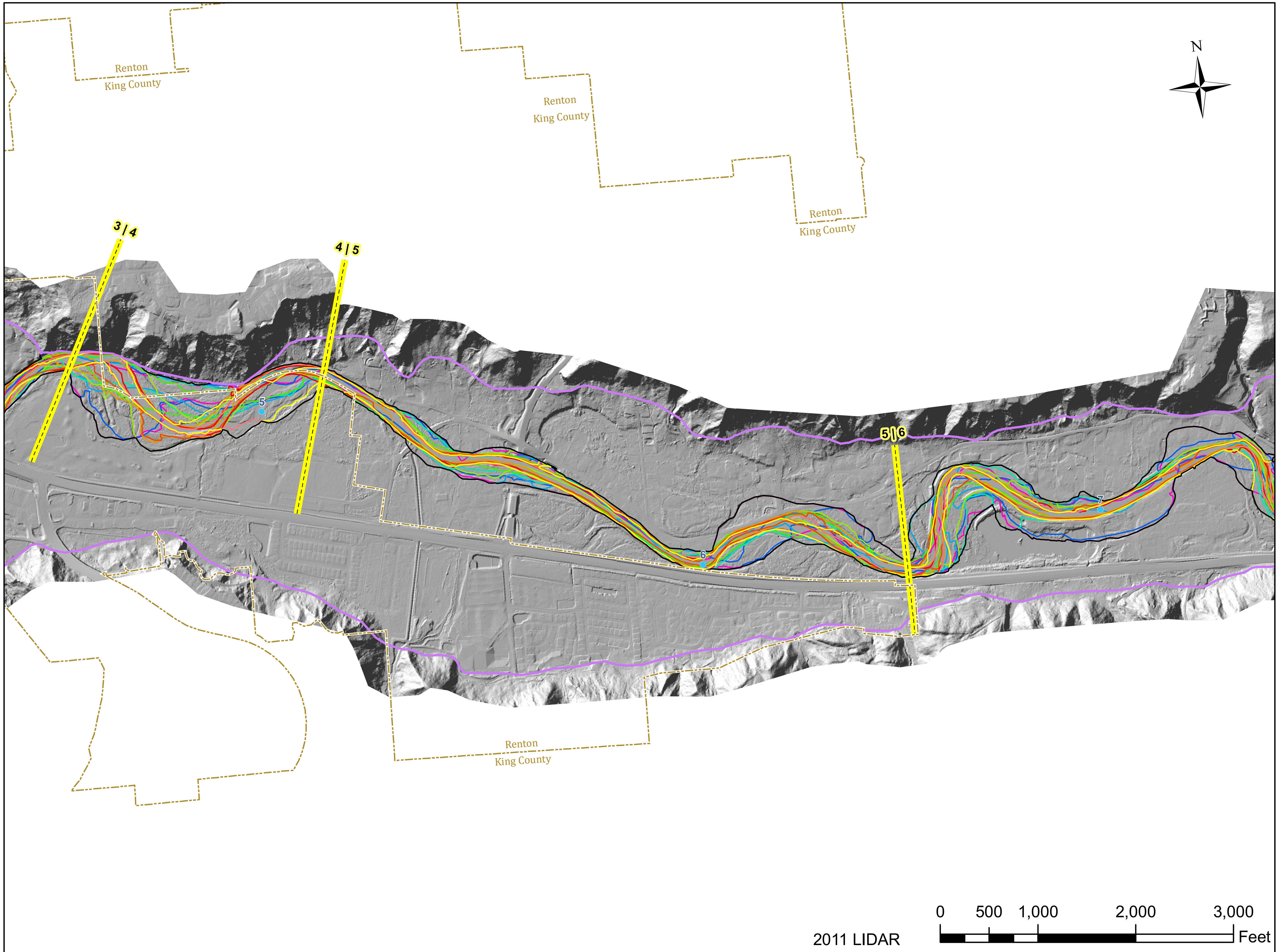

Cedar River

Map 3. Historical active channels and Historical Migration Zone (HMZ)

Panel 3 of 8

Legend

River Mile

City Boundaries

Valley Wall

Reach Boundaries

HMZ Boundary

Historical Active Channels

2011

2005

2000

1995

1989

1980

1970

1964

1959

1948

1936

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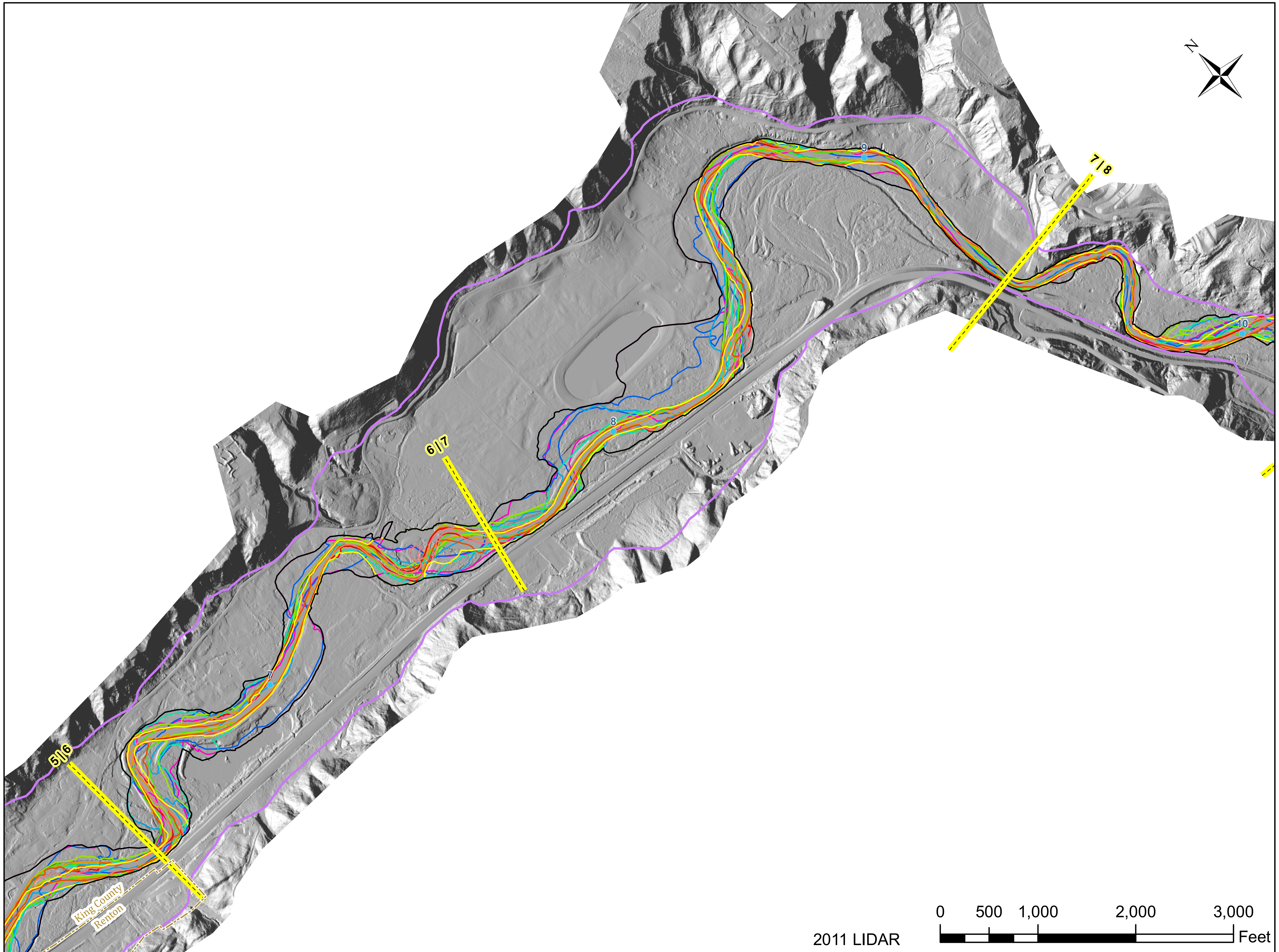

Cedar River

Map 3. Historical active channels and Historical Migration Zone (HMZ)

Panel 4 of 8

Legend

- River Mile
- City Boundaries
- Valley Wall
- Reach Boundaries
- HMZ Boundary

Historical Active Channels

- 2011
- 2005
- 2000
- 1995
- 1989
- 1980
- 1970
- 1964
- 1959
- 1948
- 1936

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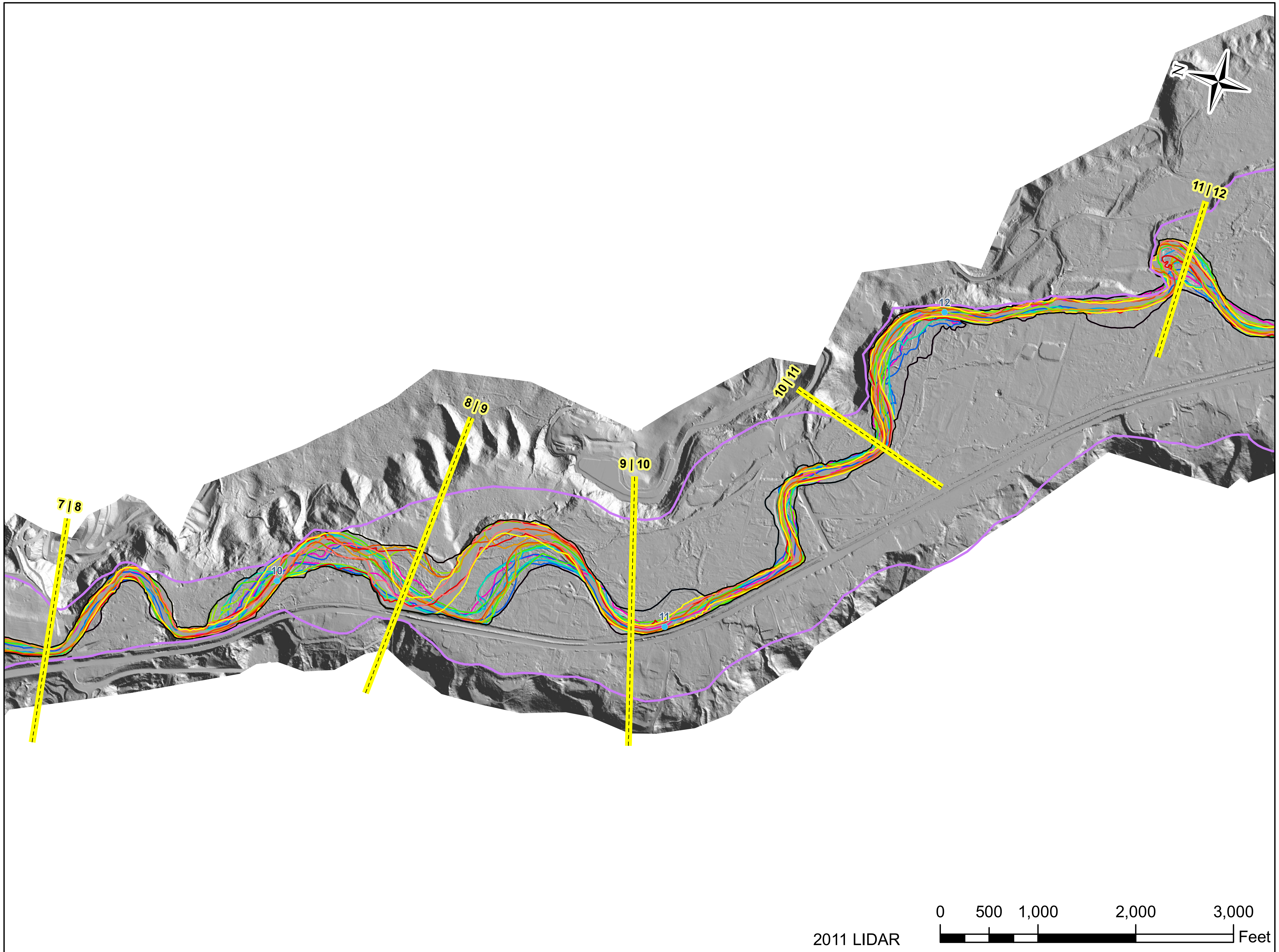
Cedar River

Map 3. Historical active channels and Historical Migration Zone (HMZ)

Panel 5 of 8



Legend

- River Mile
- City Boundaries
- Valley Wall
- Reach Boundaries
- HMZ Boundary

Historical Active Channels

- 2011
- 2005
- 2000
- 1995
- 1989
- 1980
- 1970
- 1964
- 1959
- 1948
- 1936

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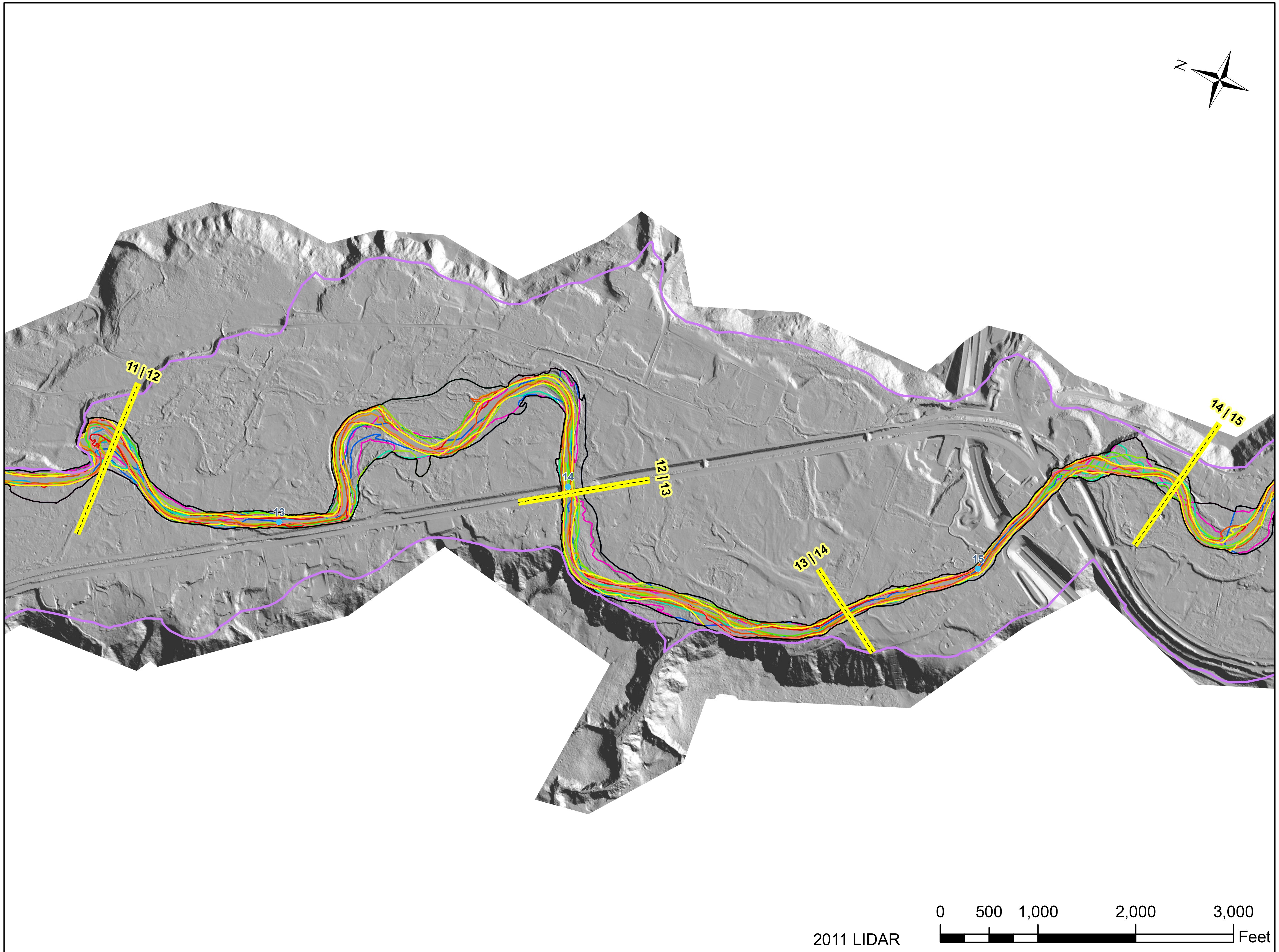

Cedar River

Map 3. Historical active channels and Historical Migration Zone (HMZ)

Panel 6 of 8

Legend

- River Mile
- City Boundaries
- Valley Wall
- Reach Boundaries
- HMZ Boundary

Historical Active Channels

- 2011
- 2005
- 2000
- 1995
- 1989
- 1980
- 1970
- 1964
- 1959
- 1948
- 1936

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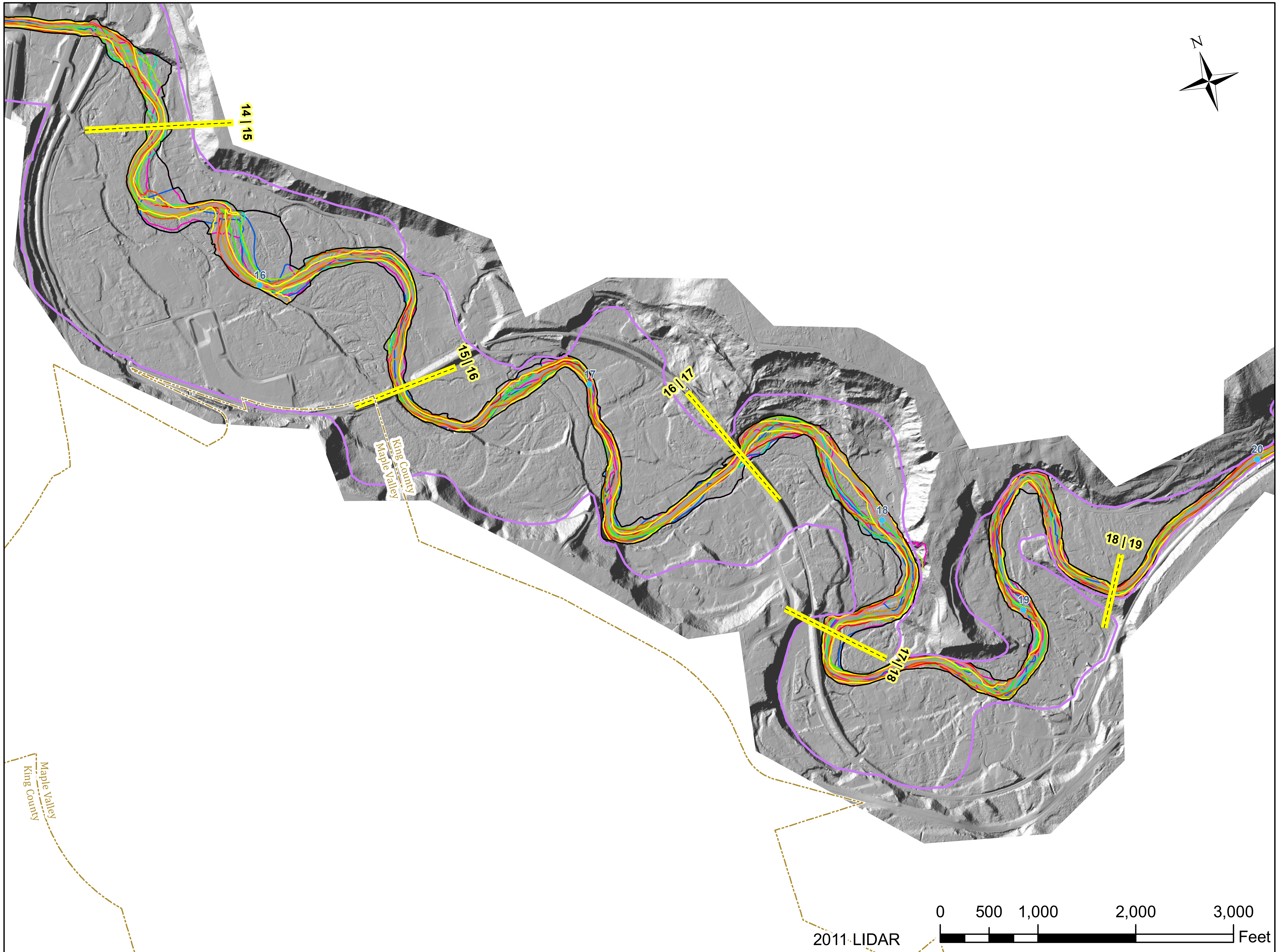
Cedar River

Map 3. Historical active channels and Historical Migration Zone (HMZ)

Panel 7 of 8



Legend

- River Mile
- City Boundaries
- Valley Wall
- Reach Boundaries
- HMZ Boundary

Historical Active Channels

- 2011
- 2005
- 2000
- 1995
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- 1980
- 1970
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- 1959
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Cedar River

Map 3. Historical active channels and Historical Migration Zone (HMZ)

Panel 8 of 8

Legend

- River Mile
- City Boundaries
- Valley Wall
- Reach Boundaries
- HMZ Boundary

Historical Active Channels

- 2011
- 2005
- 2000
- 1995
- 1989
- 1980
- 1970
- 1964
- 1959
- 1948
- 1936

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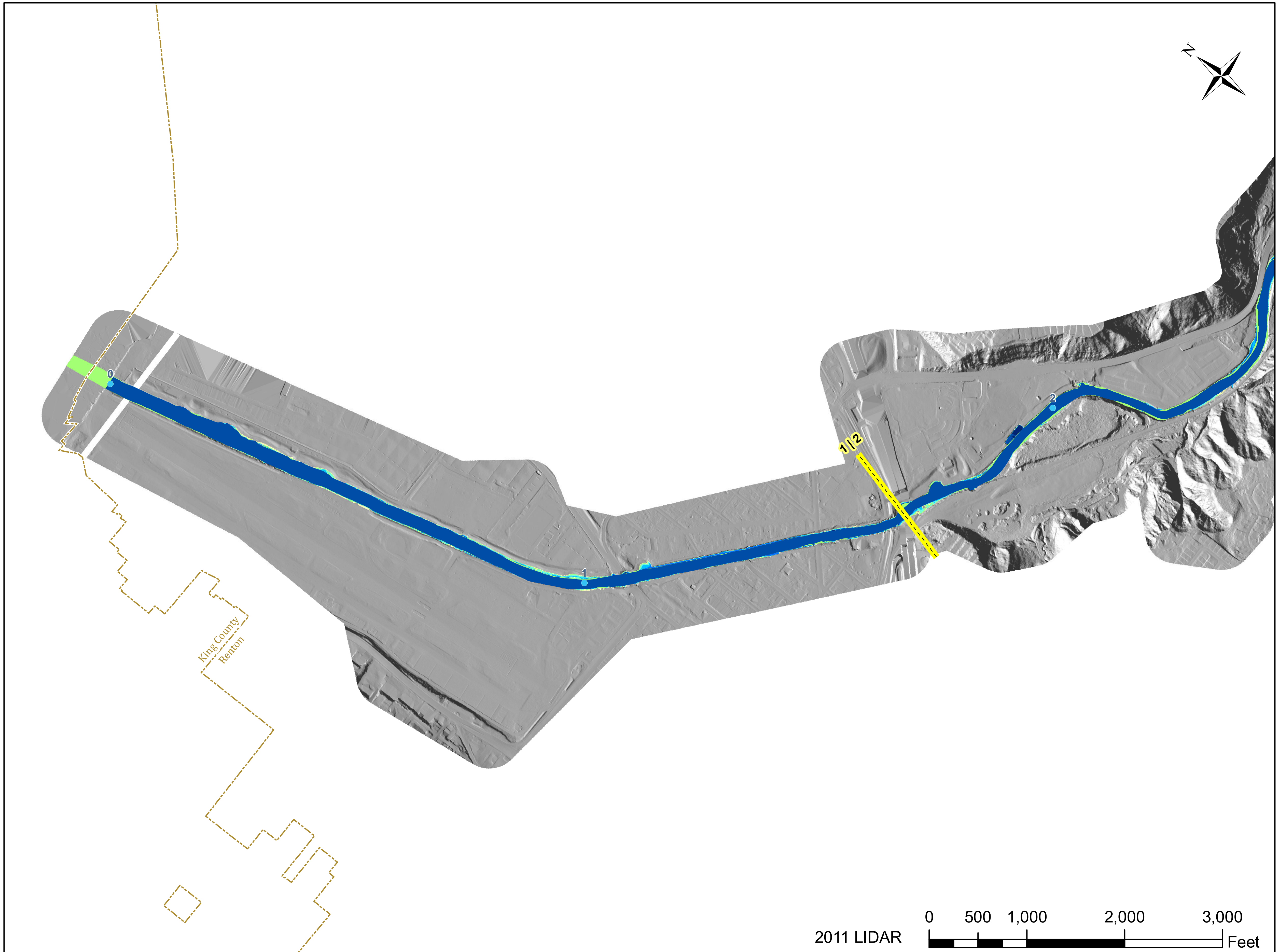

Cedar River

Map 4. Elevation difference (water surface at 5,000 cfs and surface topography)

Panel 1 of 8

Legend

- River Mile
- City Boundaries
- Reach Boundaries

Elevation Difference (feet)

- -0 to -0.5
- -0.51 to -1
- -1.01 to -2
- -2.01 to -3
- -3.01 to -4
- -4.01 to -5
- -5.01+

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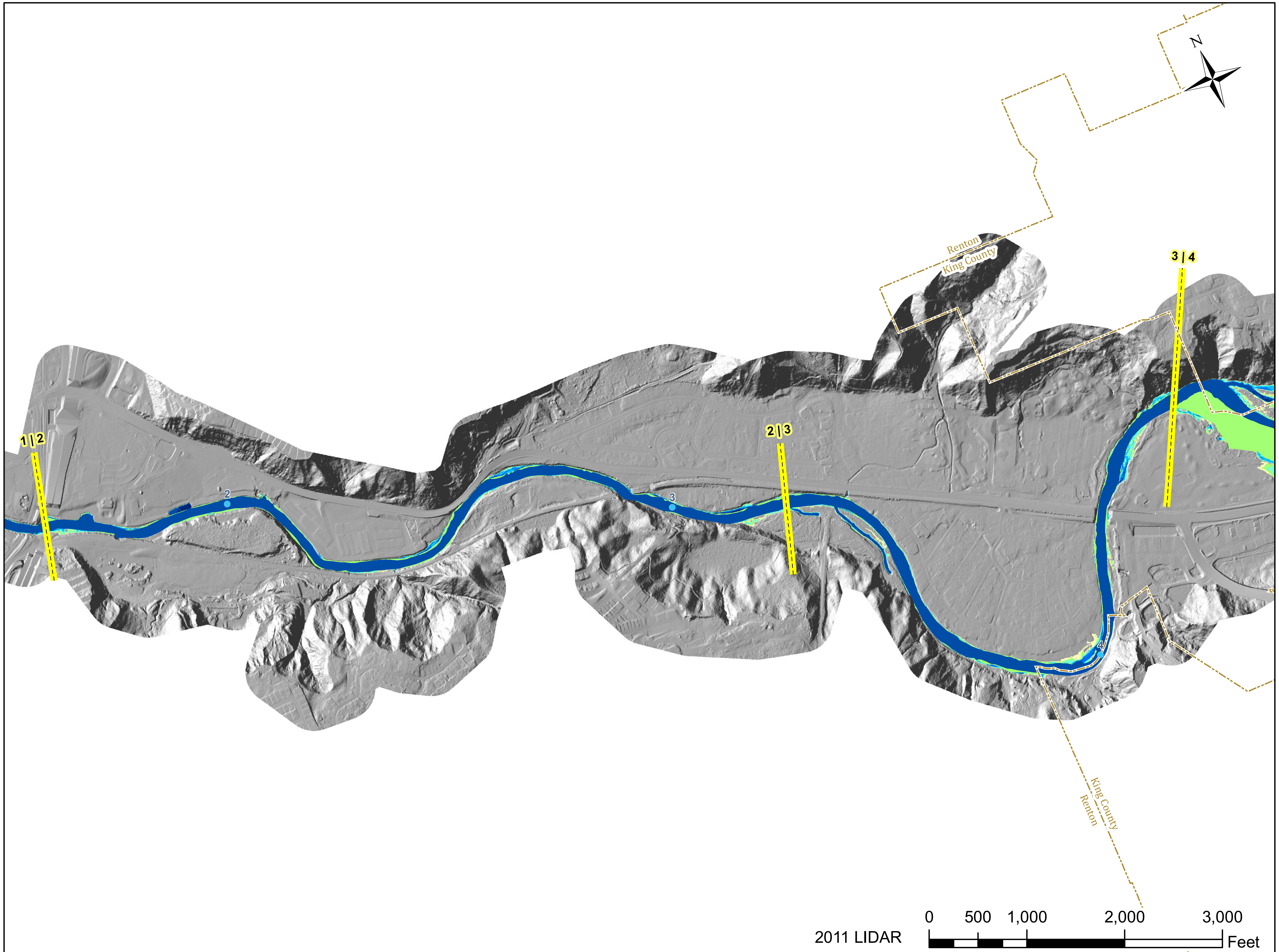
King County

Cedar River

Map 4. Elevation difference (water surface at 5,000 cfs and surface topography)

Panel 2 of 8



Legend

- River Mile
- City Boundaries
- Reach Boundaries

Elevation Difference (feet)

- -0 to -0.5
- -0.51 to -1
- -1.01 to -2
- -2.01 to -3
- -3.01 to -4
- -4.01 to -5
- -5.01+

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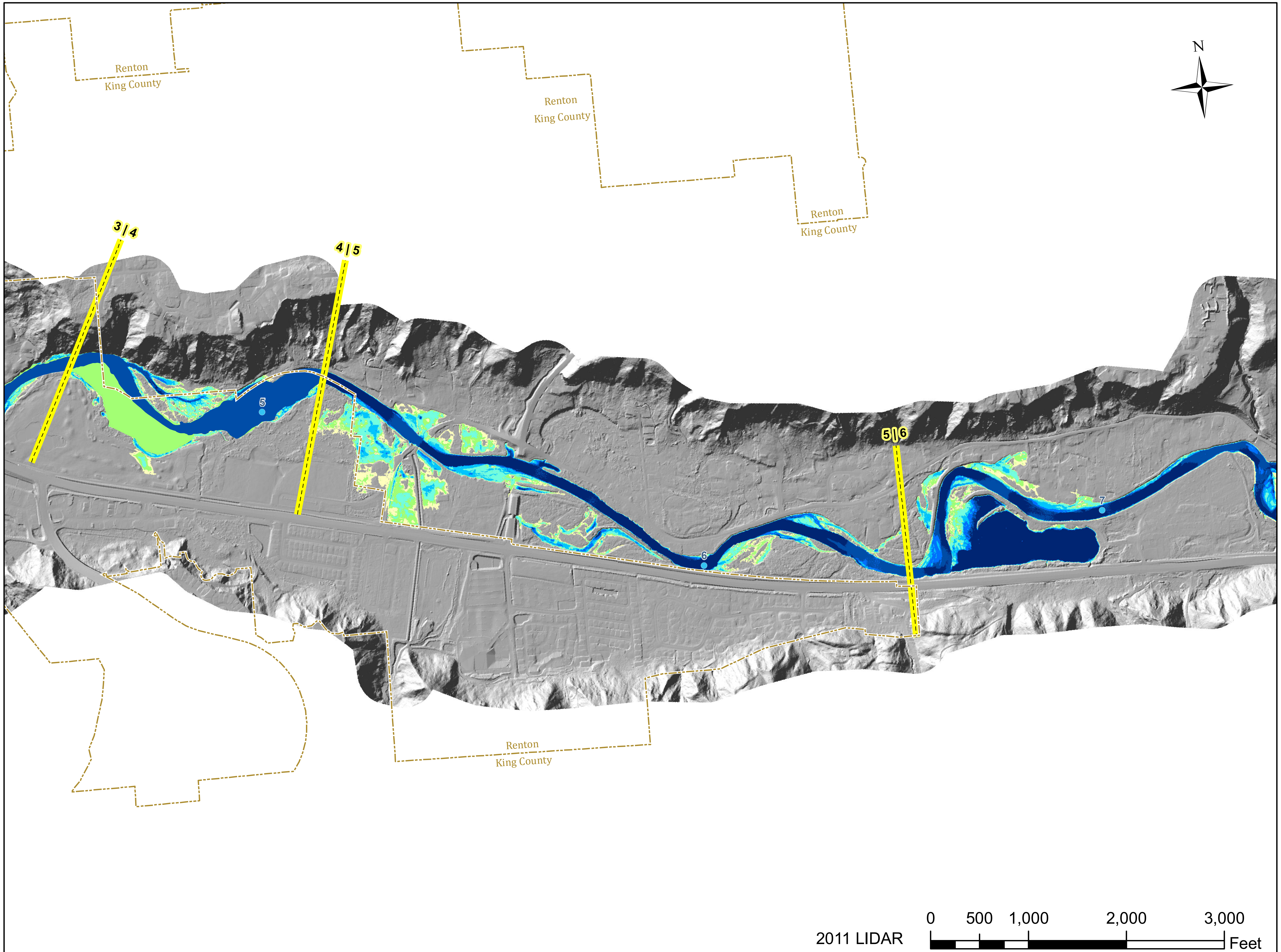

Cedar River

Map 4. Elevation difference (water surface at 5,000 cfs and surface topography)

Panel 3 of 8

Legend

- River Mile
- City Boundaries
- Reach Boundaries

Elevation Difference (feet)

- -0 to -0.5
- -0.51 to -1
- -1.01 to -2
- -2.01 to -3
- -3.01 to -4
- -4.01 to -5
- -5.01+

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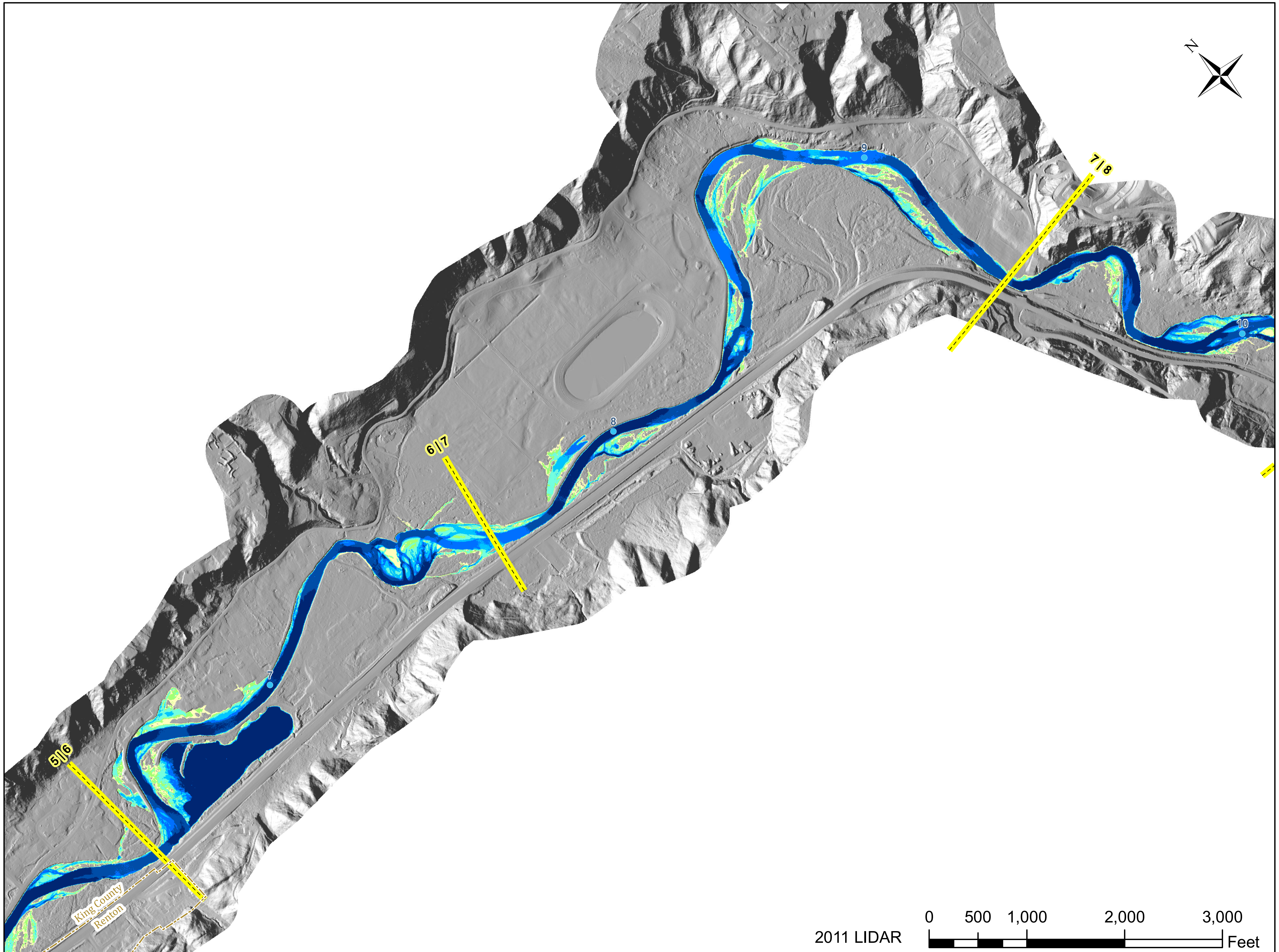

Cedar River

Map 4. Elevation difference (water surface at 5,000 cfs and surface topography)

Panel 4 of 8

Legend

- River Mile
- City Boundaries
- Reach Boundaries

Elevation Difference (feet)

- -0 to -0.5
- -0.51 to -1
- -1.01 to -2
- -2.01 to -3
- -3.01 to -4
- -4.01 to -5
- -5.01+

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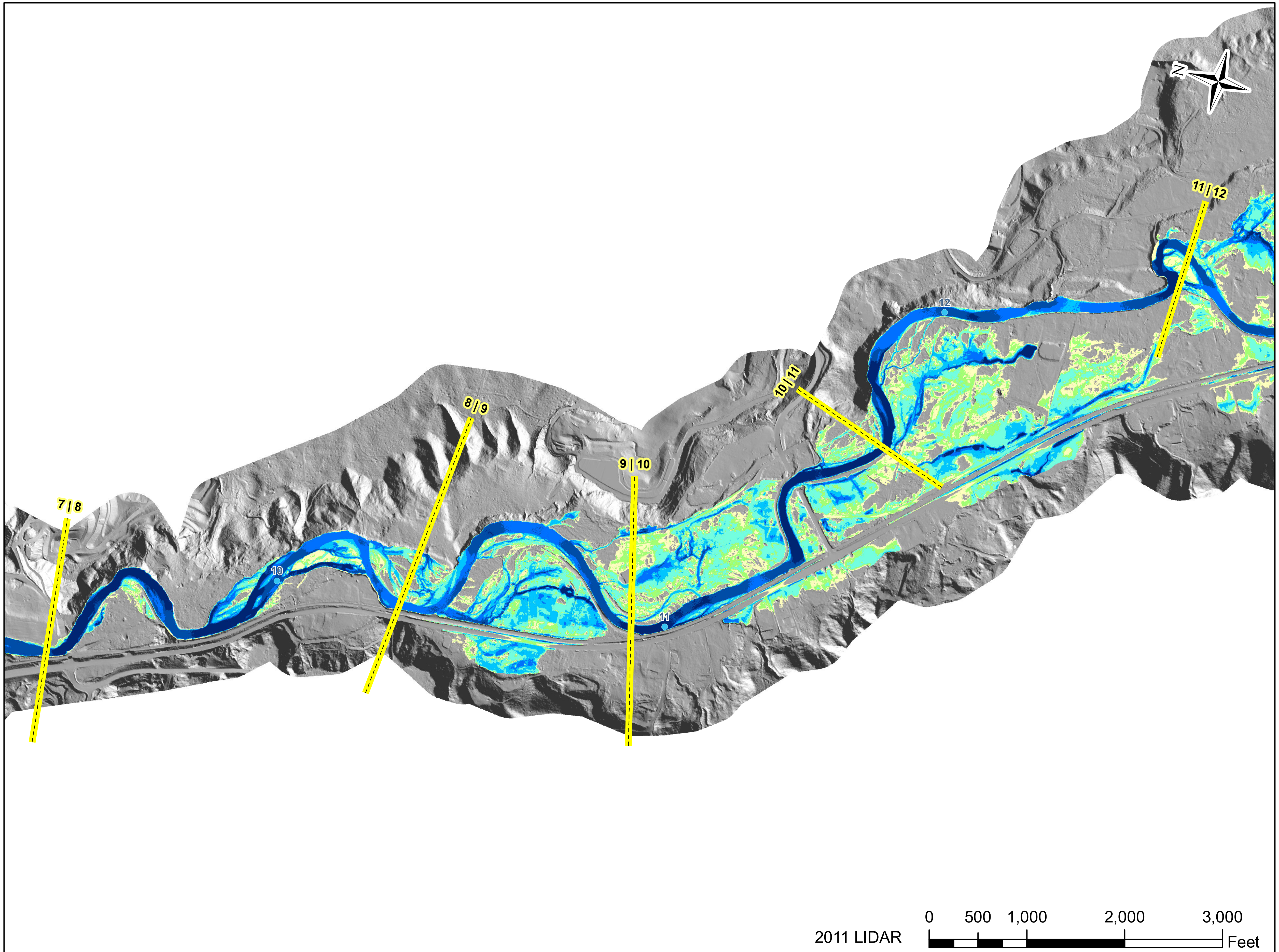
Cedar River

Map 4. Elevation difference (water surface at 5,000 cfs and surface topography)

Panel 5 of 8



Legend

- River Mile
- City Boundaries
- Reach Boundaries

Elevation Difference (feet)

- -0 to -0.5
- -0.51 to -1
- -1.01 to -2
- -2.01 to -3
- -3.01 to -4
- -4.01 to -5
- -5.01+

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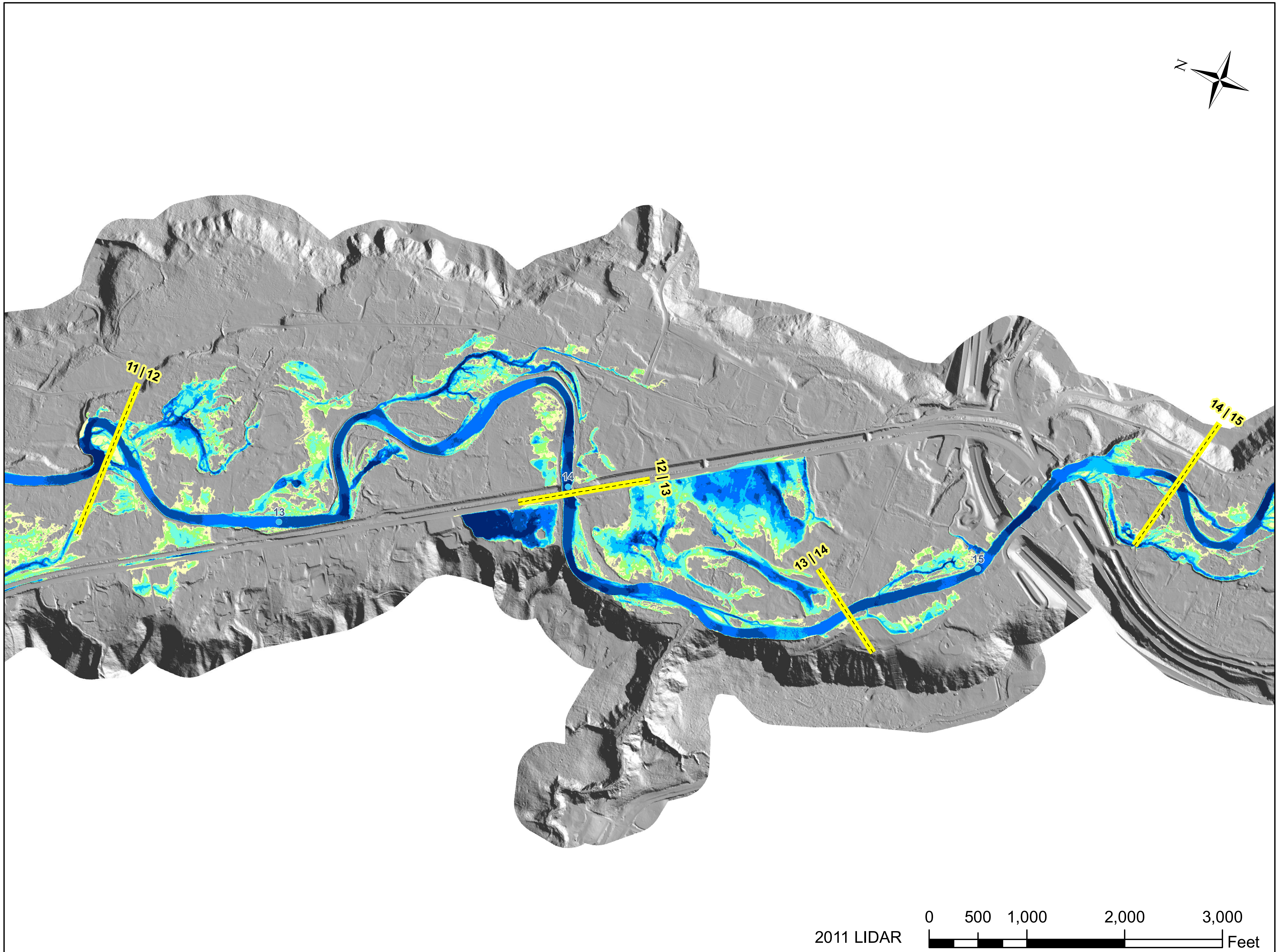

Cedar River

Map 4. Elevation difference (water surface at 5,000 cfs and surface topography)

Panel 6 of 8

Legend

River Mile

City Boundaries

Reach Boundaries

Elevation Difference (feet)

-0 to -0.5

-0.51 to -1

-1.01 to -2

-2.01 to -3

-3.01 to -4

-4.01 to -5

-5.01+

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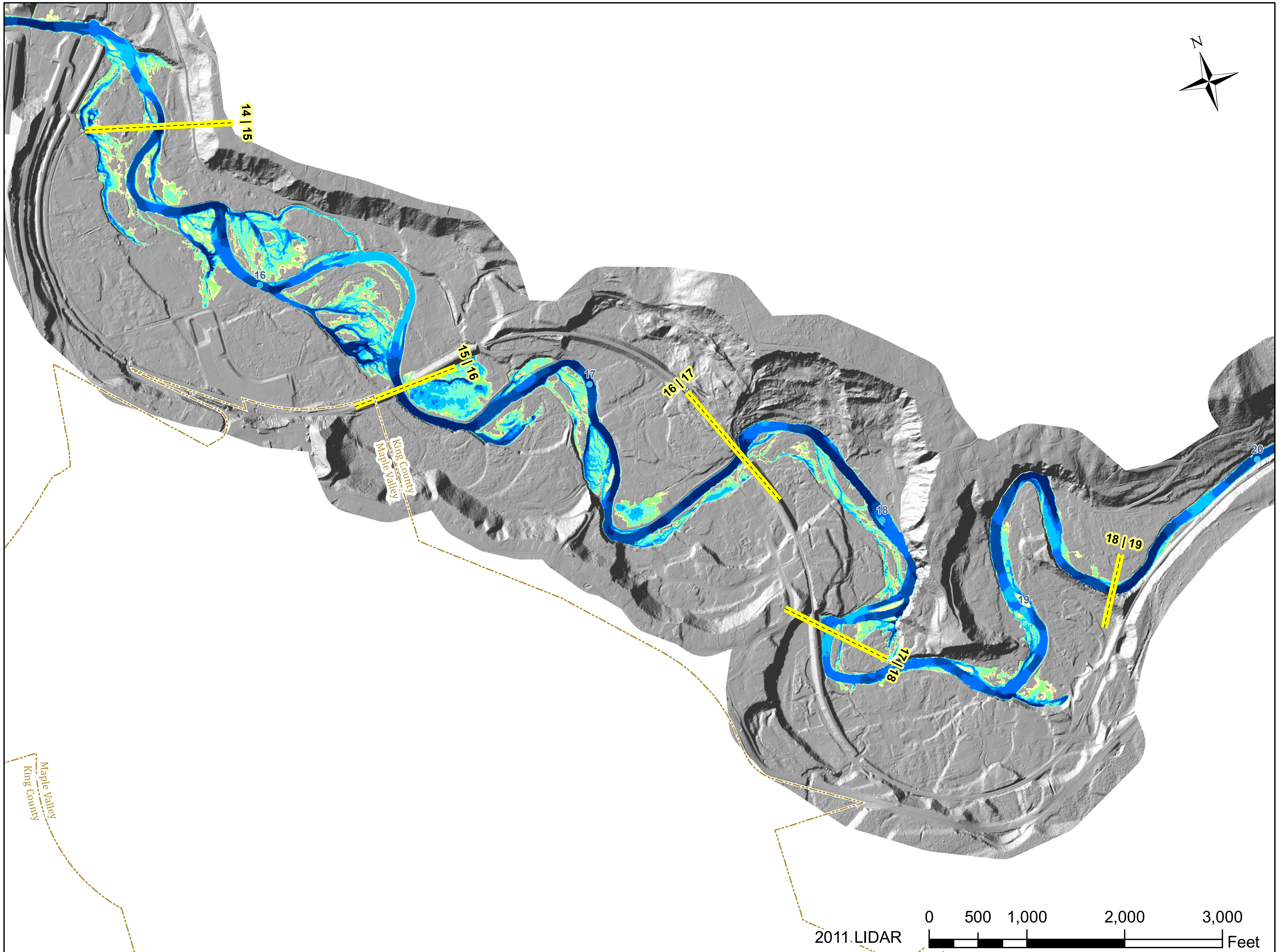

Cedar River

Map 4. Elevation difference (water surface at 5,000 cfs and surface topography)

Panel 7 of 8

Legend

- River Mile
- City Boundaries
- Reach Boundaries

Elevation Difference

(feet)

- -0 to -0.5
- -0.51 to -1
- -1.01 to -2
- -2.01 to -3
- -3.01 to -4
- -4.01 to -5
- -5.01+

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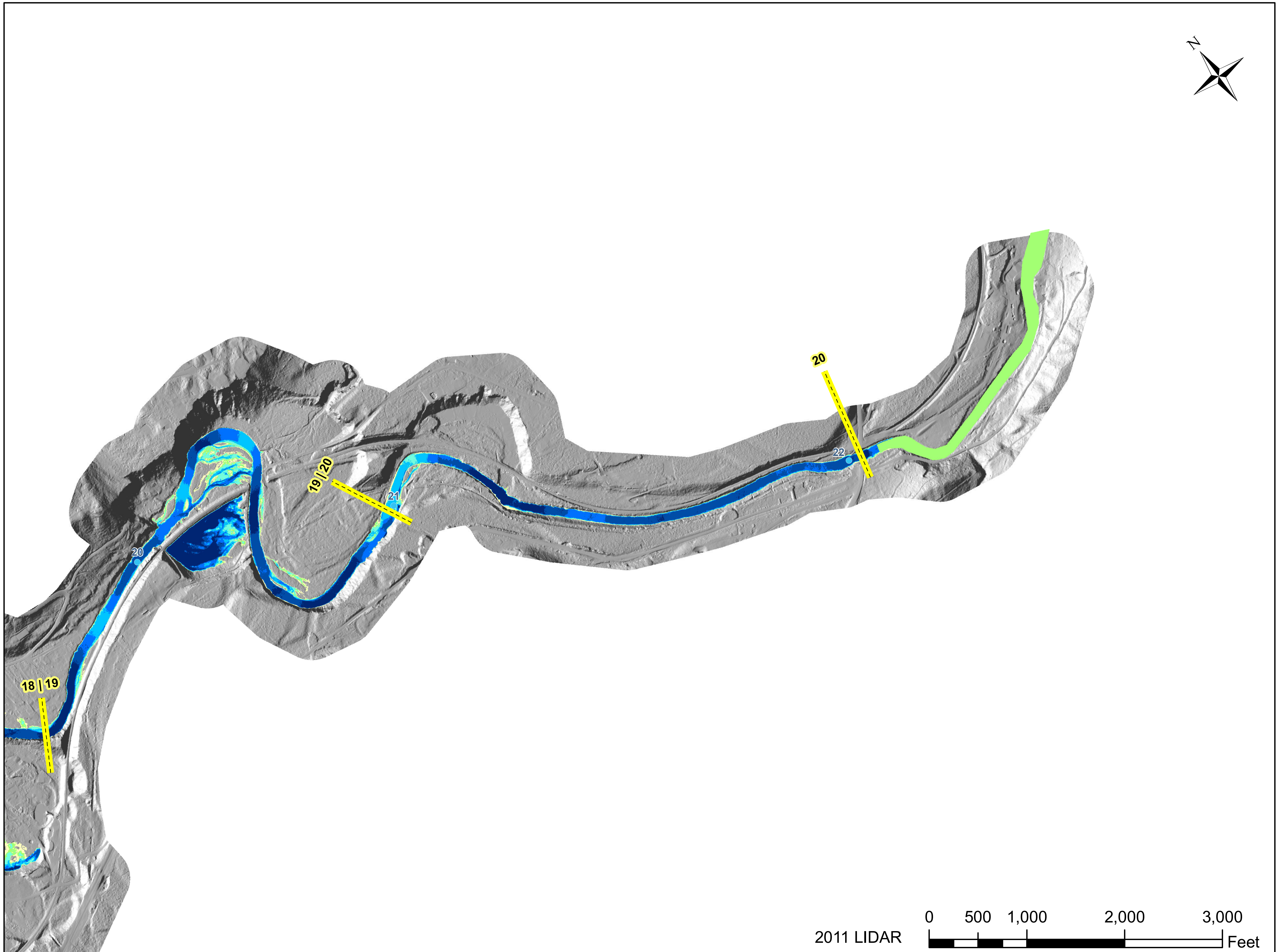

Cedar River

Map 4. Elevation difference (water surface at 5,000 cfs and surface topography)

Panel 8 of 8

Legend

- River Mile
- City Boundaries
- Reach Boundaries

Elevation Difference (feet)

- -0 to -0.5
- -0.51 to -1
- -1.01 to -2
- -2.01 to -3
- -3.01 to -4
- -4.01 to -5
- -5.01+

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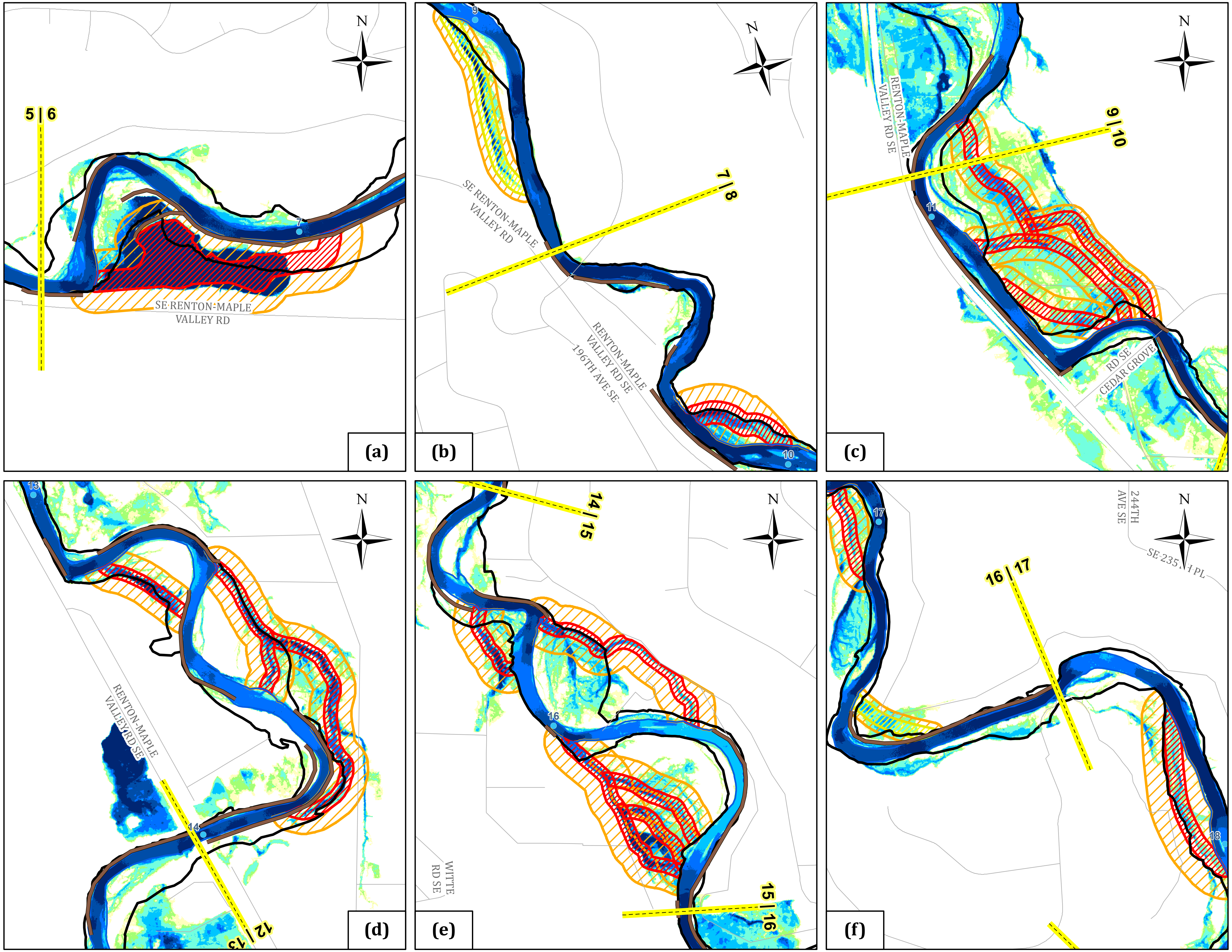

Cedar River

Map 5. Avulsion Hazard Zone (AHZ)

Legend

- River Mile
- Reach Boundaries
- Levees and Revetments
- Streets
- 2011 Active Channel
- Historical Migration Zone Boundary
- Severe AHZ
- Moderate AHZ
- AHZ Erosion Setback

Elevation difference

(feet)

- -0 to -0.5
- -0.51 to -1
- -1.01 to -2
- -2.01 to -3
- -3.01 to -4
- -4.01 to -5
- -5.01+

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0 500 1,000 Feet

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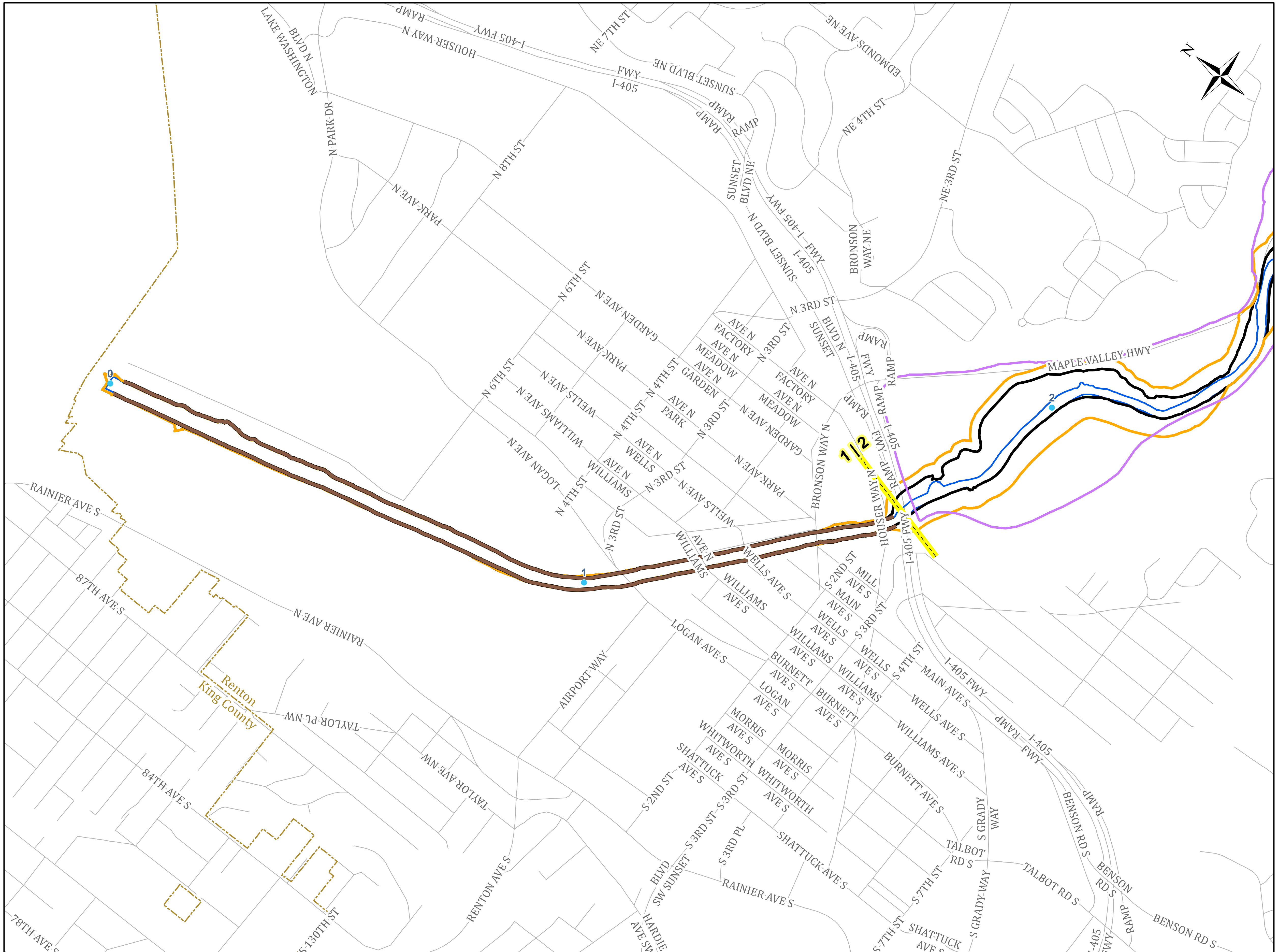
Cedar River

Map 6. Unconstrained Channel Migration Zone (CMZ)

Panel 1 of 8



Legend

- River Mile
- Valley Wall
- Reach Boundaries
- City Boundaries
- Levees and Revetments
- Unconstrained CMZ Boundary
- Historical Migration Zone Boundary
- 2011 Active Channel
- Severe Avulsion Hazard Zone (AHZ)
- Moderate AHZ
- AHZ / Erosion Setback
- Erosion Hazard Area / Geotechnical Setback
- Streets

0 500 1,000 2,000 Feet

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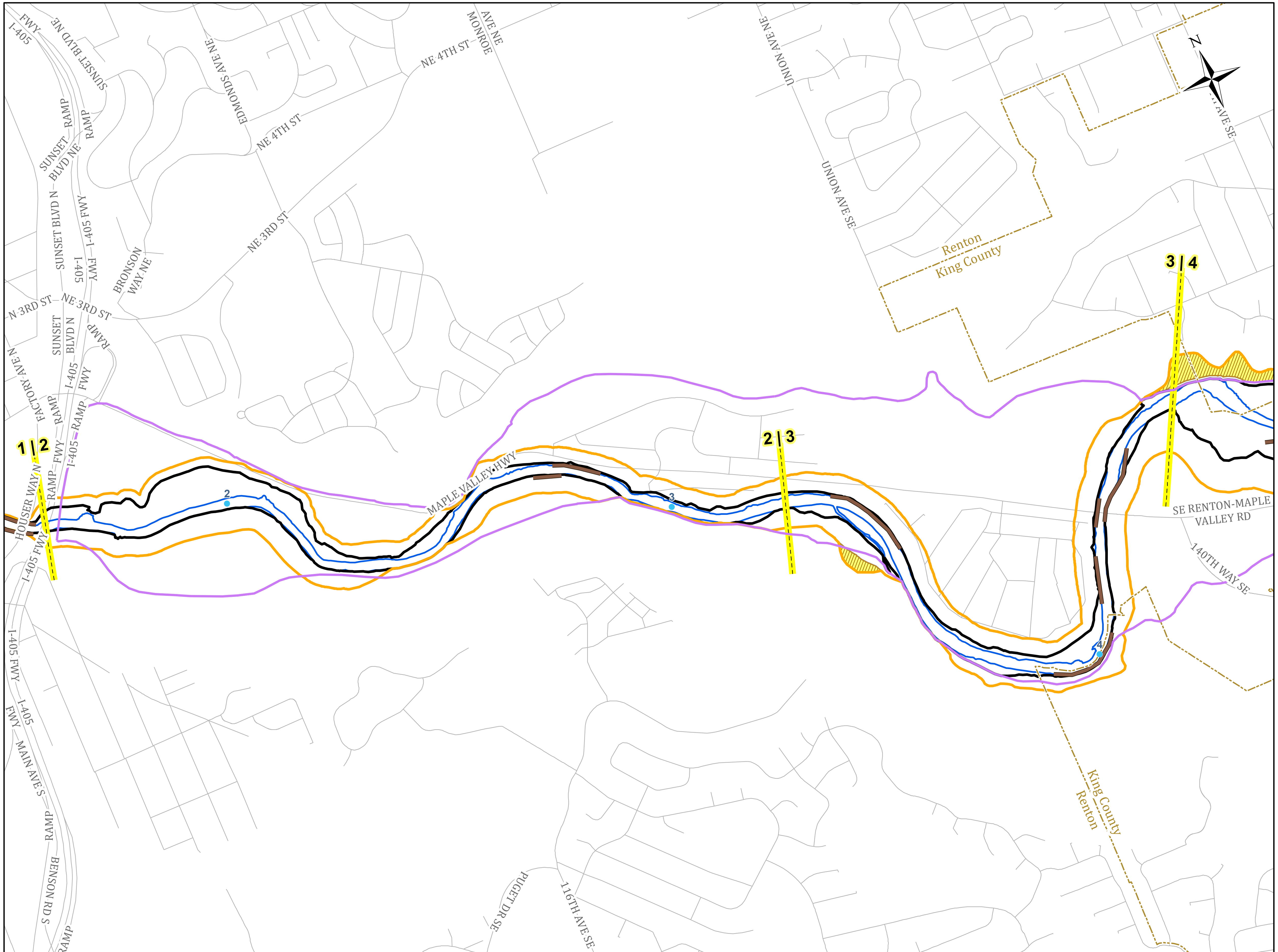

Cedar River

Map 6. Unconstrained Channel Migration Zone (CMZ)

Panel 2 of 8

Legend

- River Mile
- Valley Wall
- Reach Boundaries
- City Boundaries
- Levees and Revetments
- Unconstrained CMZ Boundary
- Historical Migration Zone Boundary
- 2011 Active Channel
- Severe Avulsion Hazard Zone (AHZ)
- Moderate AHZ
- AHZ / Erosion Setback
- Erosion Hazard Area / Geotechnical Setback
- Streets

0 500 1,000 2,000 Feet

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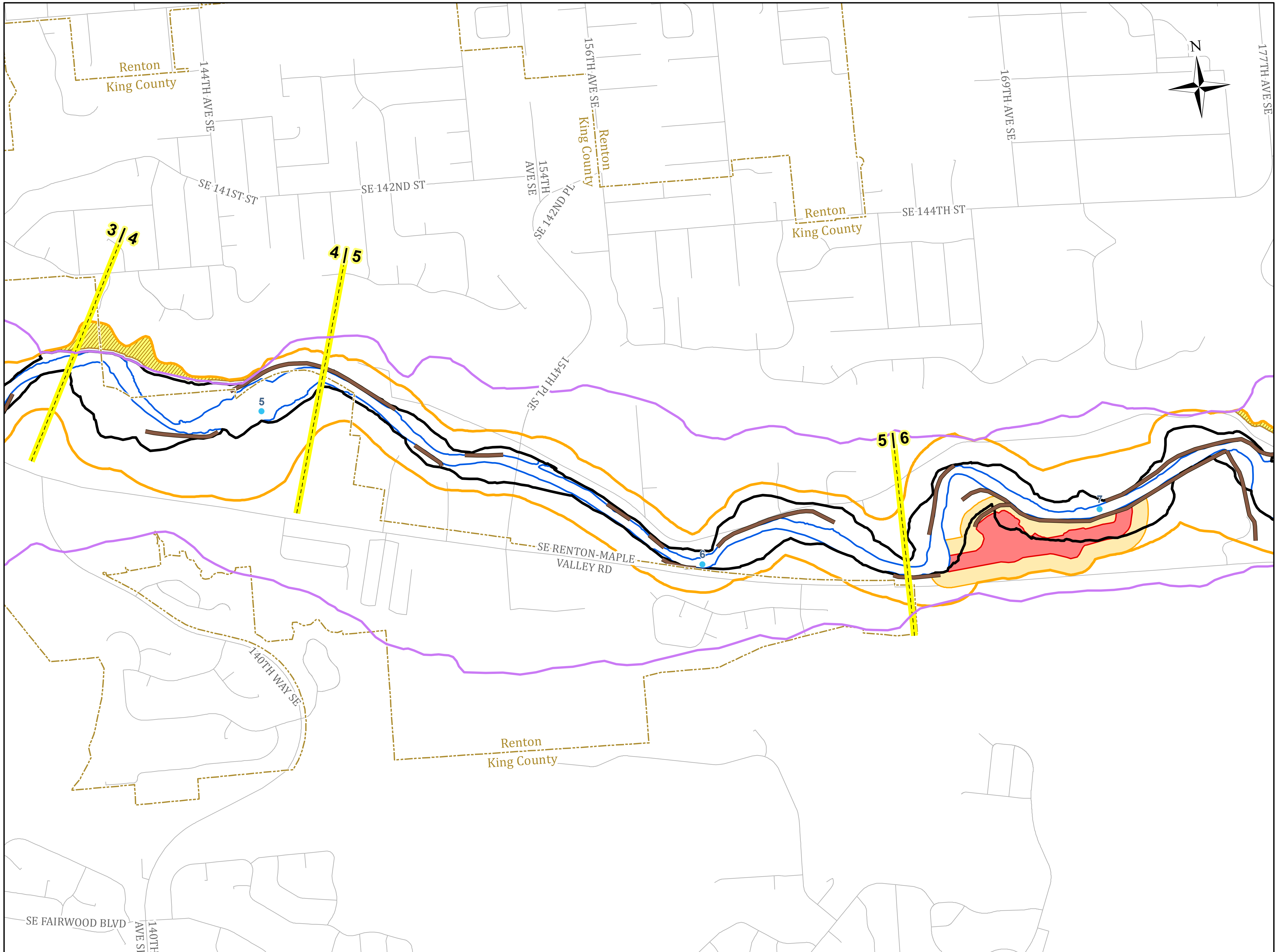
Cedar River

Map 6. Unconstrained Channel Migration Zone (CMZ)

Panel 3 of 8



Legend

- River Mile
- Valley Wall
- Reach Boundaries
- City Boundaries
- Levees and Revetments
- Unconstrained CMZ Boundary
- Historical Migration Zone Boundary
- 2011 Active Channel
- Severe Avulsion Hazard Zone (AHZ)
- Moderate AHZ
- AHZ / Erosion Setback
- Erosion Hazard Area / Geotechnical Setback
- Streets

0 500 1,000 2,000 Feet

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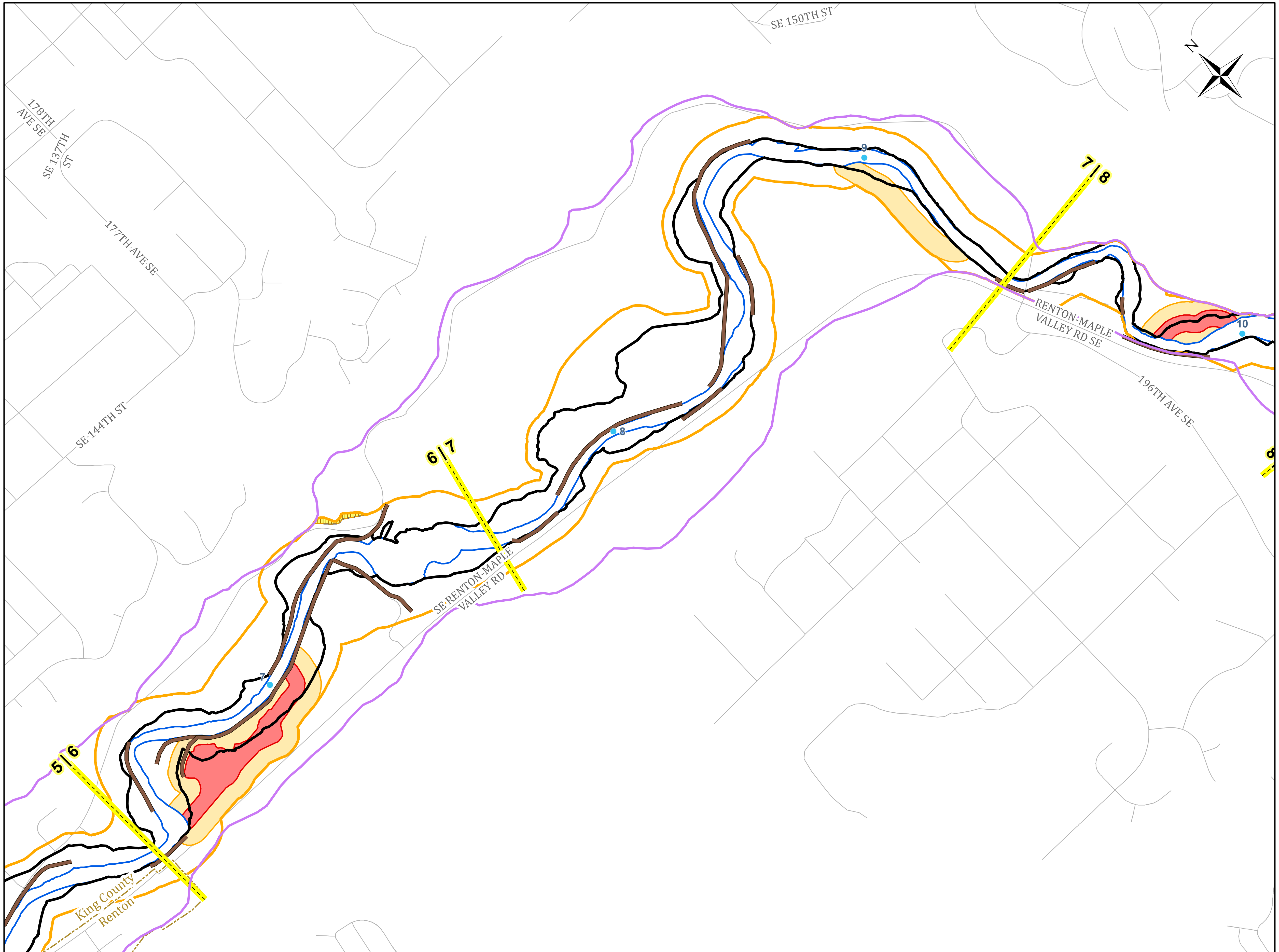
Cedar River

Map 6. Unconstrained Channel Migration Zone (CMZ)

Panel 4 of 8



Legend

- River Mile
- Valley Wall
- Reach Boundaries
- City Boundaries
- Levees and Revetments
- Unconstrained CMZ Boundary
- Historical Migration Zone Boundary
- 2011 Active Channel
- Severe Avulsion Hazard Zone (AHZ)
- Moderate AHZ
- AHZ / Erosion Setback
- Erosion Hazard Area / Geotechnical Setback
- Streets

0 500 1,000 2,000 Feet

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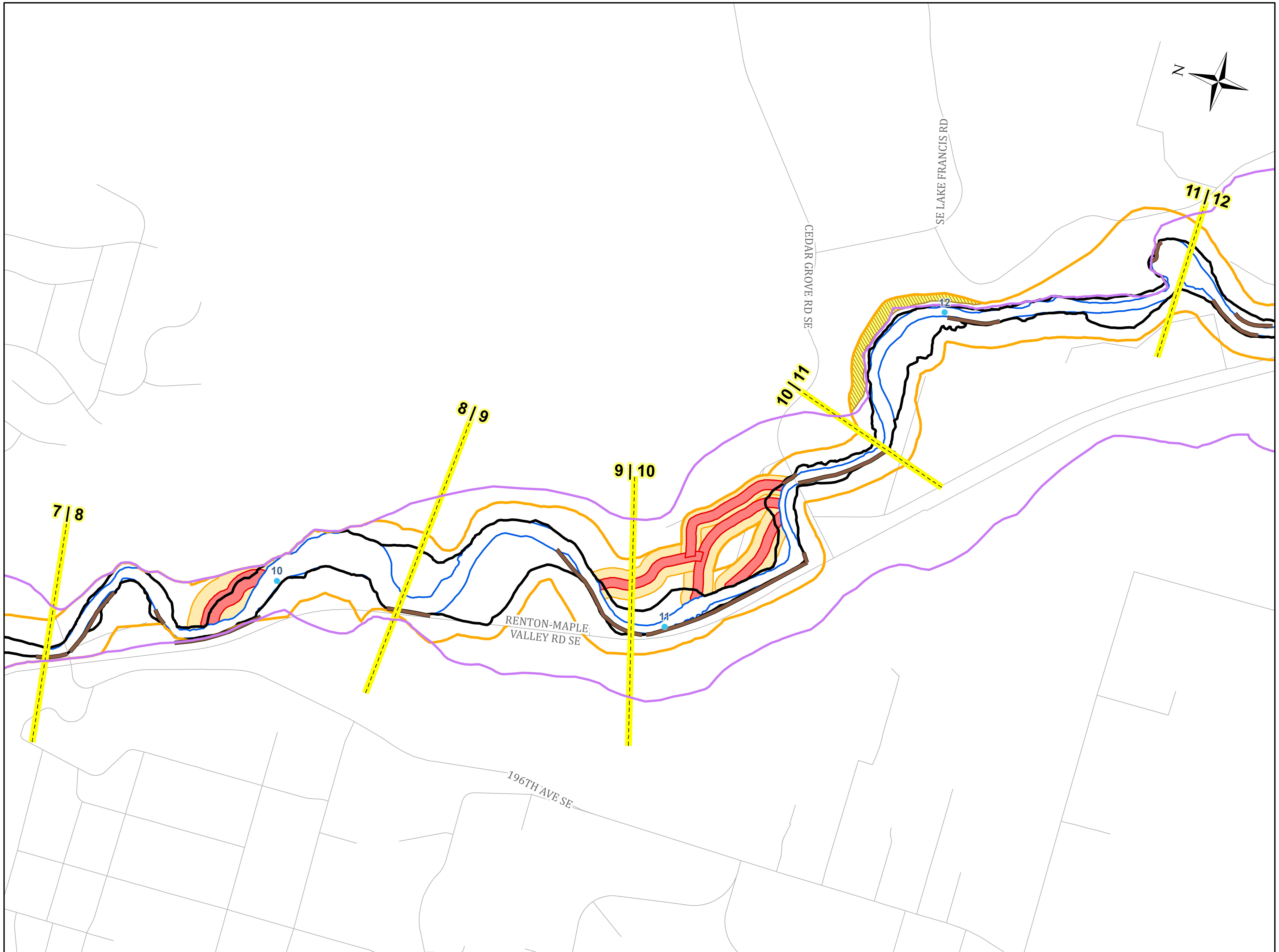
Cedar River

Map 6. Unconstrained Channel Migration Zone (CMZ)

Panel 5 of 8



Legend

- River Mile
- Valley Wall
- Reach Boundaries
- City Boundaries
- Levees and Revetments
- Unconstrained CMZ Boundary
- Historical Migration Zone Boundary
- 2011 Active Channel
- Severe Avulsion Hazard Zone (AHZ)
- Moderate AHZ
- AHZ / Erosion Setback
- Erosion Hazard Area / Geotechnical Setback
- Streets

0 500 1,000 2,000 Feet

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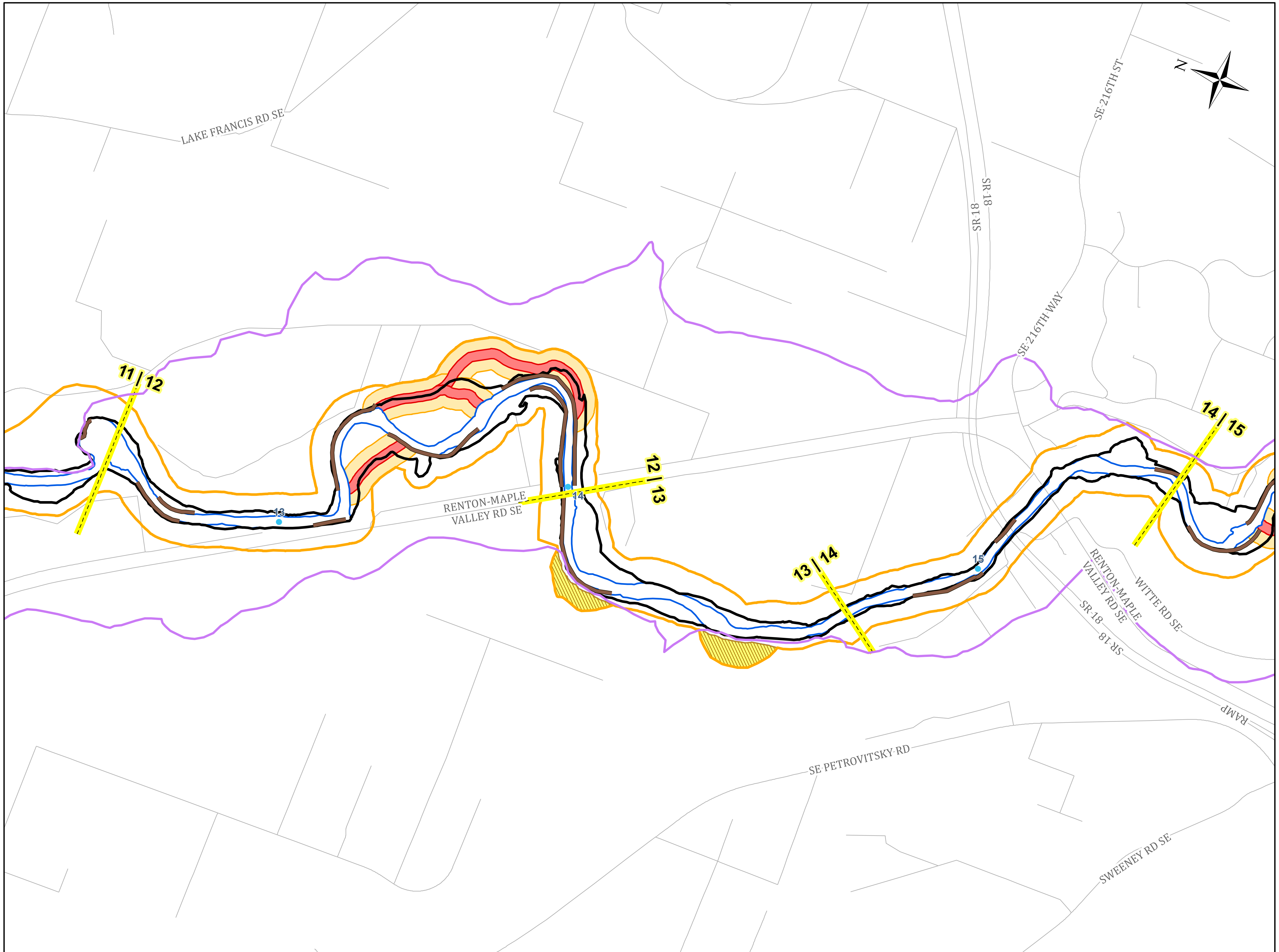
Cedar River

Map 6. Unconstrained Channel Migration Zone (CMZ)

Panel 6 of 8



Legend

- River Mile
- Valley Wall
- Reach Boundaries
- City Boundaries
- Levees and Revetments
- Unconstrained CMZ Boundary
- Historical Migration Zone Boundary
- 2011 Active Channel
- Severe Avulsion Hazard Zone (AHZ)
- Moderate AHZ
- AHZ / Erosion Setback
- Erosion Hazard Area / Geotechnical Setback
- Streets

0 500 1,000 2,000 Feet

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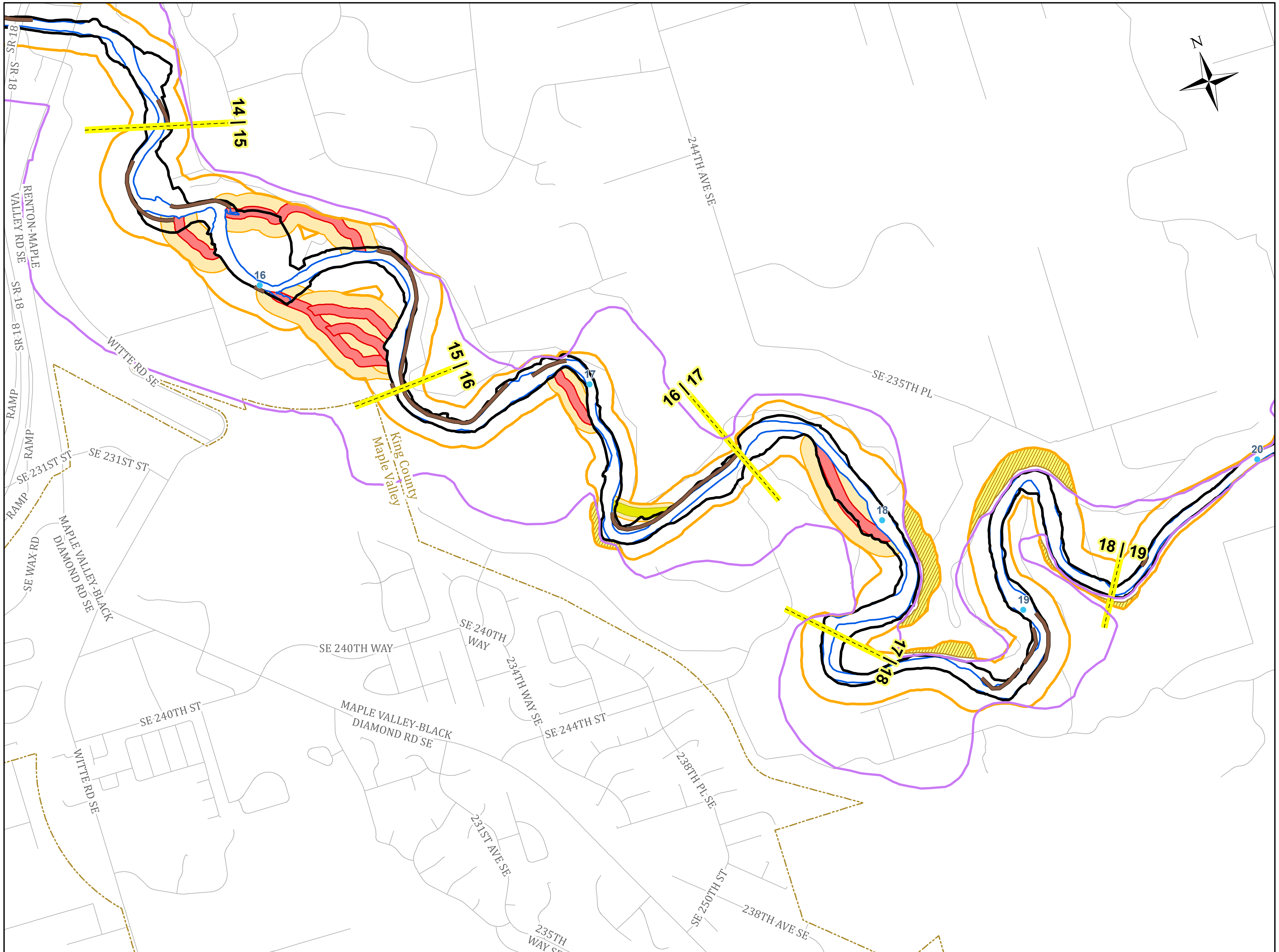
Cedar River

Map 6. Unconstrained Channel Migration Zone (CMZ)



Legend

- River Mile
- Valley Wall
- Reach Boundaries
- City Boundaries
- Levees and Revetments
- Unconstrained CMZ Boundary
- Historical Migration Zone Boundary
- 2011 Active Channel
- Severe Avulsion Hazard Zone (AHZ)
- Moderate AHZ
- AHZ / Erosion Setback
- Erosion Hazard Area / Geotechnical Setback
- Streets

0 500 1,000 2,000 Feet

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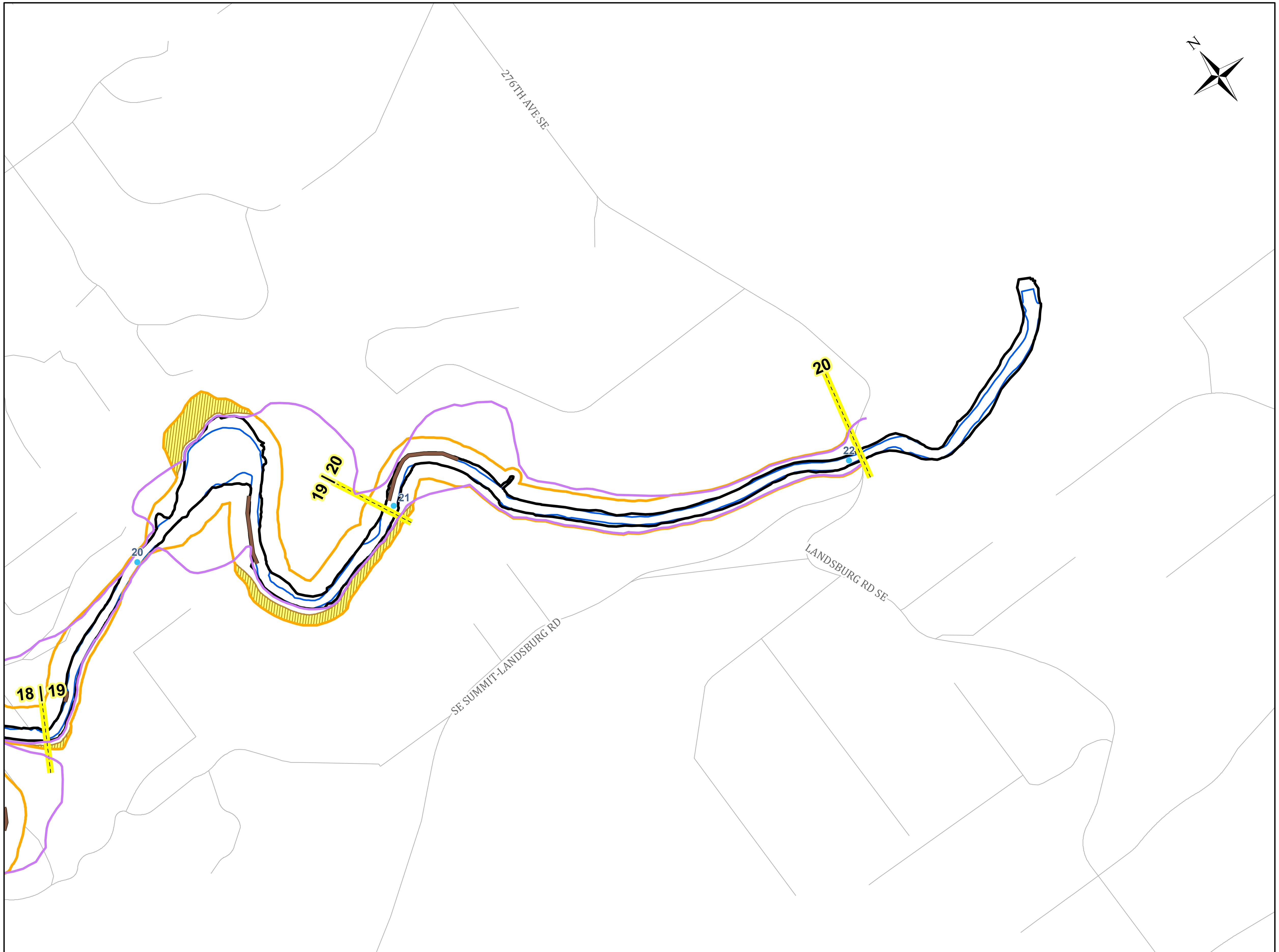

Cedar River

Map 6. Unconstrained Channel Migration Zone (CMZ)

Panel 8 of 8

Legend

- River Mile
- Valley Wall
- Reach Boundaries
- City Boundaries
- Levees and Revetments
- Unconstrained CMZ Boundary
- Historical Migration Zone Boundary
- 2011 Active Channel
- Severe Avulsion Hazard Zone (AHZ)
- Moderate AHZ
- AHZ / Erosion Setback
- Erosion Hazard Area / Geotechnical Setback
- Streets

0 500 1,000 2,000 Feet

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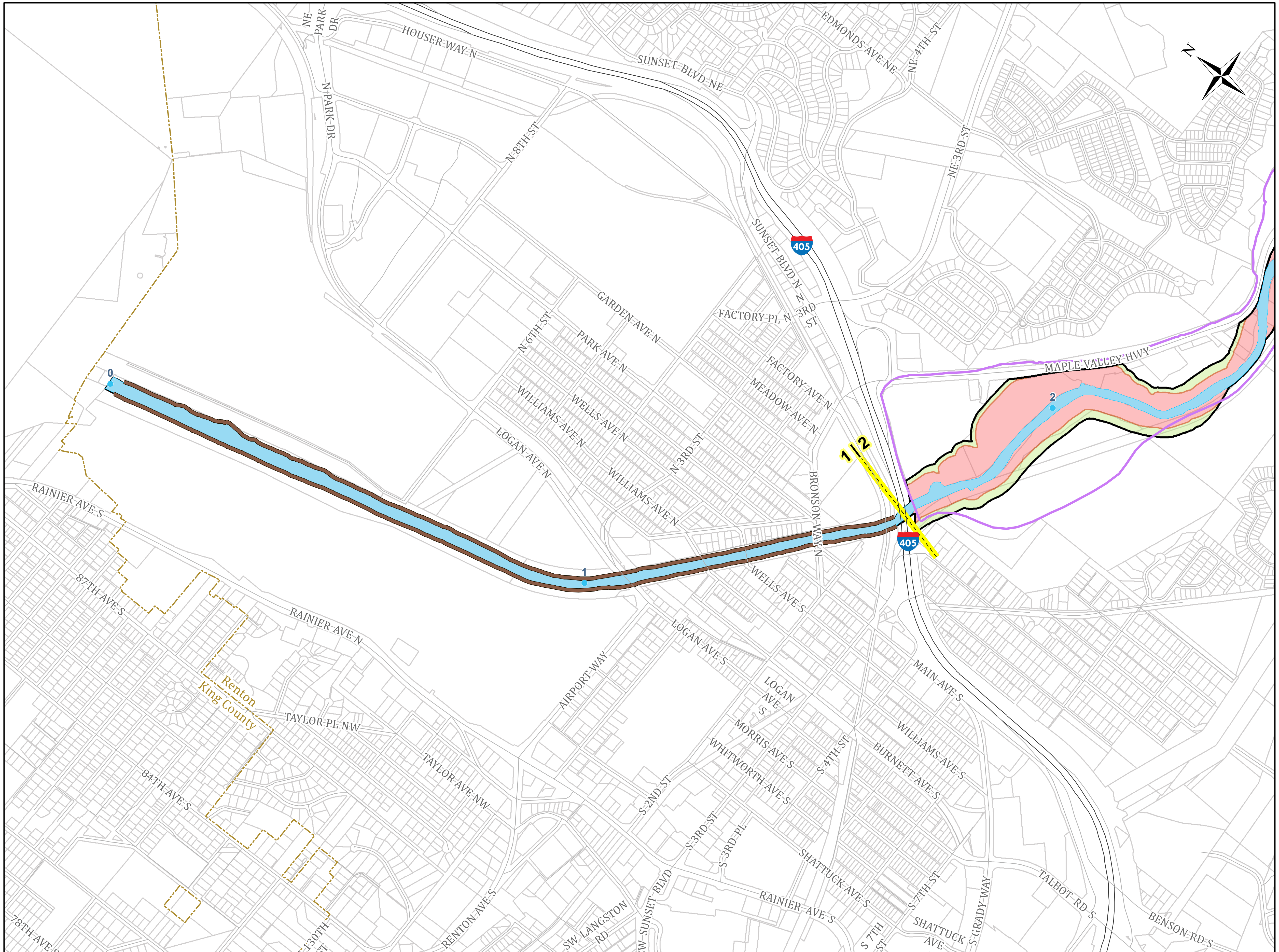

Cedar River

Map 7. Cedar River Channel Migration Zone (CMZ)

N

Panel 1 of 8

Legend

- River Mile
- City Boundaries
- Reach Boundaries
- Levees and Revetments
- Valley Wall
- Streets
- Parcels
- 2011 Active Channel
- CMZ Boundary
- Severe Hazard Area
- Moderate Hazard Area

Feet
0 500 1,000 2,000

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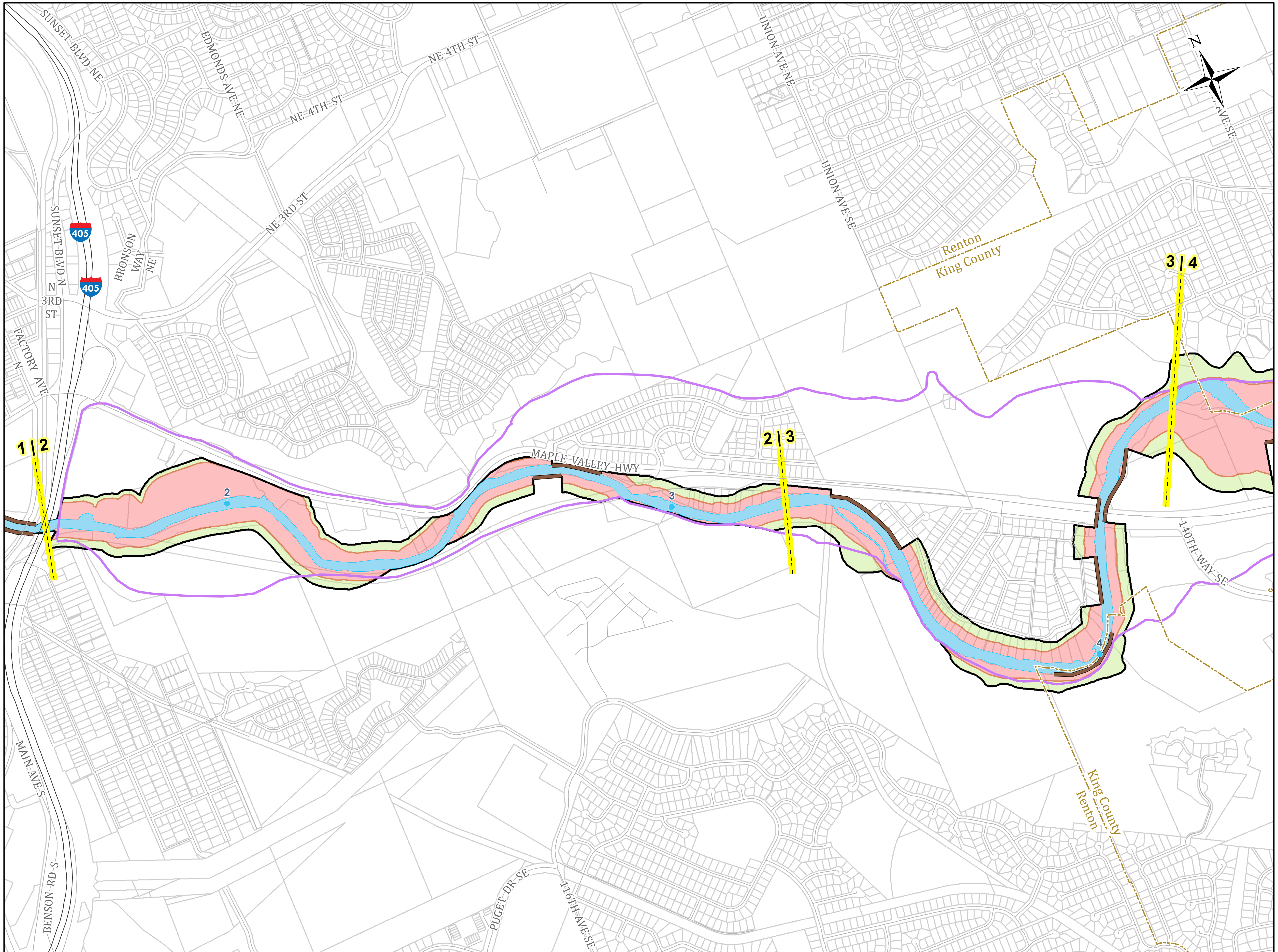

Cedar River

Map 7. Cedar River Channel Migration Zone (CMZ)

Panel 2 of 8

Legend

- River Mile
- City Boundaries
- Reach Boundaries
- Levees and Revetments
- Valley Wall
- Streets
- Parcels
- 2011 Active Channel
- CMZ Boundary
- Severe Hazard Area
- Moderate Hazard Area

Feet
0 500 1,000 2,000

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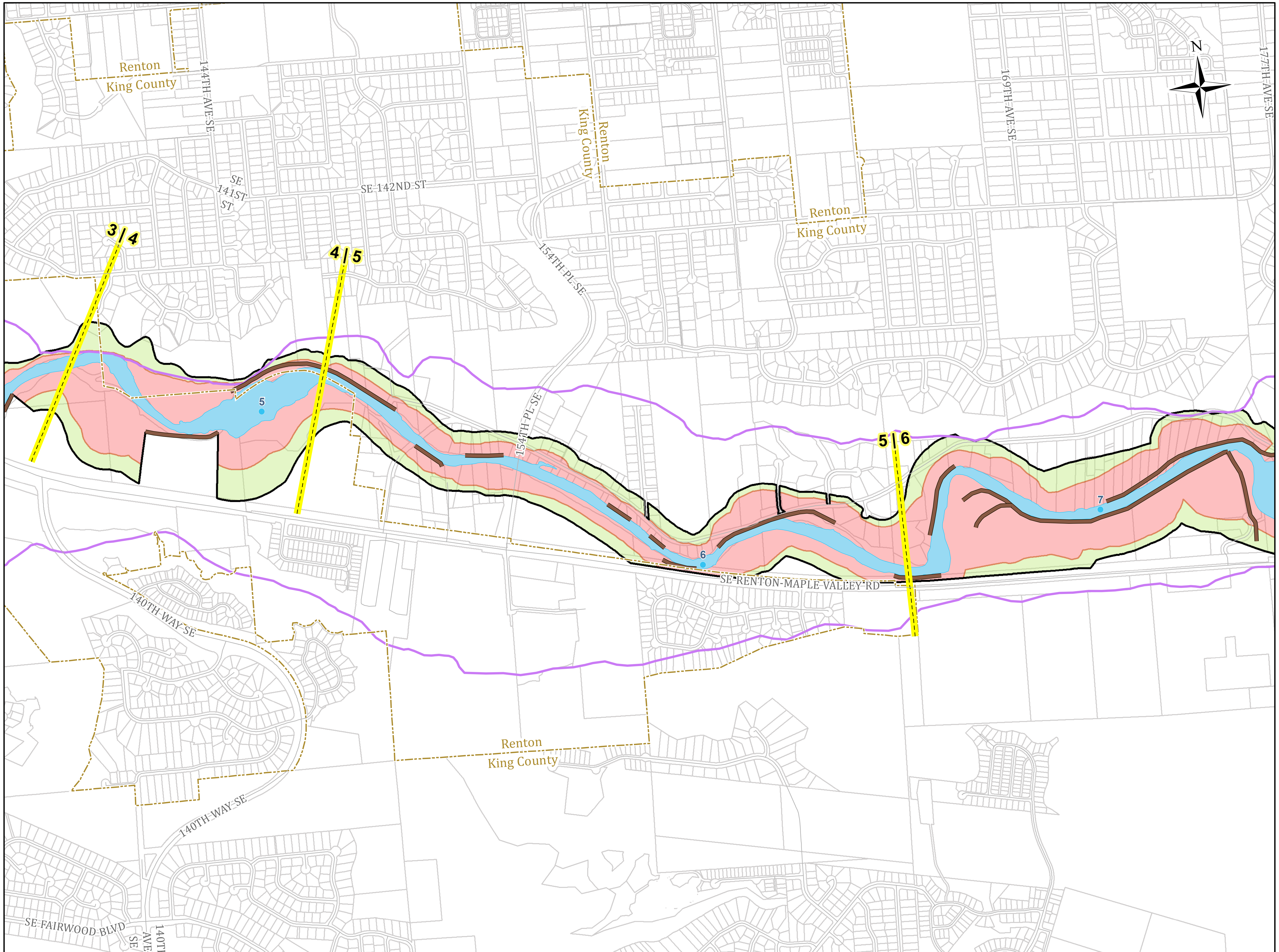
Cedar River

Map 7. Cedar River Channel Migration Zone (CMZ)

Panel 3 of 8



Legend

- River Mile
- City Boundaries
- Reach Boundaries
- Levees and Revetments
- Valley Wall
- Streets
- Parcels
- 2011 Active Channel
- CMZ Boundary
- Severe Hazard Area
- Moderate Hazard Area

Feet
0 500 1,000 2,000

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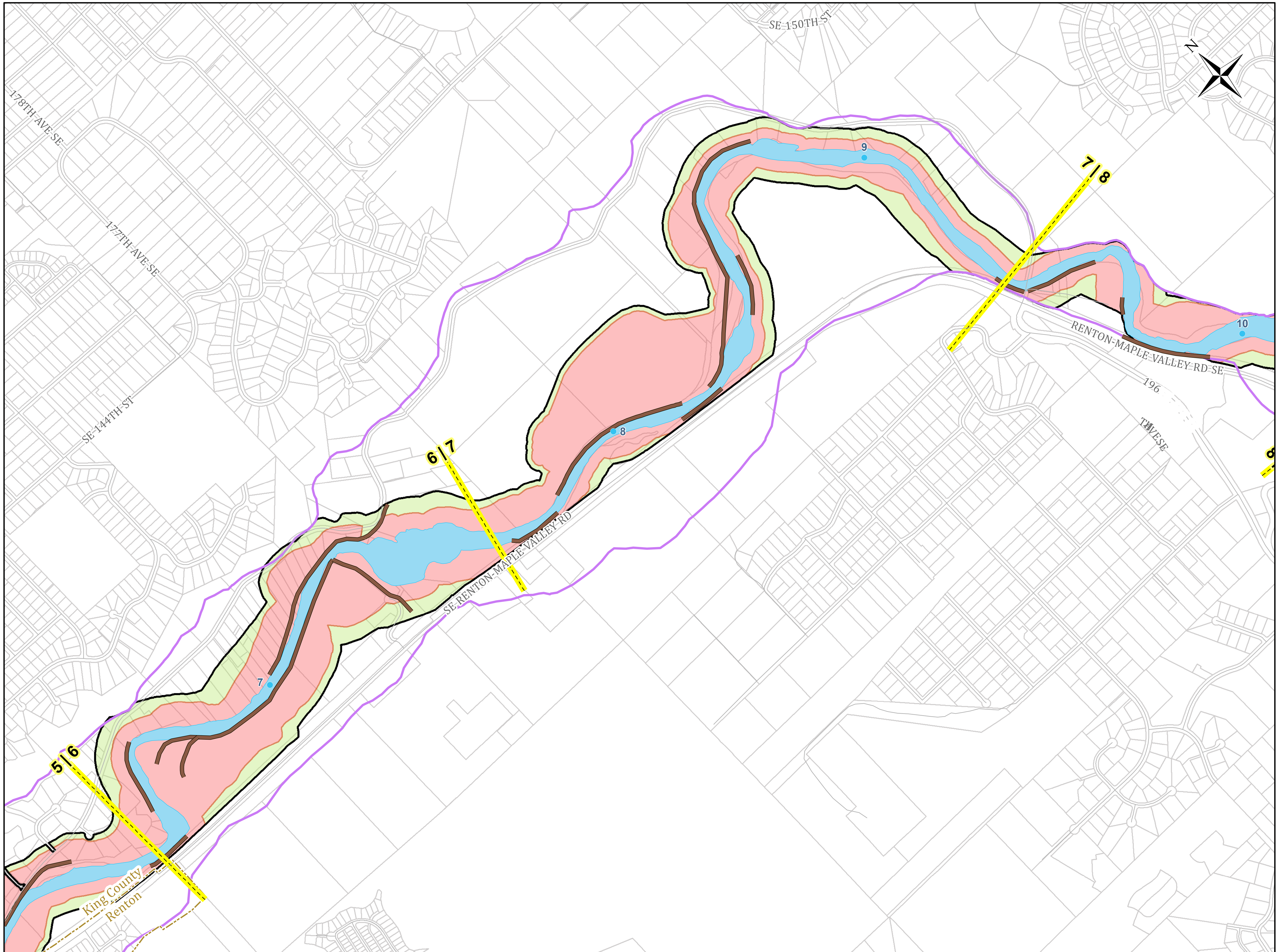

Cedar River

Map 7. Cedar River Channel Migration Zone (CMZ)

Panel 4 of 8

Legend

- River Mile
- City Boundaries
- Reach Boundaries
- Levees and Revetments
- Valley Wall
- Streets
- Parcels
- 2011 Active Channel
- CMZ Boundary
- Severe Hazard Area
- Moderate Hazard Area

Feet

0 500 1,000 2,000

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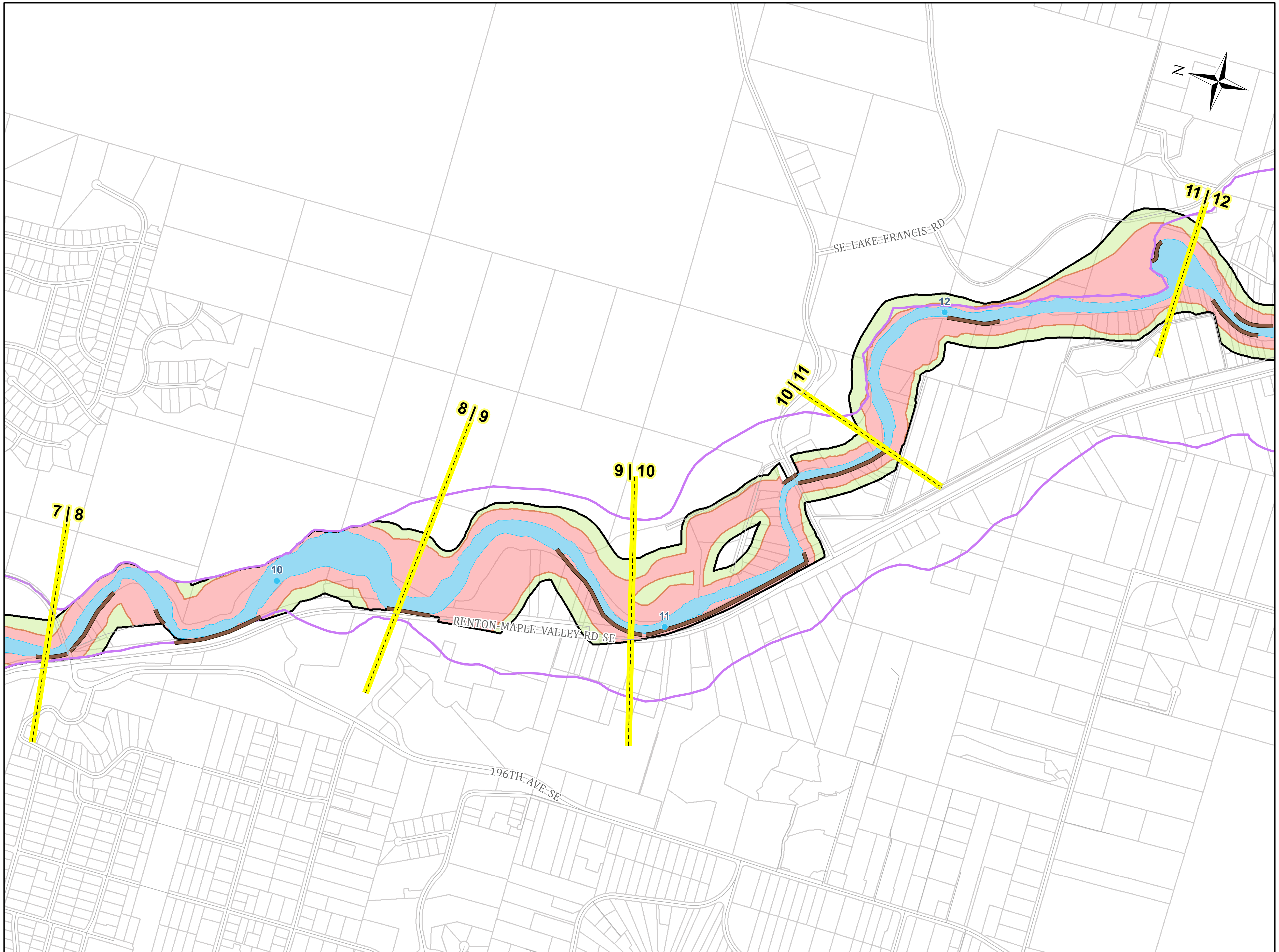
Cedar River

Map 7. Cedar River Channel Migration Zone (CMZ)

Panel 5 of 8



Legend

- River Mile
- City Boundaries
- Reach Boundaries
- Levees and Revetments
- Valley Wall
- Streets
- Parcels
- 2011 Active Channel
- CMZ Boundary
- Severe Hazard Area
- Moderate Hazard Area

Feet

0 500 1,000 2,000

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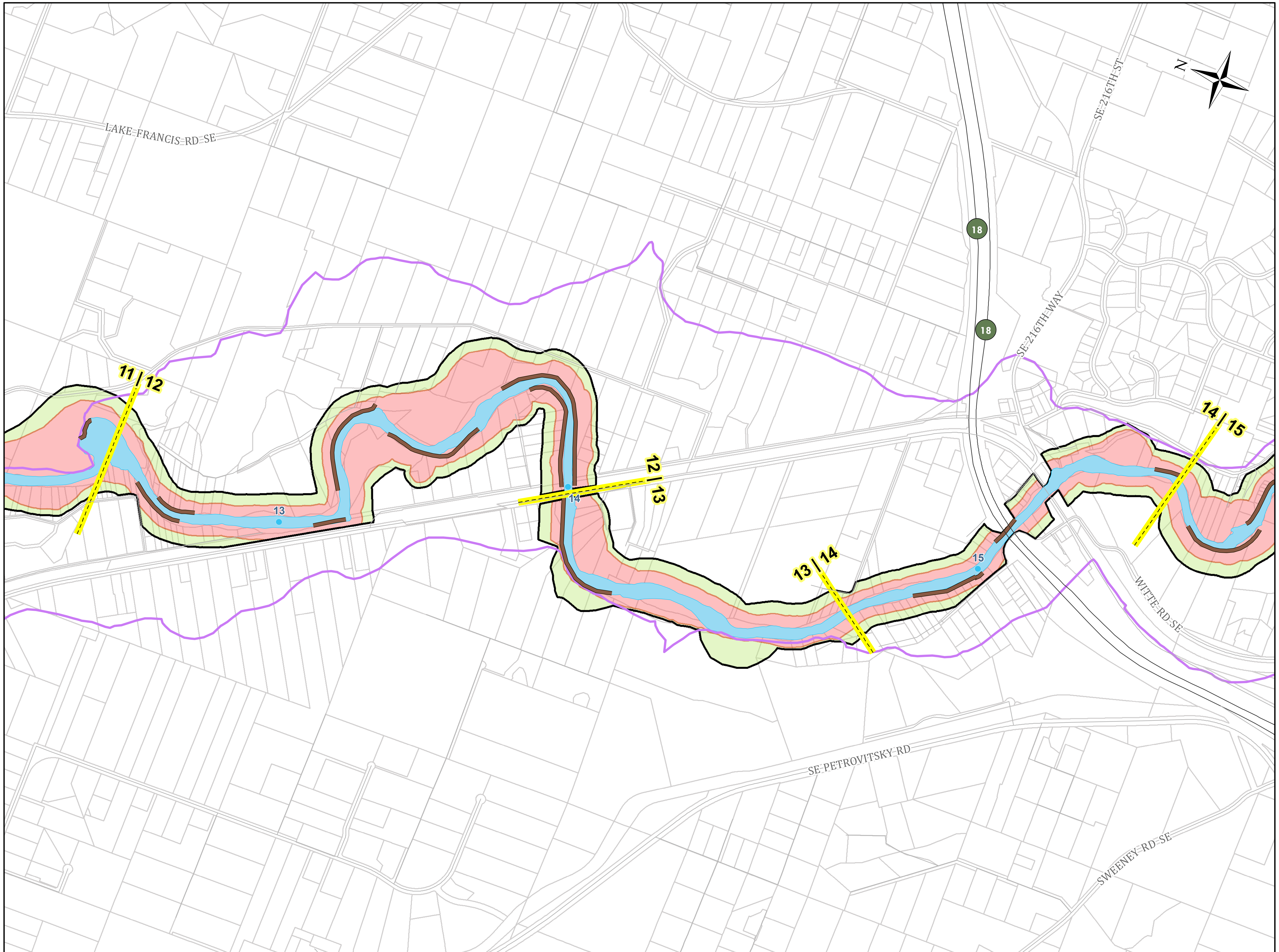
Cedar River

Map 7. Cedar River Channel Migration Zone (CMZ)

Panel 6 of 8



Legend

- River Mile
- City Boundaries
- Reach Boundaries
- Levees and Revetments
- Valley Wall
- Streets
- Parcels
- 2011 Active Channel
- CMZ Boundary
- Severe Hazard Area
- Moderate Hazard Area

0 500 1,000 2,000 Feet

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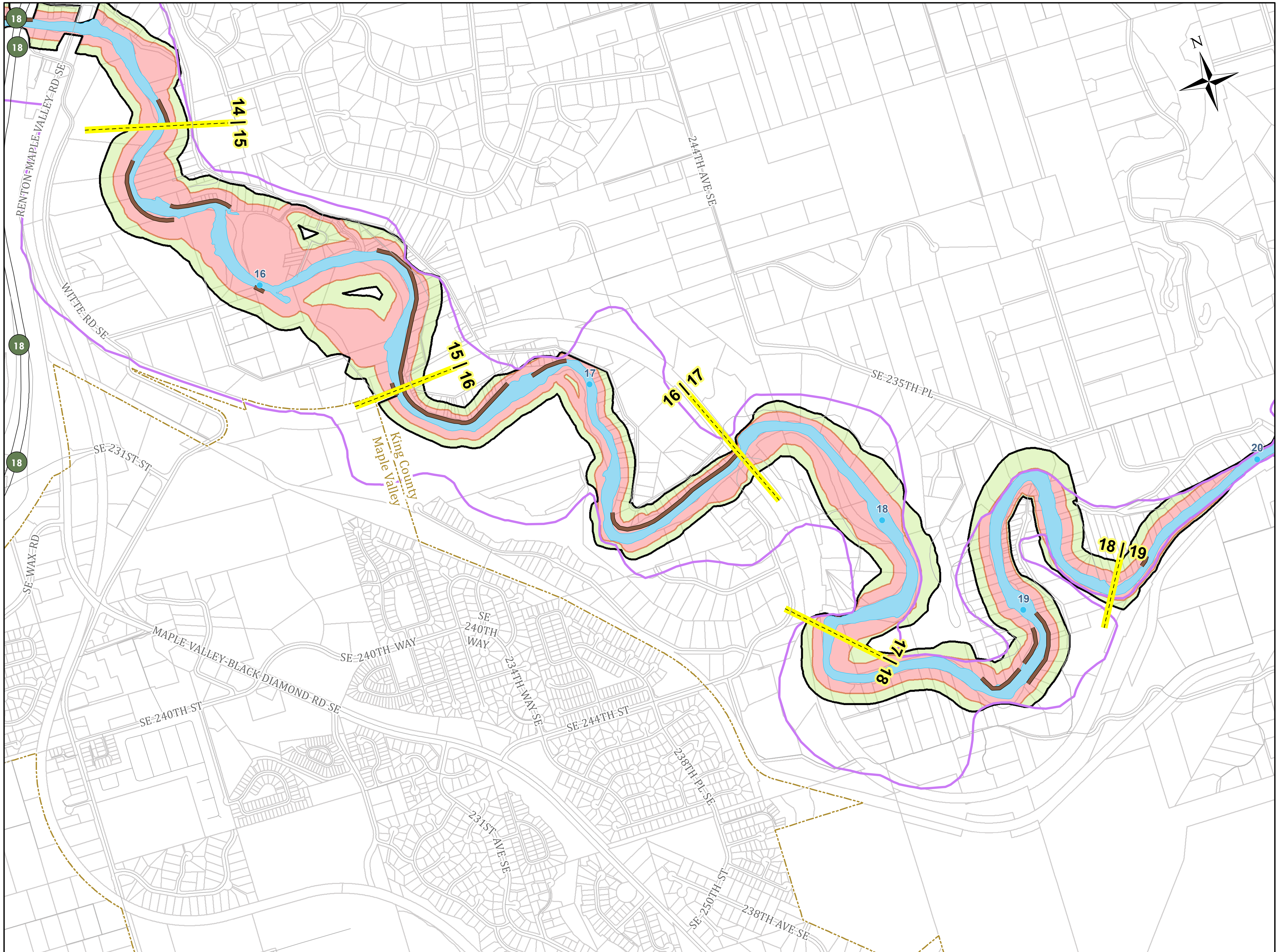
Cedar River

Map 7. Cedar River Channel Migration Zone (CMZ)

Panel 7 of 8



Legend

- River Mile
- City Boundaries
- Reach Boundaries
- Levees and Revetments
- Valley Wall
- Streets
- Parcels
- 2011 Active Channel
- CMZ Boundary
- Severe Hazard Area
- Moderate Hazard Area

Feet: 0 500 1,000 2,000

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Cedar River

Map 7. Cedar River Channel Migration Zone (CMZ)

Panel 8 of 8

Legend

- River Mile
- City Boundaries
- Reach Boundaries
- Levees and Revetments
- Valley Wall
- Streets
- Parcels
- 2011 Active Channel
- CMZ Boundary
- Severe Hazard Area
- Moderate Hazard Area

0 500 1,000 2,000 Feet

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