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Sun River
Channel Migration Mapping

Prepared for:

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Local solutions for local problems

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Executive Summary

This report contains the results of a Channel Migration Zone (CMZ) mapping effort for 51 miles of the Sun River extending from just north of Augusta downstream to Vaughn. Along this stretch, the river transitions from a fairly confined and narrow stream corridor that is tightly controlled by erosion-resistant terraces to a highly dynamic broad stream corridor that is prone to rapid migration rates and avulsions (rapid creation of new channels). Migration rates generally increase in the downstream direction as the channel slope flattens, the valley widens, and large rapidly migrating meanders traverse the floodplain. Old floodplain swales and tributaries create high flow paths and avulsion routes.

Historic imagery beginning in 1957 was used to measure migration rates through the project reach; hundreds of measurements were collected and statistically analyzed to determine mean rates of movement for each reach. Maximum migration distances measured for the 1957-2019 timeframe range from about 250 feet in upper reaches to over 900 feet near Vaughn. At least 10 avulsions have occurred in the project reach since 1957, with two currently developing.

Rapid channel migration on the Sun River is driven by a unique geologic setting on the Rocky Mountain Front, where the Sun River Glacier extended from the mouth of Sun Canyon to Augusta. The toe of the glacier near Augusta fed braided streams that carried gravels downstream, forming high terraces that bound the Sun River valley. Approaching Great Falls, the river enters low gradient areas that were historically inundated by a large glacial lake, causing coarse sediment deposition and driving rapid channel change, especially during floods.

A combined look at channel form and flood history shows that, between the late 1970s and 2011, the river was quiet in terms of floods and channel change. The river narrowed during that time, as did numerous rivers around the state. It wasn't only the drought years of the early 2000s that caused our rivers to atrophy, but a much longer period of minimal flooding. An important aspect of this trend is that newcomers to the river corridor had little direct experience with just how much the Sun River can change with time, making the floods of 2018 and 2019 especially shocking to many.

Irrigation infrastructure is largely consolidated through the project reach, which makes river management on the Sun River more effective and affordable than on many other systems we have mapped in Montana. That said, the floods starting in 2011 after several decades of virtually no flooding has caused a new, recent period of active change that is creating challenges for landowners and managers.

Our objective with the mapping and interpretations provided in this document is to assist river corridor landowners and other stakeholders in understanding the nature of Sun River lateral migration, focusing not only on the challenges that channel migration creates but also the critical contributions that these process make to stream heath, resilience, and ecological vibrancy.

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Glossary and Abbreviations

Alluvial – Relating to unconsolidated sediments and other materials that have been transported, deposited, reworked, or modified by flowing water.

Avulsion – The rapid abandonment of a river channel and formation of a new channel. Avulsions typically occur when floodwaters flow across a floodplain surface at a steeper grade than the main channel, carving a new channel along that steeper, higher energy path. As such, avulsions typically occur during floods. Meander cutoffs are one form of avulsion, as are longer channel relocations that may be miles long.

Avulsion Node– The location where a river splits or relocates from an existing channel into an avulsion path.

Bankfull Discharge - The discharge corresponding to the stage at which flow is contained within the limits of the river channel, and does not spill out onto the floodplain. Bankfull discharge is typically between the 1.5- and 2-year flood event, and in the Northern Rockies it tends to occur during spring runoff.

CD – Conservation District.

Channel Migration – The process of a river or stream moving laterally (side to side) across its floodplain. Channel migration is a natural riverine process that is critical for floodplain turnover and regeneration of riparian vegetation on newly created bar deposits such as point bars. Migration rates can vary greatly though time and between different river systems; rates are driven by factors such as flows, bank materials, geology, riparian vegetation density, and channel slope.

Channel Migration Zone (CMZ) – A delineated river corridor that is anticipated to accommodate natural channel migration rates over a given period of time. The CMZ typically accommodates both channel migration and areas prone to avulsion. The result is a mapped "footprint" that defines the natural river corridor that would be active over some time frame, which is commonly 100 years.

DNRC – Department of Natural Resources and Conservation.

Erosion Buffer—The distance beyond an active streambank where a river is likely to erode based on historic rates of movement.

Erosion Hazard Area (EHA)– Area of the CMZ generated by applying the erosion buffer width to the active channel bankline.

Flood frequency – The statistical probability that a flood of a certain magnitude for a given river will occur in any given year. A 1% flood frequency event has a 1% chance of happening in any given year, and is commonly referred to as the 100-year flood.

Floodplain- An area of low-lying ground adjacent to a river, formed mainly of river sediments and subject to flooding.

Fluvial – Stream-related processes, from the Latin word fluvius = river.

Geomorphology - The study of landforms on the Earth's surface, and the processes that create those landforms. "Fluvial Geomorphology" refers more specifically to how river processes shape the Earth's surface.

GIS – Geographic Information System: A system of hardware and software used for storage, retrieval, mapping, and analysis of geographic data.

Historic Migration Zone (HMZ) – The historic channel footprint that forms the core of the Channel Migration Zone (CMZ). The HMZ is defined by mapped historic channel locations, typically using historic air photos and maps.

Hydrology – The study of properties, movement, distribution, and effects of water on the Earth's surface.

Hydraulics – The study of the physical and mechanical properties of flowing liquids (primarily water). This includes elements such as the depth, velocity, and erosive power of moving water.

Large Woody Debris (LWD) – Large pieces of wood that fall into streams, typically trees that are undermined on banks. LWD can influence the flow patterns and the shape of stream channels, and is an important component of fish habitat.

Management Corridor – A mapped stream corridor that integrates CMZ mapping and land use into a practical corridor for river management and outreach.

Meander - One of a series of regular freely developing sinuous curves, bends, loops, turns, or windings in the course of a stream.

Morphology - Of or pertaining to shape.

NAIP – National Agriculture Imagery Program – A United States Department of Agriculture program that acquires aerial imagery during the agricultural growing seasons in the continental U.S.

Planform - The configuration of a river channel system as viewed from above, such as on a map.

RDGP - Reclamation and Development Grants Program, DNRC.

Restricted Migration Area (RMA) – Those areas of the CMZ that are isolated from active river migration due to bank armor or other infrastructure.

Return Interval- The likely time interval between floods of a given magnitude. This can be misleading, however, as the flood with a 100-year return interval simply has a 1% chance of occurring in any given year.

Riparian – Of, relating to or situated on the banks of a river. Riparian zones are the interface between land and a river or stream. The word is derived from Latin ripa, meaning river bank. Plant habitats and communities along stream banks are called riparian vegetation, and these vegetation strips are important ecological zones due to their habitat biodiversity and influence on aquatic systems.

Riprap – A type of bank armor made up of rocks placed on a streambank to stop bank erosion. Riprap may be composed of quarried rock, river cobble, or manmade rubble such as concrete slabs.

Sinuosity - The length of a channel relative to its valley length. Sinuosity is calculated as the ratio of channel length to valley length; for example, a straight channel has a sinuosity of 1, whereas a highly tortuous channel may have a sinuosity of over 2.0. Sinuosity can change through time as rivers migrate laterally and occasionally avulse into new channels. Stream channelization results in a rapid reduction in sinuosity.

Stream competency - The ability of a stream to mobilize its sediment load which is proportional to flow velocity.

Terrace – On river systems, terraces form elongated surfaces that flank the sides of floodplains. They represent historic floodplain surfaces that have become perched due to stream downcutting. River terraces are typically elevated above the 100-year flood stage, which distinguishes them from active floodplain areas.

Wetland – Land areas that are either seasonally or permanently saturated with water, which gives them characteristics of a distinct ecosystem.

1 Introduction

The Sun River Channel Migration Zone (CMZ) mapping project extends 51 river miles from just upstream of the Highway 287 bridge down to the mouth of Muddy Creek at Vaughn (Figure 1). River corridor communities located within or adjacent to the Sun River corridor include Simms, Fort Shaw, Sun River, and Vaughn. The work was funded through a Montana Department of Natural Resources and Conservation (DNRC) HB233 grant with additional support from Cascade Conservation District and the Montana Department of Environmental Quality (DEQ).

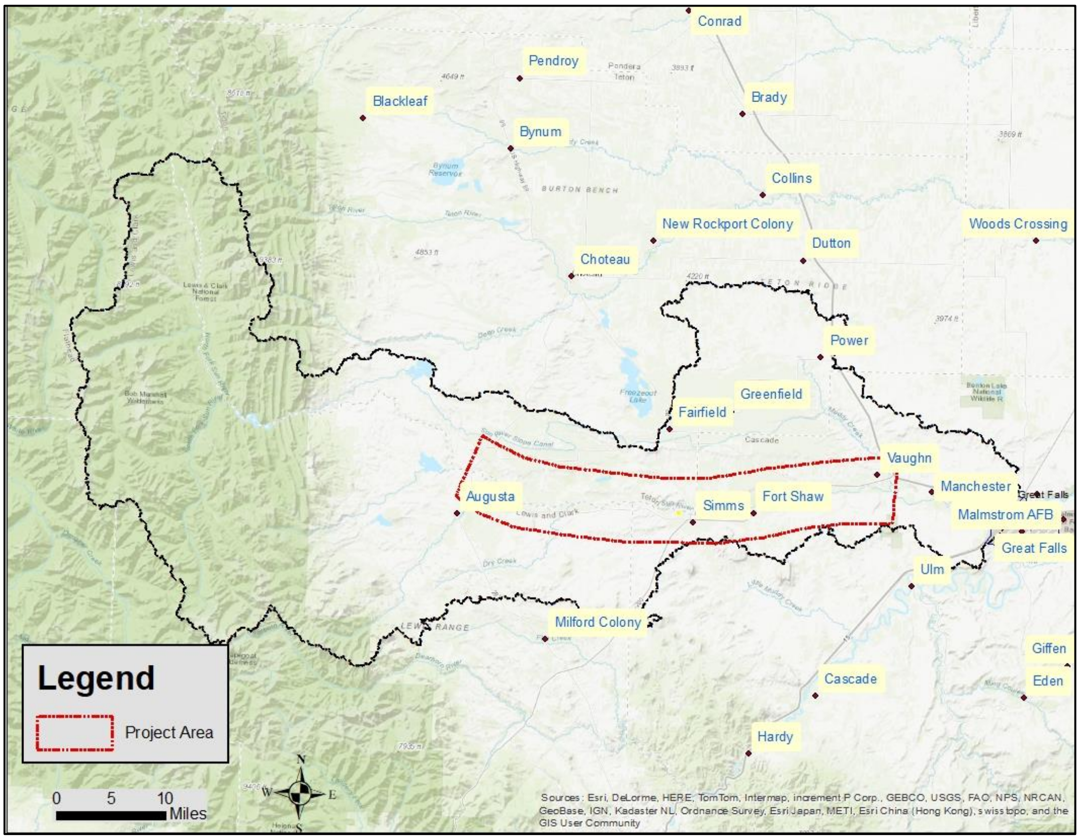


Figure 1. CMZ mapping extent on the Sun River, extending from the Highway 287 Bridge to the mouth of Muddy Creek near Vaughn.

1.1 The Project Team

This project work was performed by Karin Boyd of Applied Geomorphology and Tony Thatcher of DTM Consulting. Over the past decade, we have been collaborating to develop CMZ maps for numerous rivers in Montana, to provide rational and scientifically-sound tools for river management. It is our goal to facilitate the understanding of rivers regarding the risks they pose to infrastructure, so that those risks can be managed and hopefully avoided. Furthermore, we believe the mapping supports the premise that managing rivers as dynamic, deformable systems contributes to ecological and geomorphic resilience while supporting sustainable, cost-effective development.

1.2 What is Channel Migration Zone Mapping?

The goal of Channel Migration Zone (CMZ) mapping is to provide a cost-effective and scientifically based tool to assist land managers, property owners, agency personnel, and other stakeholders in making sound land use decisions along river corridors. Typically, projects constructed in stream environments such as bank stabilization, homes and outbuildings, access roads, pivots, and diversion structures are built without a full consideration of site conditions related to river process and associated risk. As a result, projects commonly require unanticipated and costly maintenance or modification to accommodate river dynamics. CMZ mapping is therefore intended to identify those areas of risk, to reduce the risk of project failure while minimizing the impacts of development on natural river process and associated ecological function. The mapping is also intended to provide an educational tool to show historic stream channel locations and rates of movement in any given area.

CMZ mapping is based on the understanding that rivers are dynamic and move laterally across their floodplains through time. As such, over a given timeframe, rivers occupy a corridor area whose width is dependent on rates of channel shift. The processes associated with channel movement include lateral channel migration and more rapid channel avulsion (Figure 2).

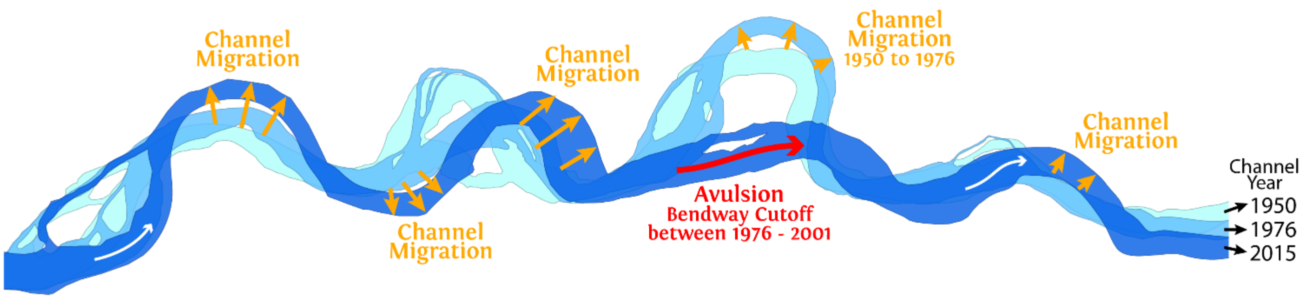


Figure 2. Typical patterns of channel migration and avulsion evaluated in CMZ development.

The fundamental approach to CMZ mapping is to identify the corridor area that a stream channel or series of stream channels can be expected to occupy over a given timeframe – typically 100 years. This is defined by first mapping historic channel locations to define the Historic Migration Zone, or HMZ (Figure 2). Using those mapped banklines, migration distances are measured between suites of air photos, which allows the calculation of migration rate (feet per year) at any site. Average annual migration rates are calculated on a reach scale and extended to the life of the CMZ, which in this case is 100 years. This 100-year mean migration distance defines the Erosion Buffer, which is added to the modern bankline to define the Erosion Hazard Area, or EHA.

Channel migration rates are affected by geomorphic influences such as geology, channel type, stream size, sediment volume, sediment size, flow patterns, slope, bank materials, and land use. For example, an unconfined meandering channel with high sediment loads would have higher migration rates than a geologically confined channel flowing through a bedrock canyon. To address this natural variability, the study area has been segmented into a series of reaches that are geomorphically similar and can be characterized by average migration rates. Reach breaks can be defined by changes in flow or sediment loads at tributary confluences, changes in geologic confinement, or changes in stream pattern. Reaches are typically on the order of five- to 10-miles-long. Within any given reach, dozens to hundreds of migration measurements may be collected.

Avulsion-prone areas are mapped where there is evidence of geomorphic conditions that are amenable to new channel formation on the floodplain. This would include meander cores prone to cutoff (Figure 2), historic side channels that may reactivate, and areas where the modern channel is perched above its floodplain.

The following map units collectively define a Channel Migration Zone (Rapp and Abbe, 2003):

- Historic Migration Zone (HMZ) – the area of historic channel occupation, usually defined by the available photographic record.
- Erosion Hazard Area (EHA) – the area outside the HMZ susceptible to channel occupation due to channel migration.
- Avulsion Hazard Zone (AHZ) – floodplain areas geomorphically susceptible to abrupt channel relocation.
- Restricted Migration Area (RMA)-- areas of CMZ isolated from the current river channel by constructed bank and floodplain protection features. The RMA has been referred to in other studies as the DMA- Disconnected Migration Area.

The individual map units comprising the CMZ are as follows:

CMZ = HMZ + EHA + AHZ

The Restricted Migration Area (RMA) is commonly removed from the CMZ to show areas that are "no longer accessible" by the river (Rapp and Abbe, 2003). In our experience, the areas that have become restricted due to human activities provide insight as to the extent of encroachment into the CMZ, and highlight potential restoration sites. These areas may also actively erode in the event of common project failure such as bank armor flanking. For this reason, the areas of the natural CMZ that have become isolated are contained within the overall CMZ boundary and highlighted as "restricted" within the natural CMZ footprint.

Each map unit listed above is individually identified on the maps to show the basis for including any given area in the CMZ footprint (Figure 3).

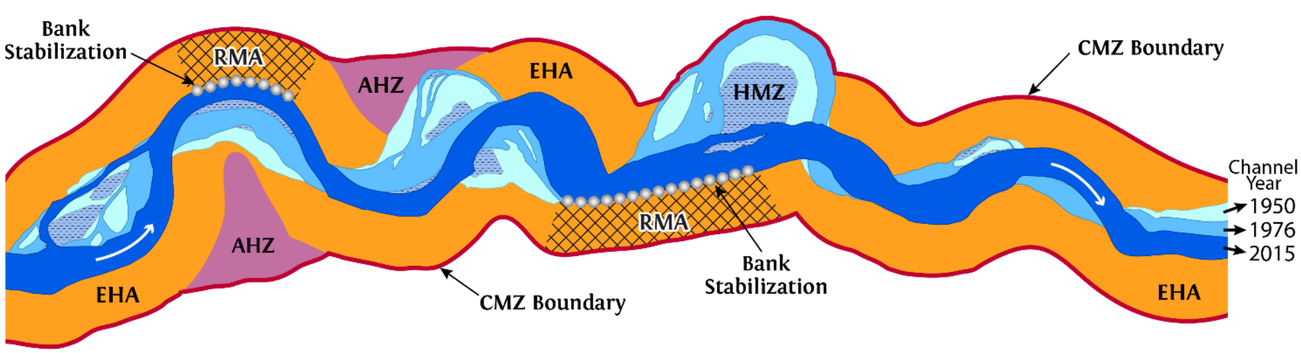


Figure 3. Channel Migration Zone mapping units.

Although the basic concept for Channel Migration Zone mapping efforts is largely the same throughout the country, different approaches to defining CMZ boundaries are used depending on specific needs and situations. These differences in assessment techniques can be driven by the channel type, different project scales, the type and quality of supporting information, the intended use of the mapping, etc. For this study, the CMZ is defined as a composite area made up of the existing channel, the collective footprint of mapped historic channel locations shown in the 1957, 1977/78, 1995, 2017, and 2019 imagery (Historic Migration Zone, or HMZ), and an Erosion Hazard Area (EHA), that is based on reach-scale average migration rates. Areas beyond the Erosion Buffer that pose risks of channel avulsion are identified as Avulsion Hazard Areas or AHZ. This approach generally falls into the minimum standards of practice for Reach Scale, Moderate to High Level of Effort mapping studies as defined by the Washington Department of Ecology (www.ecy.wa.gov). This approach does not, however include a geotechnical setback on hillslopes; these areas would require a more site-specific analysis than that presented here.

1.3 Relative Levels of Risk

The natural processes of streambank migration and channel avulsion both create risk to properties within stream corridors. Although the site-specific probability of any area experiencing either migration or an avulsion during the next century has not been quantified, the characteristics of each type of channel movement allows some relative comparison of the type and magnitude of their risk. In general, the Erosion Hazard Area delineates areas that have a demonstrable risk of channel occupation due to channel migration over the next 100 years. Such bank erosion can occur across a wide range of flows, and the risk of erosion into this map unit is relatively high. In contrast, avulsions tend to be a flood-driven process; the Avulsion Hazard Area delineates areas where conditions may support an avulsion, although the likelihood of such an event is highly variable between sites and typically depends on floods. Large, long duration floods have the potential to drive extensive avulsions, even after decades of no such events. During the spring of 2011, for example, the Musselshell River flood drove 59 avulsions in three weeks, carving 9 miles of new channel while abandoning about 37 miles of old river channel (Boyd et al, 2012).

1.4 Uncertainty

The adoption of a 100-year period to define the migration corridor on a dynamic stream channel requires the acceptance of a certain amount of uncertainty regarding those discrete corridor boundaries. FEMA (1999) noted the following with respect to predicting channel migration:

> *…uncertainty is greater for long time frames. On the other hand, a very short time frame for which uncertainty is much reduced may be useless for floodplain management because of the minimal erosion expected to occur.*

The Sun River shows historic patterns of lateral migration and avulsion, locally within a broad floodplain surface that has dense networks of historic channels. With potential contributing factors, such as woody debris jamming, sediment slugs, landslides, or ice jams, dramatic change could potentially occur virtually anywhere in the stream corridor or adjacent floodplain. As the goal of this mapping effort is to highlight those areas most prone to either migration or avulsion based on specific criteria, there is clearly the potential for changes in the river corridor that do not meet those criteria and thus are not predicted as high risk.

Uncertainty also stems from the general paradigm that "the past is the key to the future." As predicted future migration is based on an assessment of historic channel behavior, the drivers of channel migration over the past

50 years are assumed to be relatively consistent over the next century. If conditions change significantly, uncertainty regarding the proposed boundaries will increase. These conditions include system hydrology, sediment delivery rates, climate, valley morphology, riparian vegetation densities and extents, and channel stability. Bank armor and floodplain modifications, such as bridges, dikes, levees, or sand and gravel mining could also affect map boundaries.

1.5 Potential CMZ Map Applications

The CMZ mapping is intended to support a range of applications, but the mapping should be primarily viewed as a tool to support informed management decisions throughout a river corridor. Potential applications for the CMZ maps include the following:

- Identify specific problem areas where migration rates are notably high and/or infrastructure is threatened.
- Develop project priorities, timelines, and funding mechanisms.
- Strategically place new infrastructure to avoid costly maintenance or loss of capital.
- Strategically place new infrastructure to minimize impacts on channel process and associated ecological function.
- Develop river corridor best management practices.
- Improve stakeholder understanding of the risks and benefits of channel movement.
- Identify areas where channel migration easements may be appropriate.
- Facilitate productive discussion between regulatory, planning, and development interests active within the river corridor.
- Help communities and developers integrate dynamic river corridors into land use planning.
- Assist long-term residents in conveying their experiences of river process and associated risk to newcomers.

Note:

The CMZ mapping developed in this study was developed without any explicit intent of either providing regulatory boundaries or overriding site-specific assessments. Any future use of the maps as a regulatory tool should include a careful review of the mapping criteria to ensure that the approach used is appropriate for that application.

1.6 Other River Hazards

The CMZ maps identify areas where river erosion can be expected to occur over the next century. It is important to note that river erosion is only one of a series of hazards associated with river corridors.

1.6.1 Flooding

The CMZ maps do not delineate areas prone to flooding. The difference between mapped flood boundaries and CMZ boundaries can be substantial. In cases where the floodplain is broad and low, the CMZ tends to be narrower than the flood corridor (left schematic on Figure 4). In contrast, where erodible terrace units bound the river corridor, the CMZ is commonly wider than the floodplain, because the terraces may be high enough to escape flooding, but not resistant enough to avoid erosion (right schematic on Figure 4). This is a common problem in Montana because of the extent of high glacial terraces that are above base flood elevations, but not erosion-resistant.

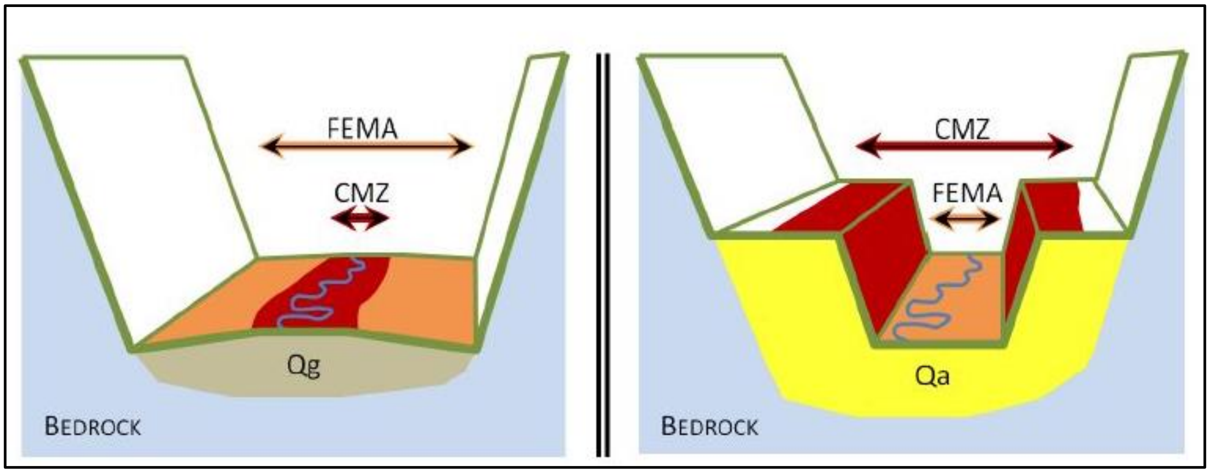


Figure 4. Schematic comparisons between CMZ and flood mapping boundaries (Washington Department of Ecology).

Figure 5 shows a property on the Yellowstone River in Park County that was progressively undermined during the 1996-1997 floods, prompting the owner to burn it down to prevent any liability associated with the structure falling into the river. This has been a chronic problem in river management, as landowners assume that if their home is beyond the mapped floodplain margin, it is removed from all river hazards. After experiencing massive 2005 flood damages in Saint George Utah (Figure 6), several property owners reflected on this issue (www.Utahfloodrelief.com):

We knew the river was there. We were 3 feet above the 100-year flood plain and made sure we were well above the flood plain. It was surveyed and the engineers told us where we had to put it and no, we don't have flood insurance or any kind of insurance that is going to reimburse us for anything.

Our property was not located within the 500-year flood plain or was it adjacent to it. The river simply took a new route that went right through our property.

I knew we were in big trouble. The river was raging and making a sharp "S" turn right behind our home. Our property seemed to take the full force of the river turning against the bank. Large chunks of earth were being swallowed up into the river. We watched 20 feet erode in less than two hours. We knew if it continued at that pace, we'd lose our house. Our contractor contacted an excavation company early that morning, but they said there was nothing they could do for us. We were also informed that our contractor's insurance was not covered for floods.

Figure 5. Yellowstone River home on high glacial terrace that was burned down in 1997 to prevent its undermining by the river.

Figure 6. Photos from a 2005 in Saint George Utah, where homes several feet above the mapped floodplain were destroyed by channel migration (www.Utahfloodrelief.com).

An example floodplain map for the Sun River upstream of Vaughn is shown in Figure 7. The floodplain boundaries cover much of the valley bottom, and the regulatory floodway, which is crosshatched in red, identifies the area of river and adjacent land areas that "must be reserved in order to discharge the base flood without cumulatively increasing the water surface elevation more than a designated height" (www.fema.gov). Communities are responsible for prohibiting encroachments including fill and new construction in floodway areas unless hydrologic and hydraulic analyses show that it will not increase flood levels in the community. On the Sun River, the floodway footprint envelops depict a complex series of active channels, gravel pits, and floodplain areas. The combined risks of flooding and channel migration on the Sun river should both be considered threats to human health and safety.

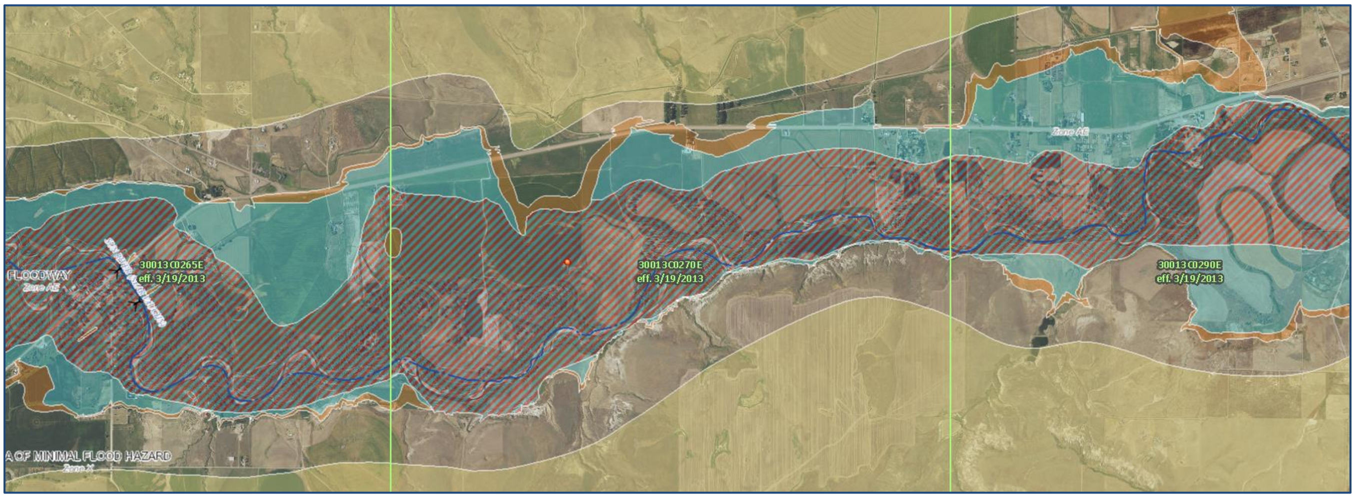


Figure 7. FEMA flood map for area between Sun River Bridge (left) and Vaughn (right).

1.6.2 Ice Jams

Another serious river hazard, especially in Montana, is ice jamming. Over 1,780 ice jams have been recorded in Montana, which is the most of any of the lower 48 states (http://dphhs.mt.gov/). Ice jams are most common in Montana during February and March. Dams can cause flooding upstream due to backwatering, and downstream of the jam ice chunks mobilized by breakups can cause damage. Breakups can occur rapidly, and it generally takes water that is almost two to three times the thickness of the ice to mobilize the jammed ice.   Ice jams can also cause avulsions by entirely blocking channels and forcing flows onto the floodplain.

The Sun River does not appear to be particularly prone to ice jamming, as it is not listed as having had 10 or more reported jams (Figure 8). In March of 2019 the Cascade County Sheriff’s office reported that ice jams on the river were starting to break up, creating flash flood concerns (Figure 9).

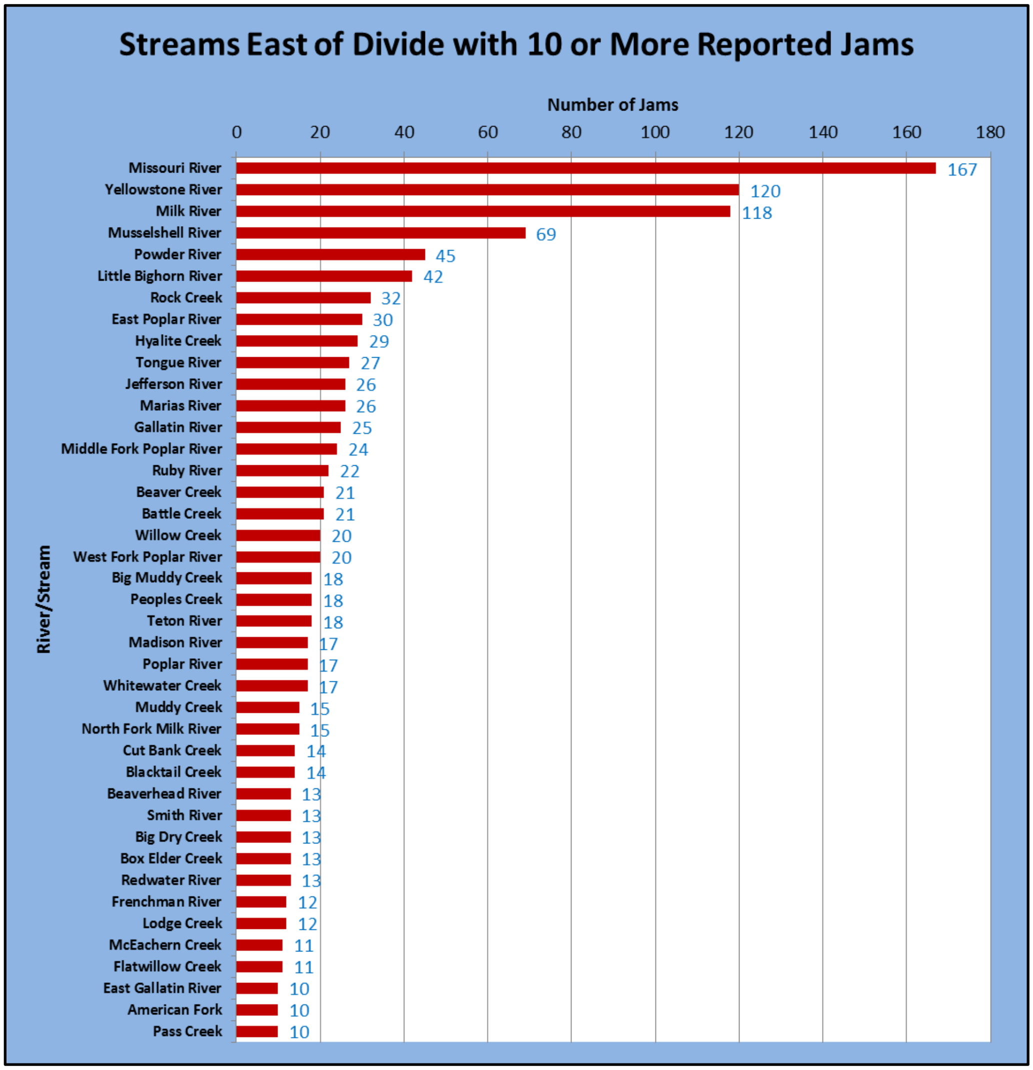


Figure 8. Montana rivers east of the continental divide with 10 or more reported ice jams (wrh.noaa.gov).

Figure 9. 2019 ice jam on the Sun River near Muddy Creek (ktvm.com)

1.6.3 Landslides

There are no mapped landslides adjacent to the Sun River in the project area. Upstream, however, landsliding in the upper watershed could impact stream process in the project reach by impounding and then releasing massive volumes of water and sediment. Just downstream of the Highway 287 bridge, a hillslope failure against the Floweree Canal caused the canal to breach, forming a large deposit on the Sun River floodplain (Figure 10). This demonstrates that, where canals are close to the river, breaches could create new floodplain channels or depositional features that may affect Sun River dynamics.

Figure 10. Google Earth photo showing Floweree Canal hisllslope failure causing canal breach (left); Sun River is to right.

1.7 Disclaimer and Limitations

The boundaries developed on the Channel Migration Zone mapping are intended to provide a basic screening tool to help guide and support management decisions within the mapped stream corridor and were not developed with the explicit intent of providing regulatory boundaries or overriding site-specific assessments. The criteria for developing the boundaries are based on reach scale conditions and average historic rates of change. The boundaries can support river management efforts, but in any application, it is critical that users thoroughly understand the process of the CMZ development and its associated limitations.

Primary limitations of this reach-scale mapping approach include a potential underestimation of migration rates in discrete areas that are eroding especially rapidly, which could result in migration beyond the mapped CMZ boundary. Additionally, site-specific variability in alluvial deposits may affect rates of channel movement. Mapping errors introduced by the horizontal accuracy of the imagery, digitizing accuracy, and air photo interpretation may also introduce small errors in the migration rate calculations. Future shifts in system hydrology, climate, sediment transport, riparian corridor health, land use, or channel stability would also affect the accuracy of results, as these boundaries reflect the extrapolation of historic channel behavior into the future. As such, we recommend that these maps be supplemented by site-specific assessment where near-term migration rates and/or site geology create anomalies in the reach-averaging approach, and that the mapping be revisited in the event that controlling influences change dramatically. A site-specific assessment would include a thorough analysis of site geomorphology, including a more detailed assessment of bank material erodibility, both within *the bank and in adjacent floodplain areas, consideration of the site location with respect to channel planform and hillslope conditions, evaluation of influences such as vegetation and land use on channel migration, and an analysis of the site-specific potential for channel blockage or perching that may drive an avulsion.*

1.8 Acknowledgements

We would like to extend our gratitude to Tracy Wendt of the Sun River Watershed Group and Tenlee Atchison of the Cascade Conservation District for their assistance in contract management, scheduling, and draft document review. During this time of Covid-19, Tracy and Tenlee sponsored a highly effective and organized public meeting outside the Sun River Methodist Church using creative technology and a good sense of humor. Turnout was excellent and attendees were engaged. To that end we would like to thank those stakeholders who have provided great input and feedback at that meeting. The community members who attended were essential in helping us strengthen our work product to address specific issues that they highlighted. We appreciate your engaged and welcoming attitude.

2 Physical Setting

The following section contains a general description of the geographic, hydrologic, and geologic influences on the Sun River, to characterize the general setting and highlight how that setting may affect river process.

2.1 Geography

The Sun River Watershed is 1875 square miles in size (1.2 million acres), originating as two forks (North and South Forks of the Sun River) within the core of the Bob Marshall Wilderness and flowing eastward off of the Rocky Mountain Front to its confluence with the Missouri River in Great Falls. Major tributaries include Willow Creek, Elk Creek, Dry Creek, Simms Creek, and Muddy Creek (Figure 11). Major communities in the river corridor include Simms, Fort Shaw, Sun River, Vaughn, Sun Prairie, Augusta, and Manchester. For much of its length in the upper watershed, the river forms the boundary between Lewis and Clark and Teton counties. Below Simms the river is entirely within the boundaries of Cascade County.

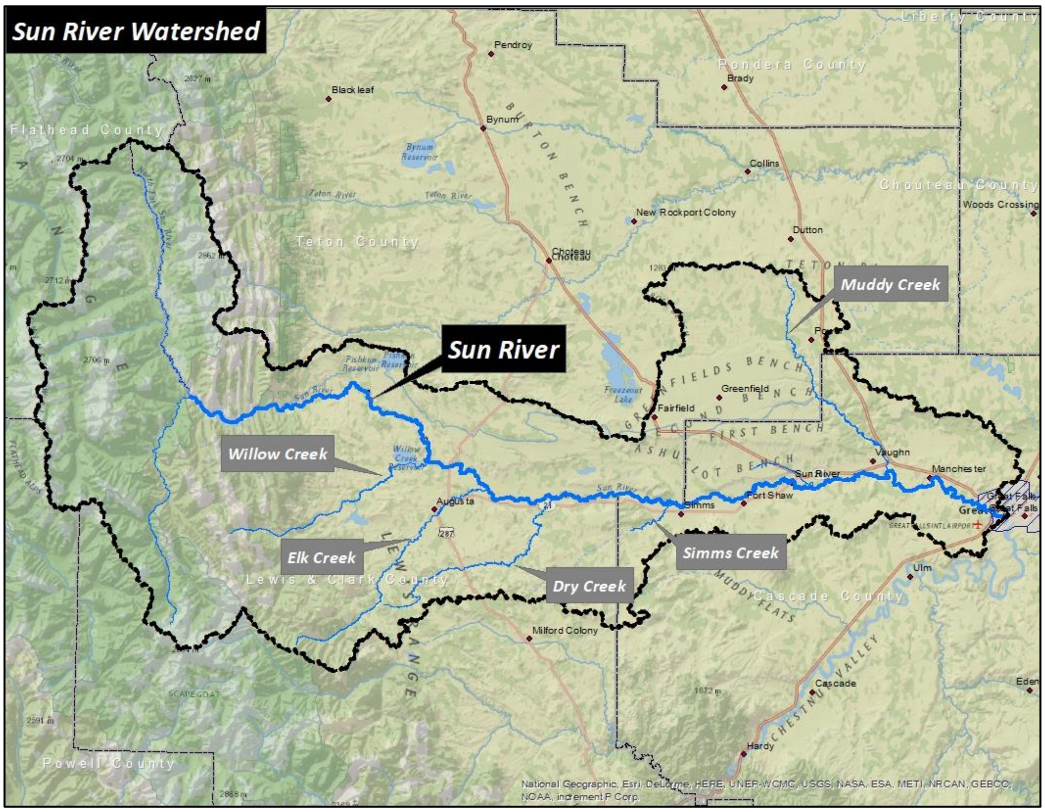


Figure 11. Sun River Watershed.

The Sun River watershed encompasses about 28 linear miles of the Rocky Mountain Front, extending from Castle Reef on the northern portion of the watershed to Steamboat Mountain to the south. Ivan Doig effectively described the Rocky Mountain Front in *This House of Sky*:

> "We came up over the crest and were walled to a stop. The western skyline before us was filled high with a steel-blue army of mountains, drawn in battalions of peaks and reefs and gorges and crags as far along the entire rim of the earth as could be seen. Summit after summit bladed up thousands of feet as if charging into the air to strike first at storm and lightning, valleys and clefts chasmed wide as if split and hollowed by thunderblast upon thunderblast." Ivan Doig, *This House of Sky*

The peaks, reefs, gorges, and crags described in *This House of Sky* capture the unique grandness of scale in this area (Figure 12). The Rocky Mountain Front ("The Front") in the Augusta-Choteau area has long been recognized by geologists as a classic example of thin-skinned, fold- and thrust-type mountain forming processes, and field trips from universities around the country are commonly held in Sun Canyon to teach structural geology. East of the canyon mouths, the combination of mountain building processes with subsequent glaciation has created a spectacular landscape where steep scarps on the eastward edge of limestone thrust sheets grade to rolling prairie hills comprised of outwash gravels that transition into a glacial lake environment near Vaughn.

Figure 12. View to the west showing Castle Reef (right); Sun River flows about ¾ mile to the left of this photo.

2.2 Geology and Glacial History

Limestone cliffs are the defining feature of the Rocky Mountain Front. Erosion through the thrust sheets has created unique stream systems that flow north-south through repeating sequences of limestones. These tributaries feed the Sun River, which flows eastward across the prairie where it joins the Missouri River at Great Falls. Figure 13 and Figure 14 shows a good example of how the Sun River cuts perpendicularly through a series thrust sheets in Sun Canyon. On Figure 14 the thrust faults are depicted as black lines that show how the faults dip to the west. The map shows that the thrust sheets have been pushed eastward, which is what forms the cliffs of Castle Reef and Sawtooth Mountain at the mouth of Sun Canyon.

Figure 13. Northward view of thrust sheets dissected by the Sun River near Augusta (www.formontana.net).

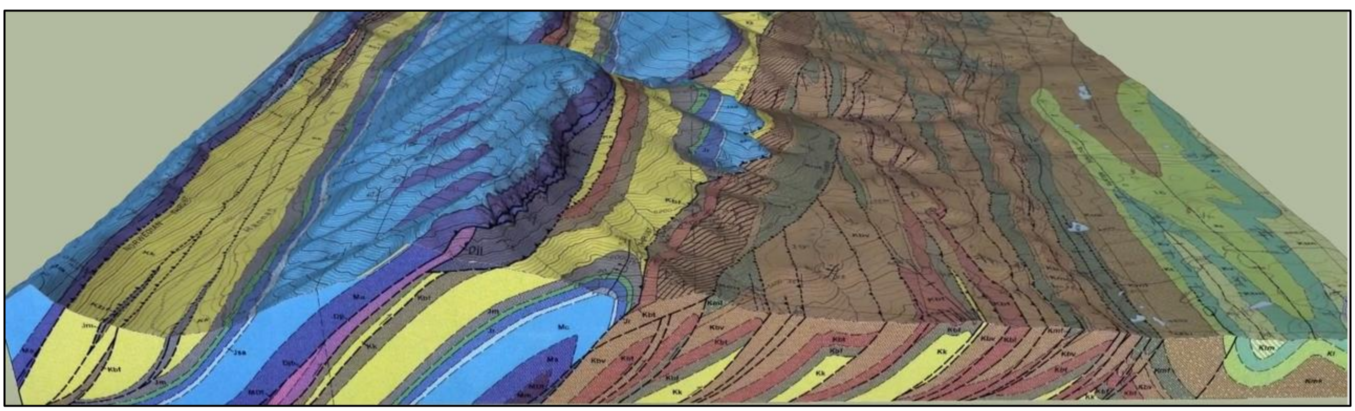


Figure 14. Geologic cross section showing northward view of Castle Reef (blue ridge in center) and dense fault system just to the east (right) (Karabinos, 2017).

As the Rocky Mountain Front was uplifted, the drainage network became controlled by that geology. Figure 13 shows how tributary streams in Sun Canyon enter the river from right angles, controlled by a series of gulches formed along the more erodible layers of the thrust sheets.

The bedrock geology is one major aspect of the watershed conditions that affect the dynamics of the Sun River as if flows out of the Bob Marshall Wilderness towards Great Falls. A second major control is the younger sediments, many of which are glacial deposits. Well after the uplift of the mountains, the Cordilleran Ice Sheet intermittently covered the western edge of Montana up until about 10,000 years ago. During that period, the ice made several advances and retreats; two distinct glacial periods in this area were the Bull Lake Glaciation (200,000 to 130,000 years ago) and the Pinedale Glaciation (~30,000 to 10,000 years ago). The Bull Lake ice is thought to have extended as far east as Choteau.

In Montana, the glacial advance to the south created ice margin lakes across Montana (Figure 15). Part of this study areas lies within the footprint of Glacial Lake Falls, and those deposits are exposed in some eroding banklines (Kellogg, 2014).

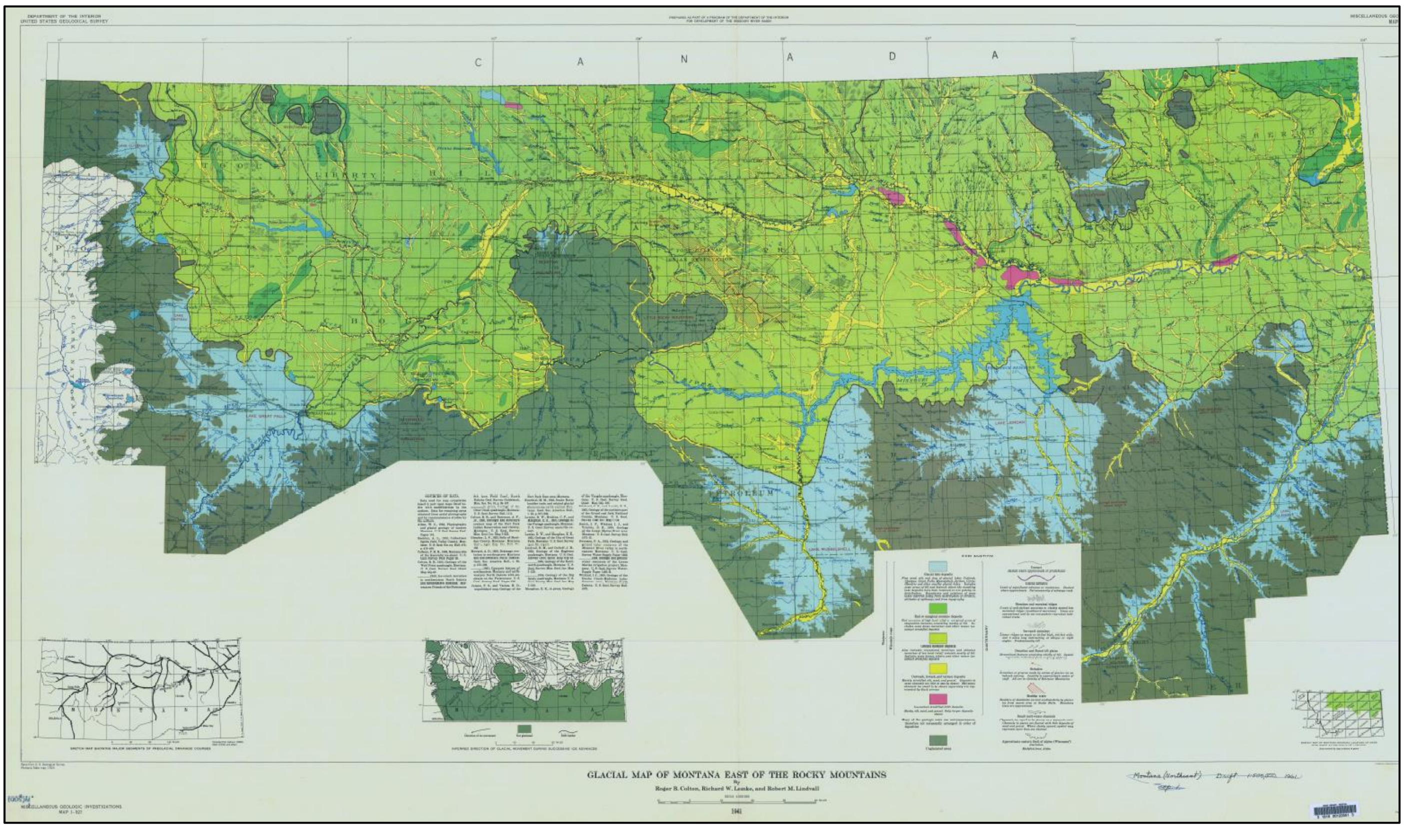


Figure 15. Map of northern Montana showing extent of glacial deposits (light green) and glacial lakes (light blue) that formed south of those deposits, including Lake Choteau and Lake Great Falls on the left, as well as Lake Musselshell (center) and Lake Jordan (center right) the lake shown on the lower right follows the current path of the Yellowstone river and was called Lake Glendive (Colton, et. al., others, 1961).

Figure 16 shows a map from the 1930s, showing the glacial ice sheet covering what is now the Teton River corridor, Great Falls Lake, and also the Sun River Glacier extending off of the front towards Augusta. The author (Alden, 1934), described the Sun River Glacier as exceeded in size “only by the great Two Medicine Glacier”. The valley glacier was four miles wide near the mouth of Sun Canyon and spread out towards Augusta for 18 miles, reaching a maximum width of about 15 miles. It covered more than 200 square miles of the plains west of Augusta. On the edges of the ice it appears to have been over 200 feet thick, and about 1,500 feet thick at the mouth of the canyon (Alden, 1934). Figure 17 and Figure 18 show 1930s photos of large limestone blocks that were carried by the Sun River Glacier onto the prairie near Augusta.

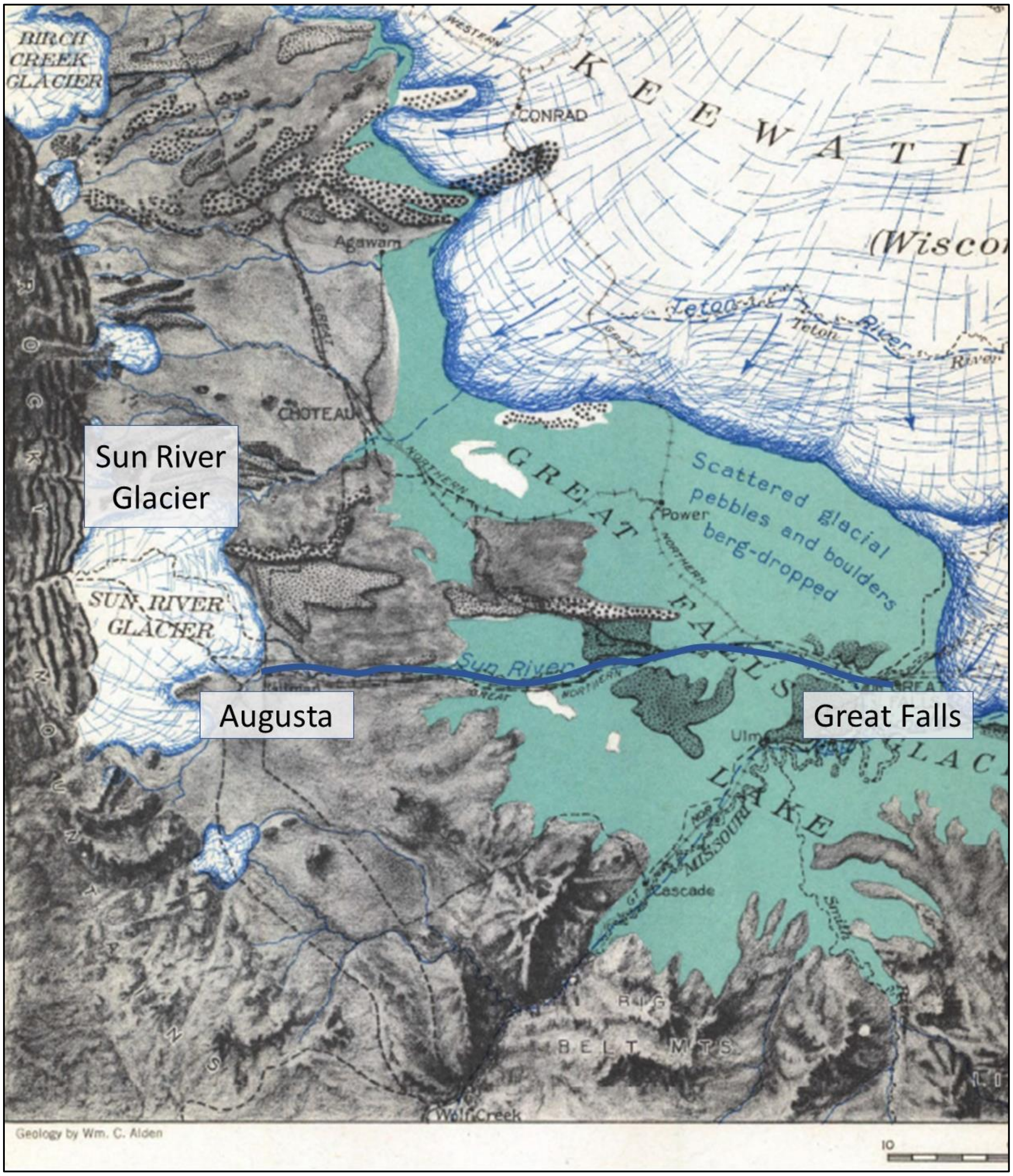
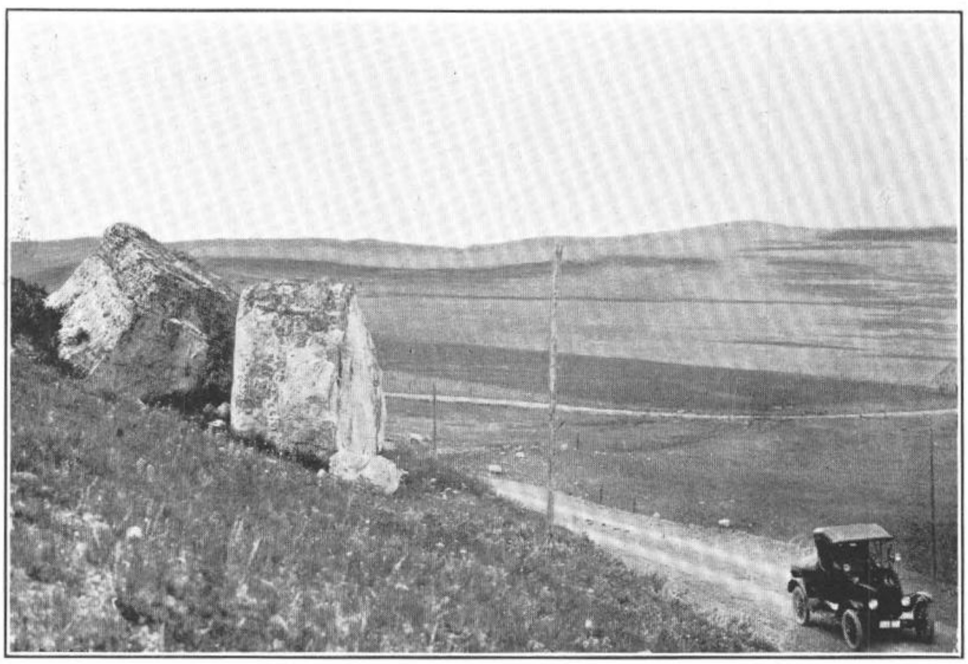


Figure 16. Map of Sun River Glacier extending from the Sun Canyon to Gilman near Augusta (Alden, 1934).

B. BLOCKS OF PALEOZOIC LIMESTONE TRANSPORTED BY SUN RIVER GLACIER, ON THE PLAIN 8 MILES EAST OF THE MOUTH OF THE SUN RIVER CANYON

The blocks are 10 by 13 by 30 feet.

Figure 17. Mid-1930s photo showing glacial erratic on plains east of Sun River Canyon (Alden, 1934).



C. BLOCKS OF PALEOZOIC LIMESTONE TRANSPORTED BY SUN RIVER GLACIER 4 MILES NORTHWEST OF AUGUSTA, MONT.

On moraine 15 miles southeast of the mouth of the Sun River Canyon. The blocks are 15 to 20 feet long.

Figure 18. Mid-1930s photo showing glacial erratic on what appears to be modern Highway 287 hillslope (Alden, 1934).

The geologic and glacial histories of this area are both important to one's overall understanding of the behavior of the Sun River. The Rocky Mountain Front provides a major source of both flow and sediment to the river, as do glacial outwash sediments that extend into the project area (Figure 19). As the river continues eastward towards Great Falls, it enters a glacial lake environment characterized by much lower slopes. This setting, where a large coarse-grained sediment load progressively encounters flatter slopes (reduced transport energy), makes the Sun River especially prone to major changes, especially during flood events when high volumes of sediment are mobilized. A simplified modern geologic map of the watershed is shown in Figure 20, with the project area shown in a black polygon. The map shows glacial tills in the upper end of the project area, and near Simms and Fort Shaw gravel terraces along the river that have glacial origin as outwash deposits formed by braided streams at the toe of the glaciers (Figure 19). The light blue color reflects older rocks such as the Two Medicine Formation, that form bluffs along the river. The Two Medicine Formation units can be highly resistant to erosion (sandstones) but are sometimes prone to failure. The glacial gravels are highly erodible. As a result, the valley margins affect river behavior in terms of both sediment contributions and erosion resistance.

Figure 19. Gravel deposits on terrace adjacent to Sun River—river corridor is in cottonwood gallery in background.

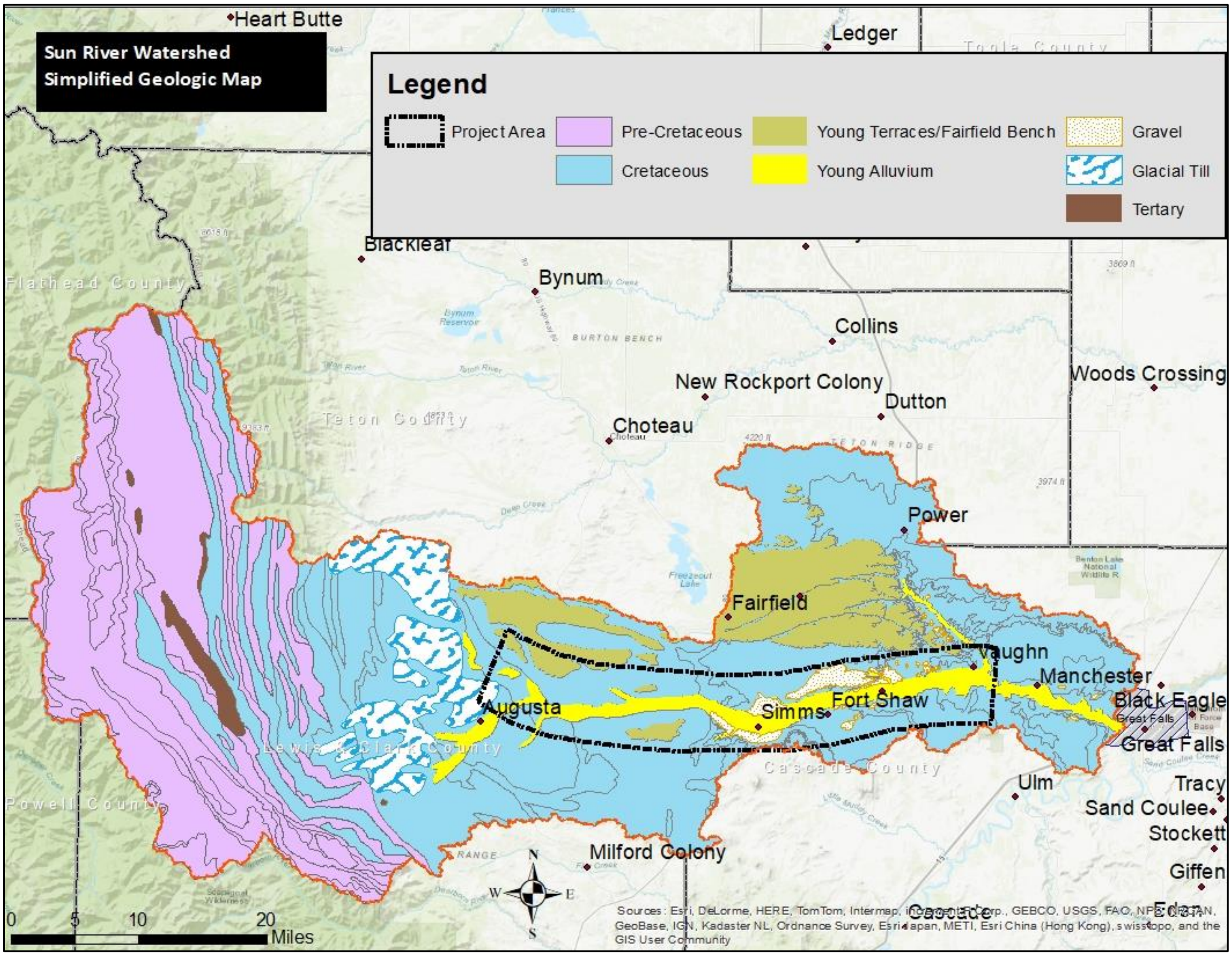


Figure 20. Simplified USGS geologic map of the Sun River Watershed.

2.3 Hydrology and Flow Management

The hydrology of the Sun River reflects a typical snowmelt system, with peak flows occurring between late May and early July.

2.3.1 Water Development

The biggest and oldest water development project in the watershed is the Sun River project. This project launched in 1907 when the U.S. Reclamation Service approved the construction of the Greensfields and Fort Shaw divisions, each with its own irrigation district. The project includes three storage reservoirs, two diversion dams, 131 miles of main canals, 562 miles of smaller side canals, and 265 miles of drain canals (Kellogg, 2014). Additional irrigation projects include Nilan Water Users, Broken O Ranch, Rocky Reef, and the Sun River Valley Ditch Company. According to Kellogg (2014), the eight-mile reach from Lowry bridge to the mouth of Big Coulee is especially susceptible to dewatering during droughts, although recent cooperative actions by water users have resulted in improved in-stream flows in recent years.

2.3.2 Sun River Flood History

To get a better perspective of the flood history of the Sun River, a long-term dataset from the Sun River near Vaughn is summarized below. Much of the hydrologic workup has been pulled directly from a recent project that AGI was involved to evaluate the impacts of recent floods on Elk Creek and its tributaries (CCI and AGI, 2020).

The Sun River gaging station near Vaughn (USGS 06089000) has continuously recorded mean daily flows since 1934, measuring flow contributions from the Upper Sun River, Lower Sun River, Elk Creek, and Muddy Creek watersheds. These mean daily flows are complimented by instantaneous peak discharges during flood events.

The annual instantaneous peak flow record for the Sun River near Vaughn gage is shown in Figure 21, and flood frequency estimates for the gage are shown as horizontal lines on the plot. The Sun River data indicate that at Vaughn, the 1964 flood exceeded a 200-year discharge. The second highest peak was in 1975 when a 100-year event was exceeded. The 2018 and 2019 floods exceeded 25-year and 5-year events, respectively. The flooding pattern generally shows flooding every decade or so from 1953 to 1975, followed by a long period of minimal flooding beginning in the early 1980s. The 2011 flood marked a resurgence of flooding, with three large floods occurring during the 2010-2020 decade.

To identify all major floods on the Sun River, each peak flood was evaluated with respect to a 10-year flood event. Figure 22 shows all recorded floods at Vaughn that exceeded a 10-year flood, and the bar height represents how much the 10-year flood was exceeded, so for example the 1964 event was about 55,000 cfs larger than a 10-year flood. Since 1936, a total of 8 floods have been larger than a 10-year event. The 2018 and 2019 floods are included in this analysis, however their magnitude is based on a published mean daily flow rather than instantaneous peak, so the true exceedance value is probably larger. Using mean daily flows from 2018 and 2019, the 2018 event exceeded a 10-year flood and the 2019 flood did not.

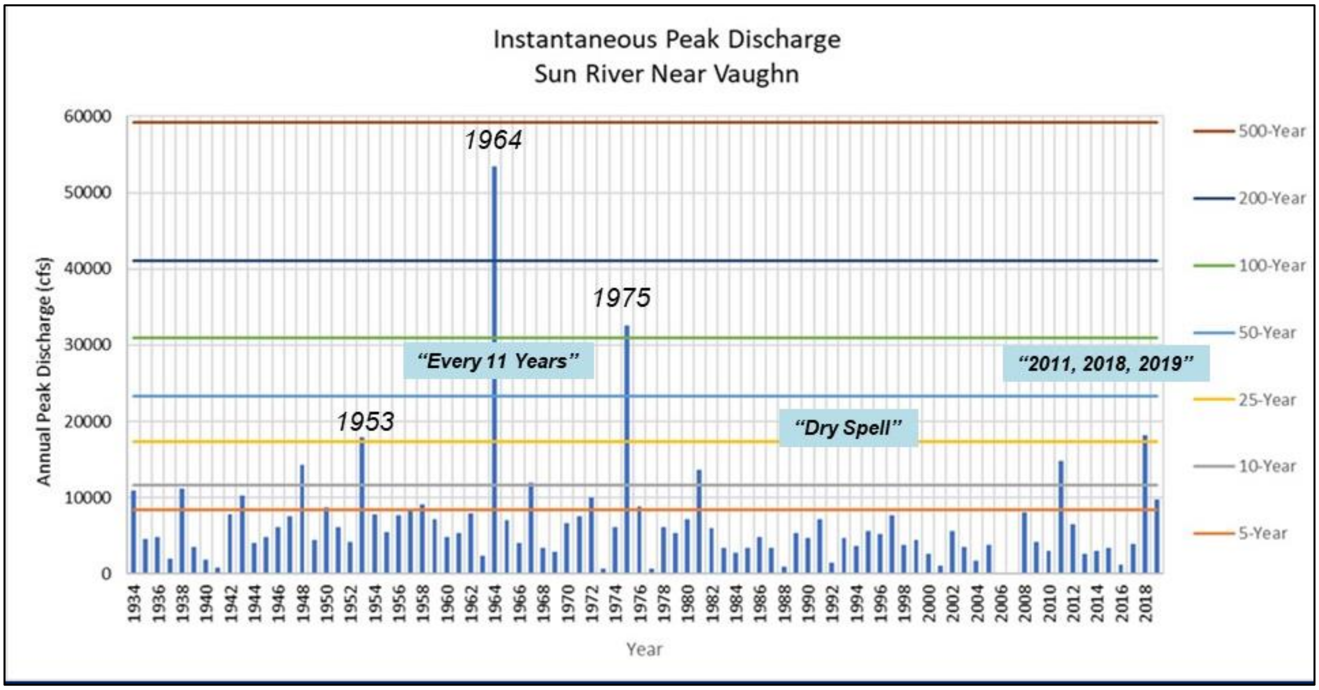


Figure 21. Annual Instantaneous Peak Discharges from 1934-2017, Sun River near Vaughn (USGS 06089000).

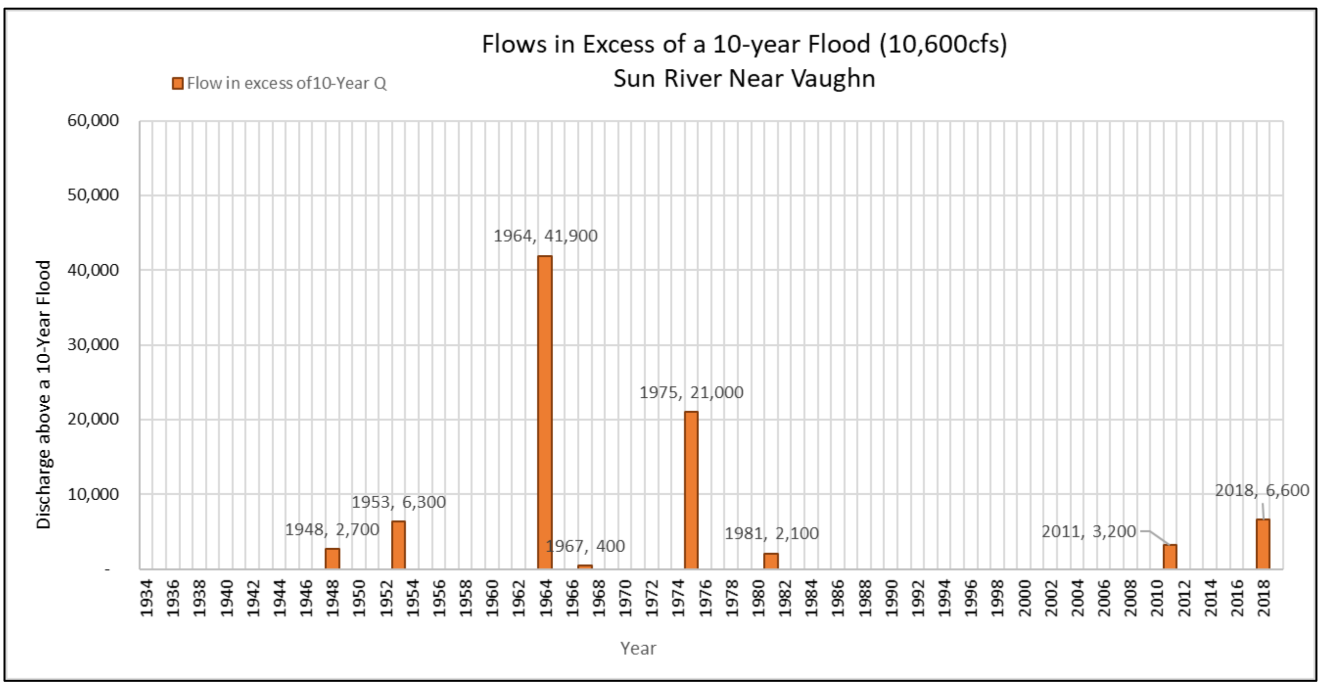


Figure 22. Instantaneous peak flow volumes in excess of a 10-year flood event; 2018 is based on mean daily flow versus instantaneous peak.

2.4 Major Recent Floods

The following section contains a brief summary of major flood events.

2.4.1 The 1953 Flood(s)

The flood of 1953 was caused by heavy rains from May 24 to June 4. According to the USGS (USGS, 1957), the persistent heavy rains caused flooding that "approached the disastrous flood of June 1908". This was a long duration event that was driven by three individual storms (Figure 23). The early storms dropped snow in the high country that was subsequently melted by rainfall events. During the first storm (May 24-26), Rogers Pass received 61.3 inches of snow. A total of 4.6 inches of rainfall fell in Augusta during the three storms. Although no lives were lost during the floods, two boys at Haver were killed by a post-storm landslide. Over 200 bridges were washed out or impassable. 1953 flood damages in the Sun River drainage were about $8.3 million in today's dollars. Almost 600 people were evacuated. The Sun River at Vaughn peaked at 17,900cfs on June 4 with a gage height of 16.4 ft.

The three storms associated with the 1953 flood are visible as three distinct steps in the rising limb of the Sun River hydrograph for that event (Figure 23).

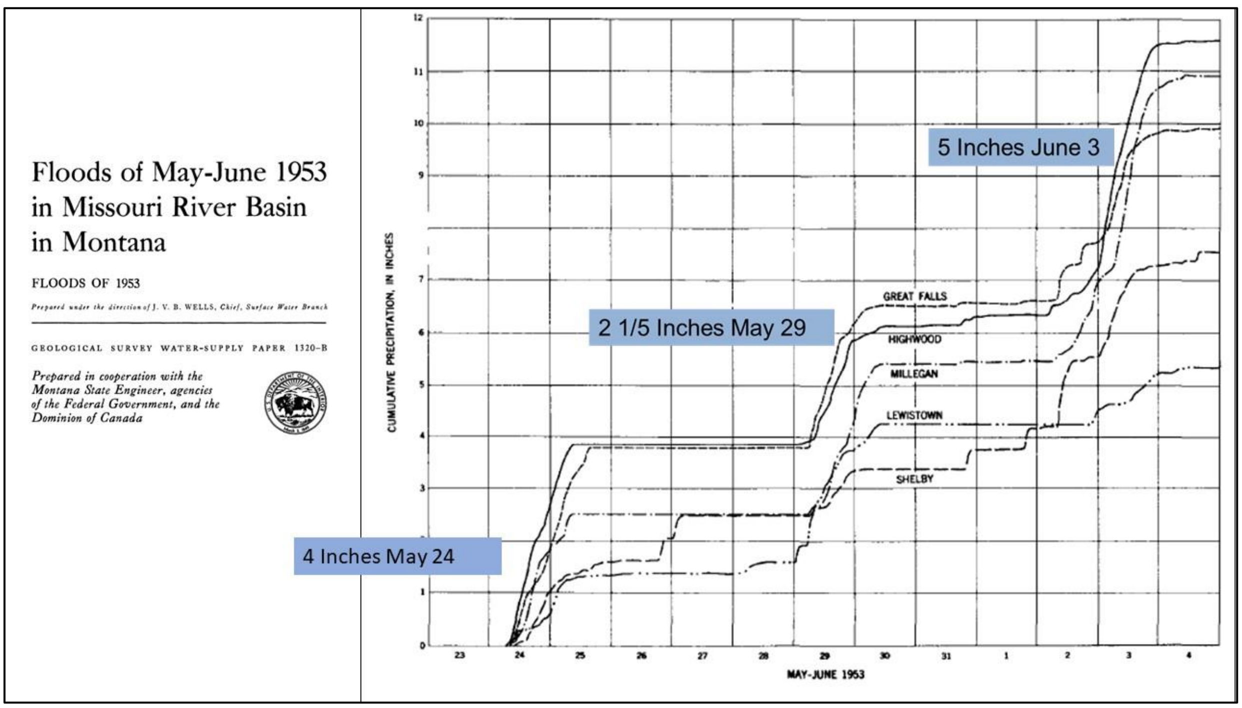


Figure 23. Cumulative precipitation during spring of 1953 showing three distinct storm events on May 24, May 29, and June 3; Great Falls is shown on the topmost line (USGS, 1957).

2.4.2 The 1964 Flood

The most severe flood ever recorded on the Rocky Mountain Front happened in the late spring of 1964. Fortunately, the flood prompted an interagency meeting in Great Falls on June 12, 1964 to address how to document this "outstanding" event (Boner and Stermitz, 1967). The resulting report, published in 1967, carefully documents the flood and its impacts.

Between June 6th and 8th of 1964, up to 14 inches of rain fell in a 36-hour period, when streams were already high from snowmelt. According to the United States Geological Survey (USGS), 6.5 inches of rain fell at the base of Sawtooth Ridge (Augusta 11 WNW), and 4.7 inches were recorded in Augusta (Boner and Stermitz, 1967). The floodwaters rose rapidly, increasing on the Sun River (near Vaughn) from a mean daily flow of 4,260 cfs on June 7th to 37,000 cfs on June 10. On June 8 rumors circulated that Gibson Dam had failed. A U.S. Forest Service pilot was sent to investigate, finding a three-foot wall of water coming over the top of the dam (Spence, 2011; Figure 25). The USBR estimated 66,000 cfs at the dam, at least half of which was coming over the top. The 200-foot tall dam held.

As Gibson Dam overtopped, the river peaked at 53,500 cfs at Vaughn, which is over a 200-year event (Figure 24). As a comparison, a flow of 40,000 cfs is the typical peak runoff for the Yellowstone River at Glendive, Montana.

Hadley (1967) reported that, in 1964, "upland erosion was severe" and that the North Fork of the Sun River deepened several feet and widened by about 25 feet. Near Dutton, the Teton River widened by about 100 feet.

The 1964 flood claimed 30 lives, most from the Blackfeet Reservation on the Two Medicine River south of Browning. Flood damage was concentrated between the Dearborn River and Glacier National Park. Much of the town of Augusta was inundated, and flooding was described as "much worse than the big flood of 1953".

In today's dollars, the 1964 flood caused $474 million in damages.

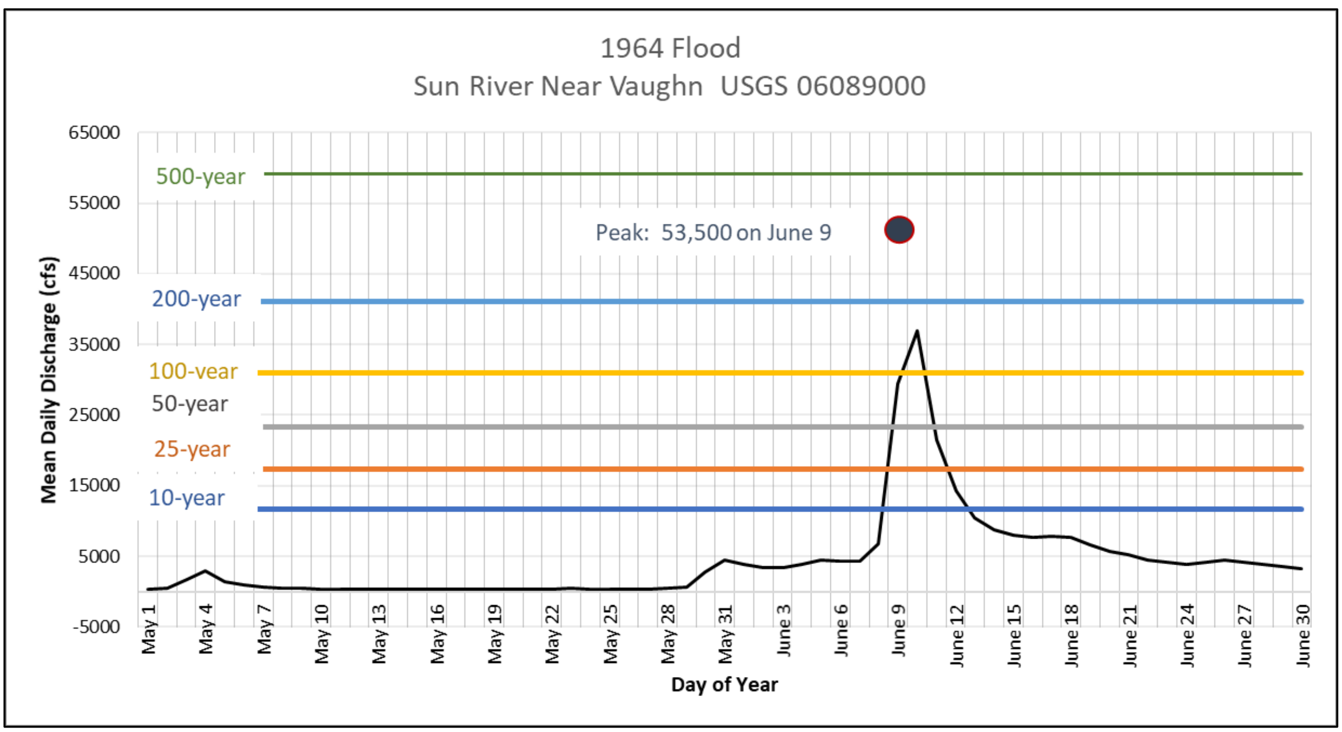


Figure 24. Hydrograph for 1964 flood as measured at Vaughn gage.

Figure 25. Gibson Dam overtopping with over 3 feet of water on the dam crest during 1964 flood (USGS).

2.4.3 The 1975 Flood

The 1975 flood was only a fraction of the 1964 flood. However, the 1975 flood is the second largest flood on record, with the Sun River having peaked at 32,600 cfs on June 20. Landowners reported heavy damages from this event.

2.4.4 The 2011 Flood

During the winter of 2010-2011, watersheds all across Montana developed deep snowpack that persisted into late spring. Flooding was pervasive state-wide, with the most intense flooding occurring wherever spring rains rapidly melted snowpack. At Vaughn, the peak was 14,800 cfs on June 10, which is just over a 10-year event.

2.4.5 The 2018 Flood

The 2018 flood was driven by rain; 7.5 inches of rain fell at Gibson Reservoir between June 16 and June 19. One somewhat unusual aspect of this flood is its late timing; whereas snowmelt-driven floods in this area are common in May or early June, the 2018 flood happened after the second week of June. During the peak of the event, the streets of Sun River were flooded (Figure 26) and broad inundation extended across the river's floodplain. Further upstream, tributaries to the Sun River in Sun Canyon showed areas of extreme erosion and instability. The impacts of the 2018 flood were described in the Prairie Populist: "Landowners suffered thousands of dollars of damages to their fences or property. Bridges built after the 1975 flood were washed away. Drinking wells were contaminated. Culverts, headgates, and pivots were destroyed".

The 2018 event can be considered a major, but not extreme, flood. Even so, it is the third-largest ever recorded on the Rocky Mountain Front, exceeding a 10-year event on both the Sun River and Elk Creek. Near Vaughn, the Sun River peaked out on June 21 at a mean daily flow of 18,200 cfs. Probably the most important aspect of the 2018 flood was its duration---prior to the peak, water had been high for weeks from snowmelt runoff.

Figure 26. 2018 flooding on Sun River and tributaries (Great Falls Tribune)

2.4.6 The 2019 Flood

The 2019 flood happened on Memorial Day. Gage data and eyewitness accounts indicate that although the peak flood was relatively short-lived, high water persisted for almost a week after the flood crest. Flows on the Sun River peaked out at 9,820 cfs at Vaughn on May 28, and flows remained at about a 2-year event through June 6. Some of the worst flooding was on Elk Creek in Augusta (Figure 27).

The Prairie Populist wrote an article comparing the 2018 and 2019 floods, and pointed out the difference in timing, as the 2018 flood was unusually late in June, versus the typical late May high water of 2019. Locals were described as more prepared for this event with sandbags on hand and sump pumps in basements. But the floods were similar in that they both followed a brutal winter that impacted calving. Both floods damaged fences and barns, and contaminated water. Key bridges were lost during both events (http://prairiepopulist.org/augusta-flood-2019/).

Figure 27. View looking south down Highway 287 of flooding in Augusta, 2019 (from Scott Gasvoda).

2.5 Influence of Flood History on Channel Dynamics

Between 1953 and 1975, major floods typically occurred every 11 years on the Sun River (1953, 1964, and 1975). From 1975 until a few years ago, floods were relatively rare, with only two 5-year floods (1981 and 2011) occurring over 41 years. Over the last two years (2018 and 2019), flooding has been the rule rather than the exception. These patterns are important when considering channel form and resilience, as floods can have a major, long-term influence on stream stability and rates of change. The following section describes the flow data with respect to its likely influence on stream process.

In snowmelt-driven stream systems, channel size and form are strongly influenced by spring runoff events. Typical spring runoff is commonly estimated by a 2-year flow, or that flow that occurs on average every two years. The 2-year flow ("Q2") is commonly used by restoration practitioners to design channel size and pattern.

The number of days in which a 2-year flood is exceeded can also be used to estimate how much “channel forming” energy was exerted on a stream during any given event or series of events. This in turn can shed light on the geomorphic changes seen in any given stream, as increased durations of flows over Q2 typically reflect higher rates of sediment transport and sorting, and associated channel change. As a result, channel forming processes relate not only to how big a flood is (peak flow), but how long it lasts (duration).

Each major flood described above is plotted in Figure 28, showing how many days flows exceeded a 2-year discharge during that flood season at Vaughn. This in turn can be used as a rough indication of how much work was performed on the channel. The results show that 1953 and 2018 had the longest duration of channel forming flows, and thus these floods have the potential to impart major channel change. In contrast, the 2019 event had the shortest duration of flows over a 2-year event. What is perhaps most relevant to this work is the long duration of the 2018 event; clearly this flood had the potential to drive high rates of channel change.

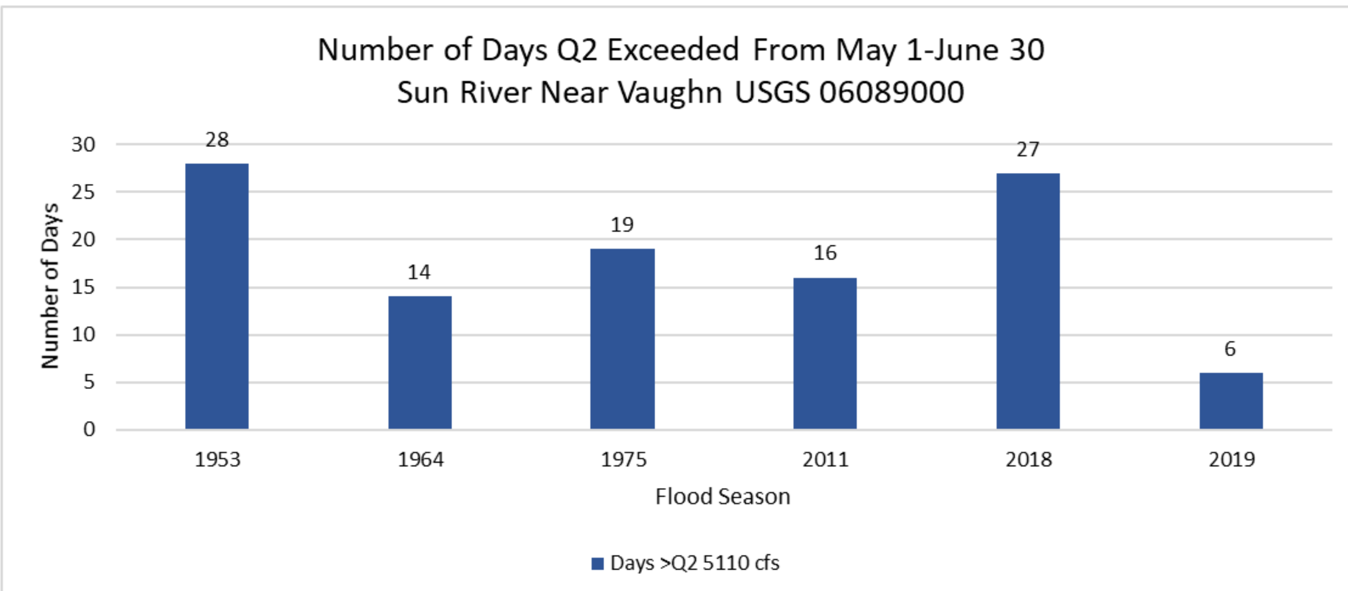


Figure 28. Number of days a 2-year discharge was exceeded during major flood events, Sun River near Vaughn.

When taken in broader context, it is important to recognize that work is performed on channels all the time, not just during major floods. Figure 29 shows the number of days the 2-year discharge was exceeded during any year (not just flood years) on the Sun River near Vaughn. What is striking about this graph is the lack of channel forming events since the 1975 flood. This is also shown on Figure 30 as a cumulative plot. The line shows a distinct break in slope, with conditions that would support much more work occurring prior to 1976.

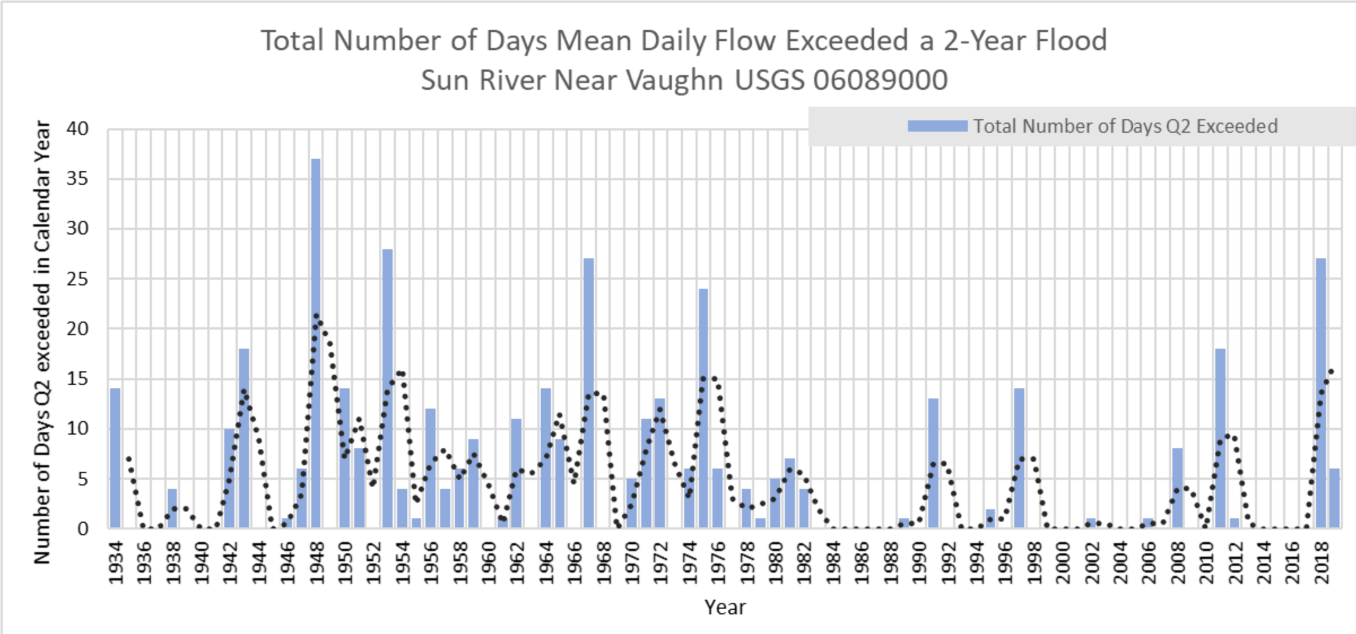


Figure 29. Number of days a 2-year discharge was exceeded annually since 1934 on the Sun River near Vaughn.

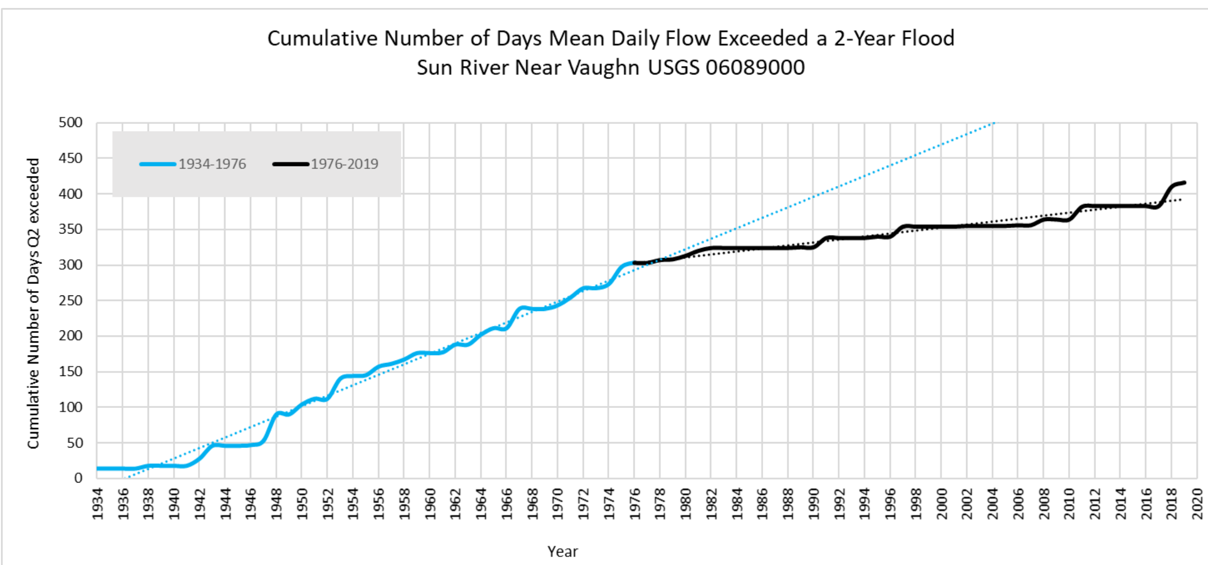


Figure 30. Cumulative number of days that Sun River flows have exceeded a 2-year flood event since 1934.

The data shown in Figure 30 shows an important aspect of the Sun River's geomorphic history. From 1976 to 2018 (or to 2011 in some areas), the river was quiet in terms of flood-driven change. The Sun River and its tributaries such as Elk Creek narrowed and grew in with vegetation. An example of this is shown in Figure 31, where open gravel bars near Lowry grew in between 1978 and 2011. Vegetation encroachment reduces channel capacity, making that channel especially prone to dramatic change during the next long flood event. This is a common phenomenon across the state; it wasn't only the drought years of the early 2000s that caused our rivers to atrophy, but a much longer period of minimal flooding that began in the late 1970s. An important aspect of this trend is that newcomers to the river corridor had no direct experience regarding how much the river can change with time, making the floods of 2018 and 2019 especially shocking to many.

2.6 Dikes and Levees

The Vaughn Levee, shown in Figure 32 on the following page, is the only major flood control structure we were able to map in the study area. The levee is about 2.5 miles long, built in 1969 in response to the 1964 floods. The levee protects 250 households from Sun River floodwaters (Kellogg, 2014). A second levee separates the river from an old gravel pit on the south bank about four miles upstream of Vaughn.

Figure 31. Sun River at RM 44 (just below Lowry Bridge) showing broad open bars in 1977 (top) and more dense riparian stands in 2011 (bottom).

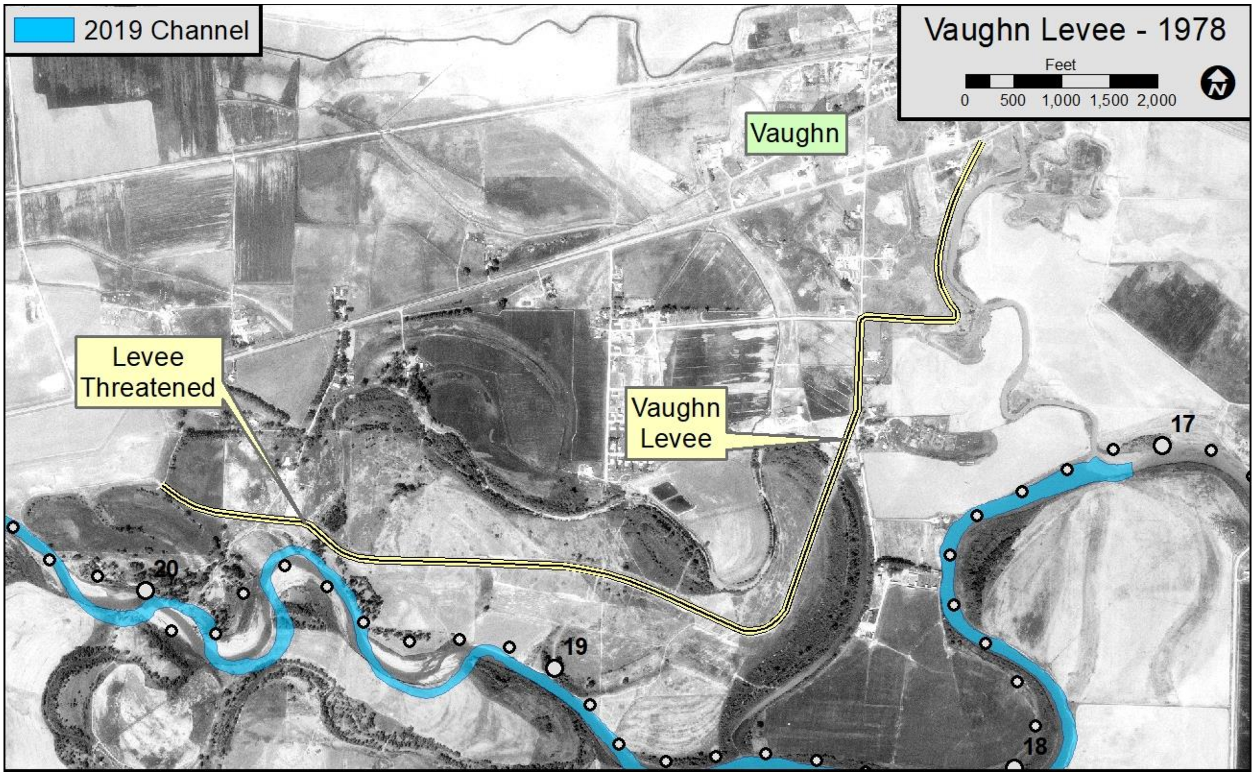


Figure 32. Vaughn Levee showing conditions a decade after it was built (1978 air photo); blue shows 2019 Sun River course and highlights large meander approaching and threatening levee.

2.7 Bank Armor

Bank armor was mapped where visible on air photos, Google Earth, or oblique photographs. Since there was no ground inventory, the mapping probably captures a conservative estimate of the extent of bank armor on current and historic channels. Additionally, the bank armor inventory has not assessment of condition or functionality. Along the length of the Sun River, we mapped 4.7 miles of bank armor which covers about 5% of the total bankline. The bank armor consists of rock riprap, barbs, and other revetments such as root structures, and potentially concrete rubble.

The extent and impact of bank armoring on the CMZ is described in more detail in Section 4.5.

2.8 Transportation Infrastructure

Transportation infrastructure, including roads, bridges, and railroads are high-value features that often have extensive bank armoring associated with them. This is especially true where the feature parallels the channel. Armoring will restrict the ability for a stream to migrate laterally in an effort to protect the feature from damage. With the exception of local impacts at eight bridge crossings, the Sun River within the study area is generally unaffected by transportation infrastructure.

2.9 Sand and Gravel Mining

A total of 41 gravel pits were mapped in the stream corridor, and all of them are downstream of the town of Sun River in Reach SR1 (Figure 33). There are currently four permitted open cut sites within or adjacent to the stream corridor, indicating that the vast majority of pits are not currently operating. Figure 34 shows the number of new pits visible on each suite of imagery; the rate of development was fairly constant from the 1950s until 2011 but has dampened since then. Prior to 2011, about six new pits per decade are visible on the imagery.

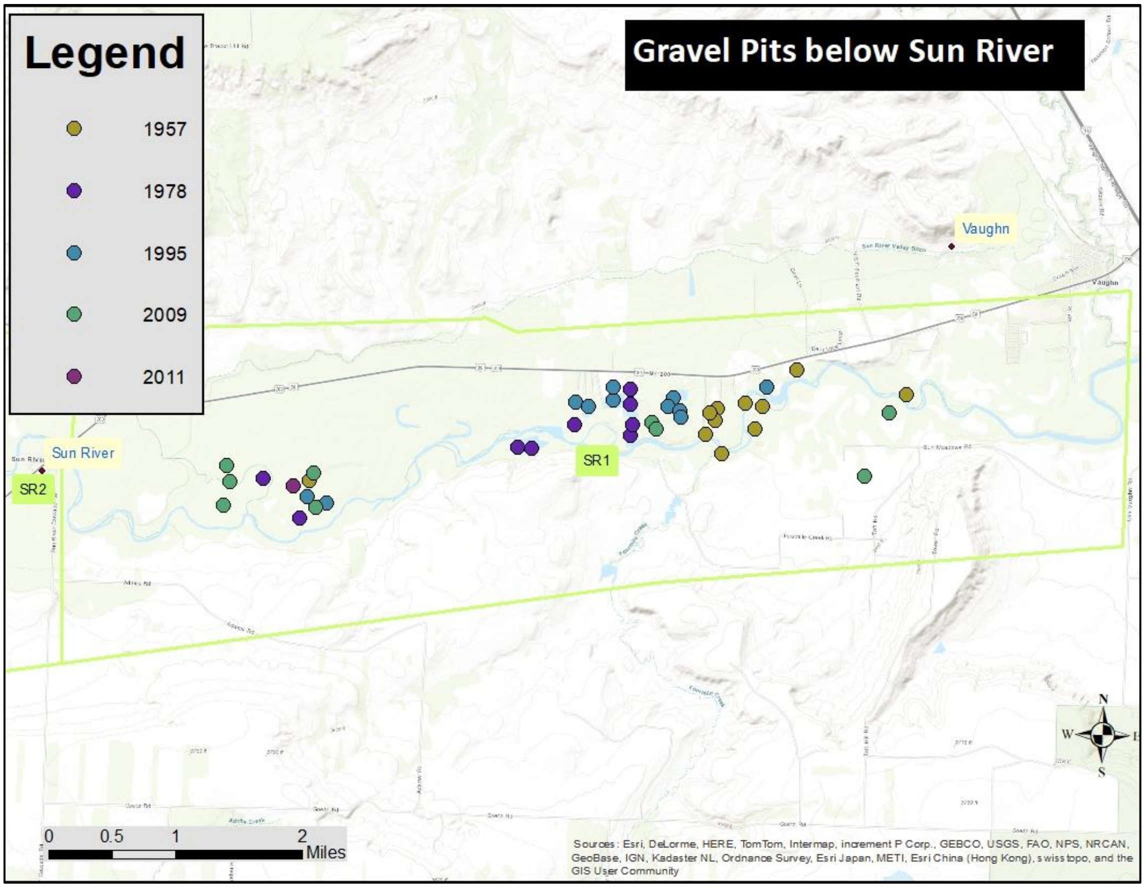


Figure 33. Gravel pits visible on imagery showing first year of visible activity.

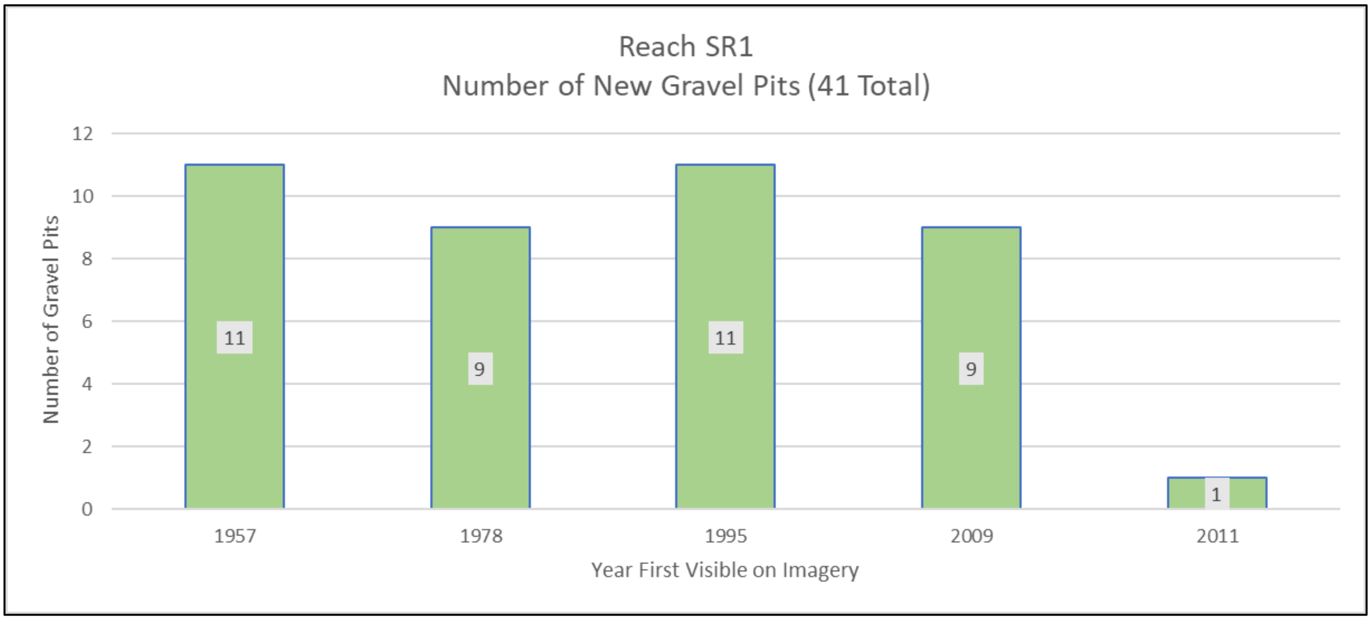


Figure 34. General rate of gravel pit development shown as first time pits were visible in imagery.

3 Methods

The development of the Sun River Channel Migration Zone (CMZ) mapping is based on established methods used by the Washington State Department of Ecology (Rapp and Abbe, 2003), and closely follows methodologies used on over 1,200 miles of rivers in Montana.

3.1 Aerial Photography

CMZ development from historic imagery is dependent on the availability of appropriate imagery that covers the required time frame (50+ years), the spatial coverage of that imagery, and the quality of the photos. It is important to use imagery with the best possible quality, scale, extent, and dates so that historic and modern features can be mapped in sufficient detail. Several imagery sources are available for the Sun River study area. The most recent sources, starting around 1995 with the black-and-white Digital Orthophoto Quad imagery (DOQ) and continuing through the current NAIP (National Agriculture Imagery Program) imagery, are freely available in GIS-compatible format. The quality of these images, both spatially and resolution, ranges from good to excellent and they cover the entire project area.

Imagery older than 1995 must be acquired from various archival services as digital scans, and then mosaiced into a single spatially-referenced image for use in the GIS. For this project, the historic imagery scans were ordered from the United States Department of Agriculture (USDA) Air Photo Field Office (APFO) in Salt Lake City, Utah.

A total of 79 individual images were ordered from the APFO to cover two time periods for the Sun River – 57 for 1957 and 22 for 1977/78. The 1970s imagery was collected in two different years, with 10 images from 1978 covering the river upstream of Simms and 12 images dated 1977 covering the river downstream. No significant flood events occurred between the image suites, so they could be combined as single time period. The USDA scans were delivered as high-resolution (12.5 micron) TIFF images, each approximately 330 MB in size. They were then orthorectified by Aerial Services, Inc. (ASI) in Cedar Falls, Iowa, using NAIP imagery as the spatial reference, providing identifiable ground control points. Table 1 lists imagery used for this project from the USDA and archives of current GIS data sets. Examples of the imagery used in the analysis are shown in Figure 35 through Figure 39.

Table 1. Aerial photography used for the Sun River Channel Migration mapping study.

Year	Source	Scale	Number of Images	Image Date	Notes
1957	USDA APFO	1:20,000	57	7/10 to 7/18/1957	High-resolution Scans (black-and-white)
1977/78	USDA APFO	1:40,000	22	8/17/1977 8/3/1978	High-resolution Scans (black-and-white)
2013 NAIP	USDA	~ 1 meter resolution	NA	Mostly 8/9/1995, with remaining 7/1 to 8/5/1995	Digital Download, Compressed County Mosaics (color)
2017 NAIP	USDA	~ 1 meter resolution	NA	7/3 to 7/17/2017	Digital Download, Compressed County Mosaics (color)
2019 NAIP	USDA	~ 1 meter resolution	NA	7/27 to 7/30/2019	Digital Download, Compressed County Mosaics (color)

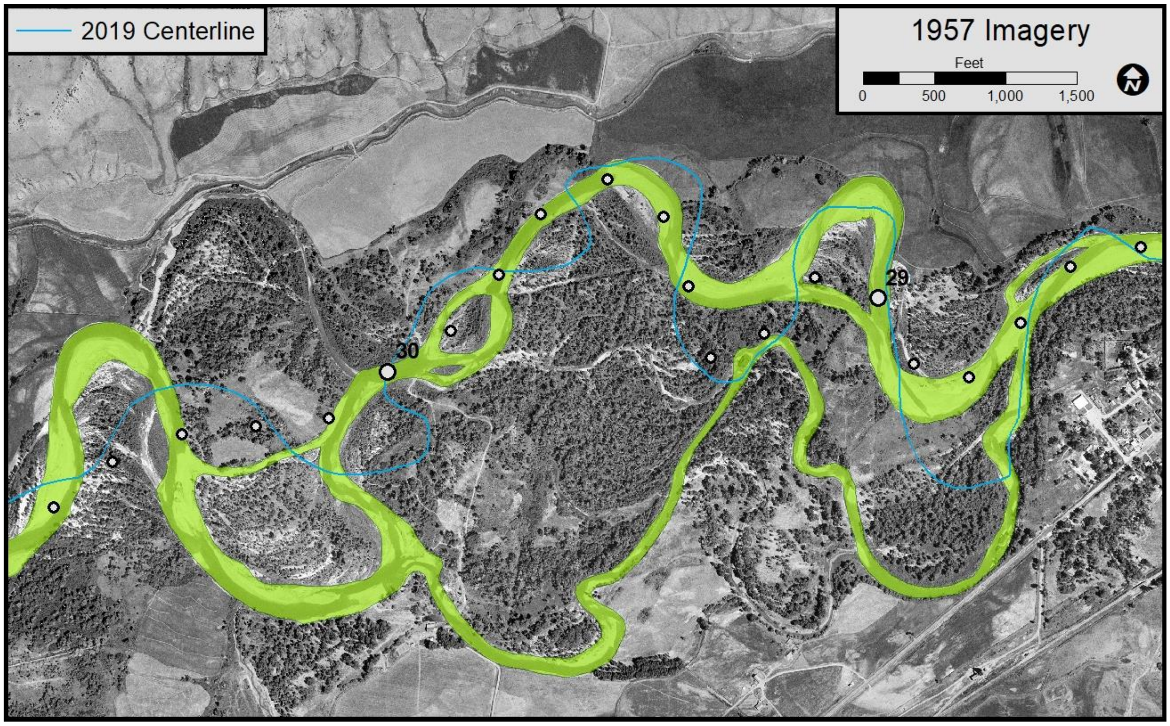


Figure 35. Example 1957 imagery upstream of Sun River.

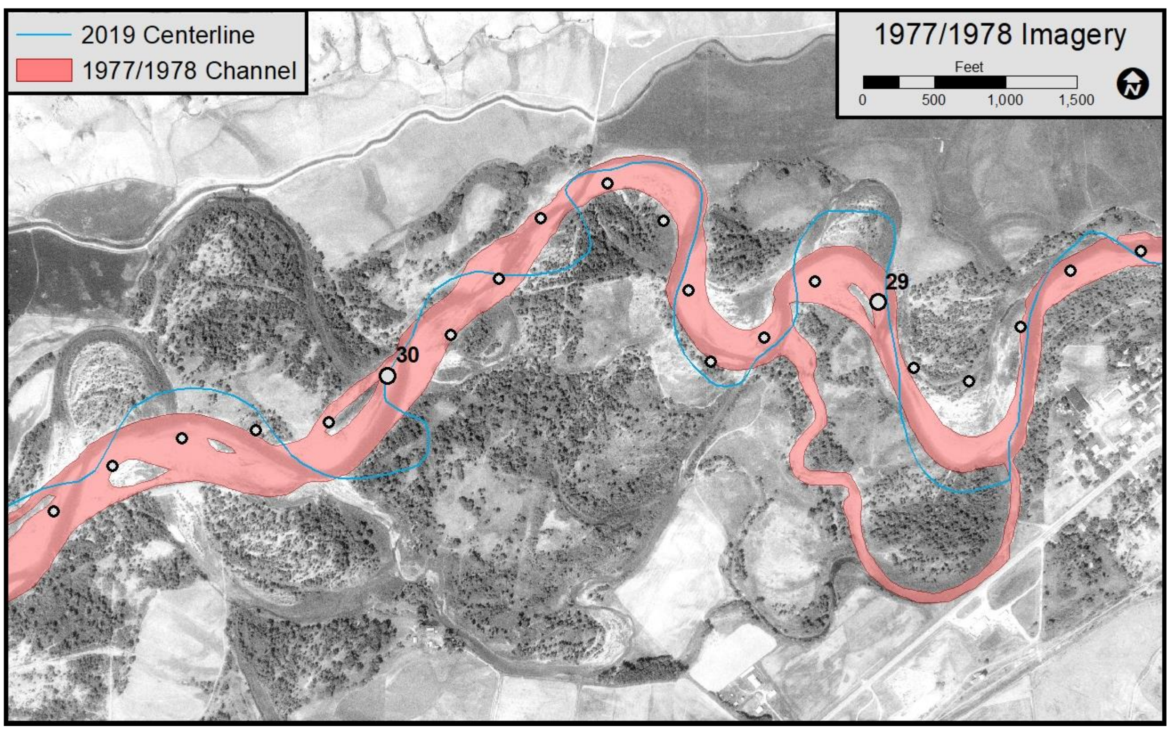


Figure 36. Example 1977/78 imagery upstream of Sun River.

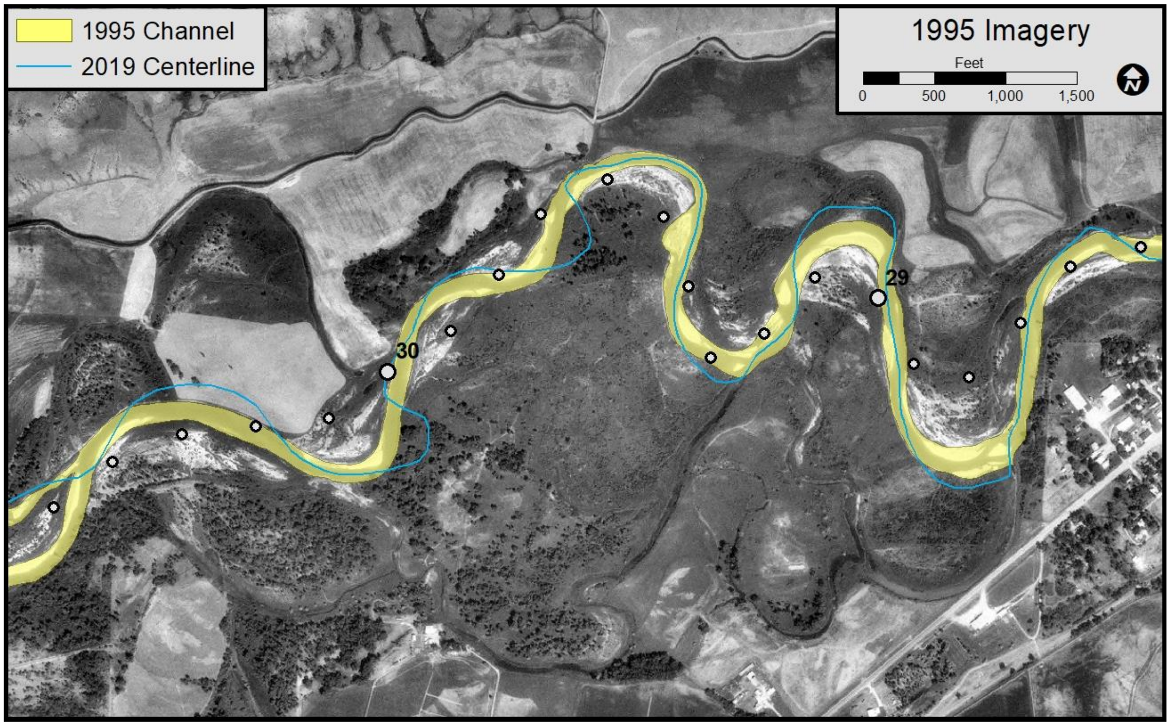


Figure 37. Example 1995 DOQ imagery upstream of Sun River.

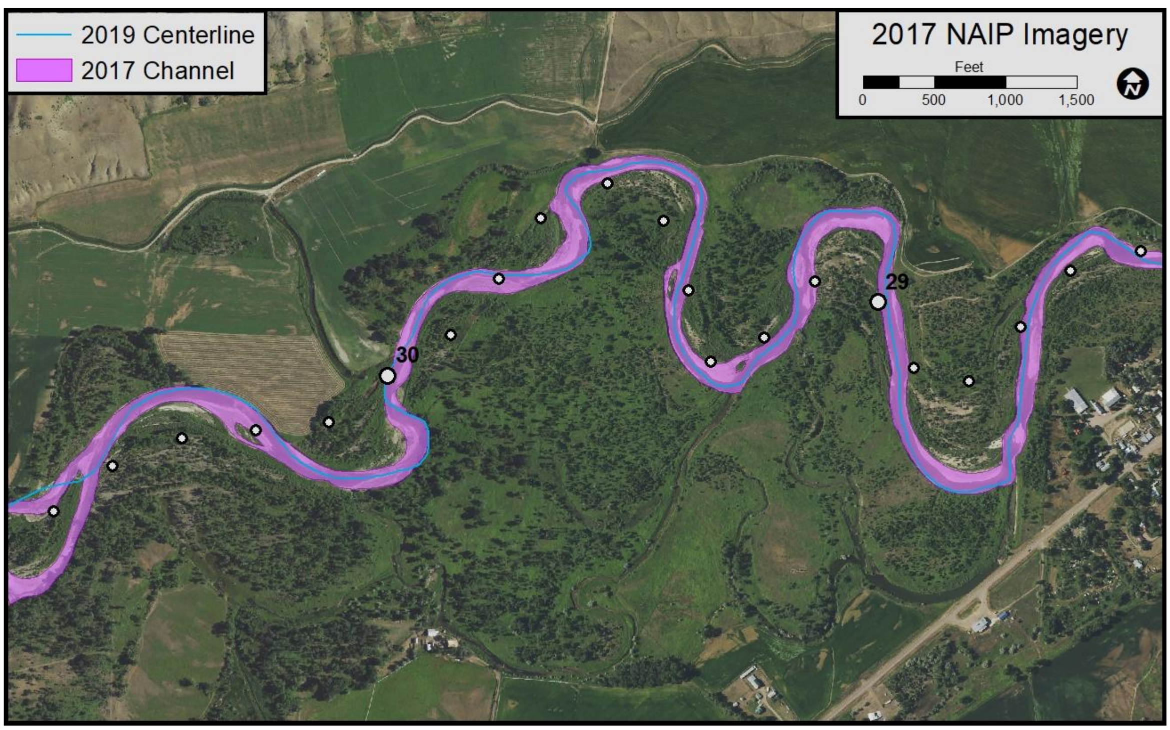


Figure 38. Example 2017 NAIP imagery upstream of Sun River.

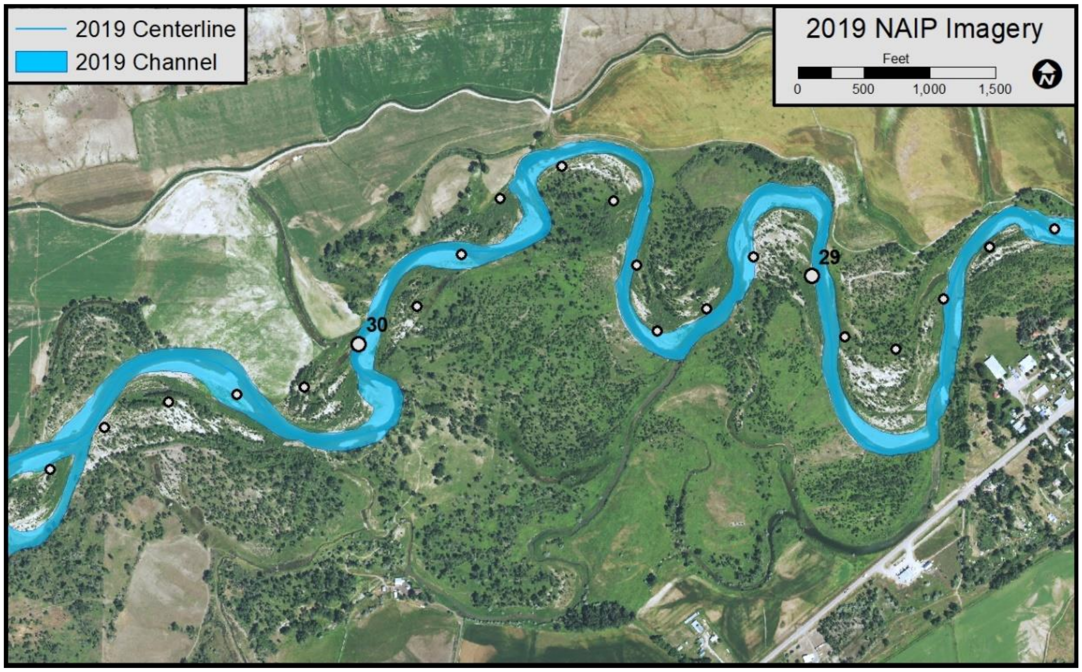


Figure 39. Example 2019 NAIP imagery upstream of Sun River.

Figure 40 shows how the dates of the imagery relate to the flood history of the river. The 1957 imagery captures conditions shortly after the 1953 flood; in many locations, extensive braiding the 1957 imagery suggests that that event left a strong signature channel form. The 1978 photos capture the two largest recorded floods, and similarly shows broad open bars and a relatively large channel cross section. Numerous avulsions and extensive channel movement occurred during the 1957-1978 window. In contrast, 1995 captures a period of quiescence as vegetation encroached onto open gravel bars. And lastly, the 2017/2019 images bracket the two most recent floods. The prevalence of large open bar area in the earliest imagery suites (1957 and 1978) may be purely the result of flood impacts; alternatively, it may indicate that sediment storage in Gibson Reservoir is beginning to affect this section of river by reducing loads and associated bar development.

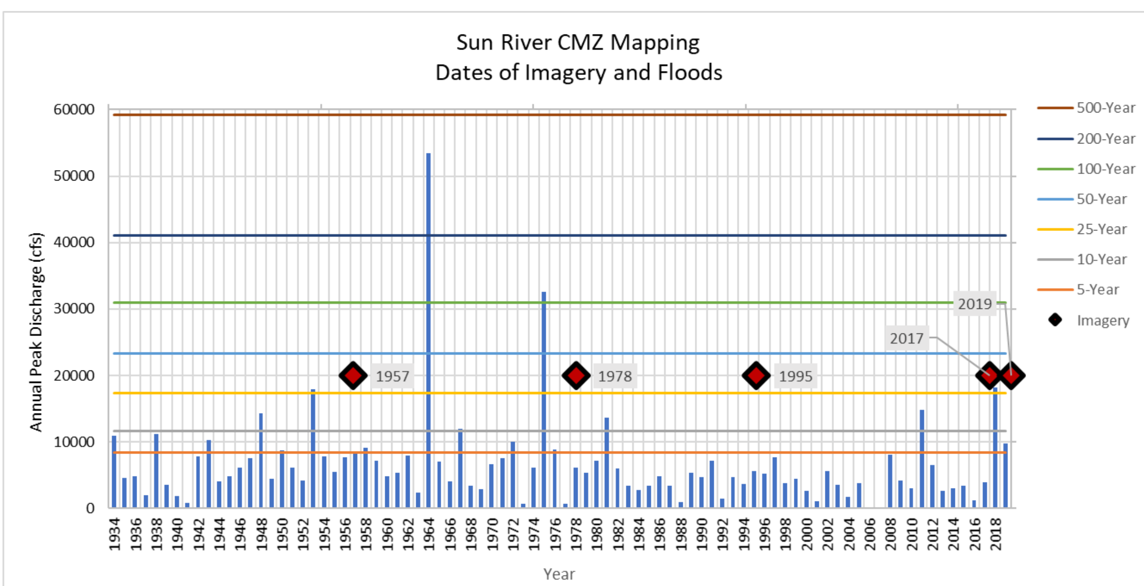


Figure 40. Dates of imagery (diamonds) showing their relationships to flood events.

3.2 GIS Project Development

All project data was compiled using ESRI's ArcMap Geographic Information System (GIS) utilizing a common coordinate system - Montana State Plane NAD83 Meters. The orthorectified air photos provide the basis for CMZ mapping; other existing datasets included roads, MT Fish Wildlife and Parks stream stationing, flood studies, scanned General Land Office Survey Maps obtained from Bureau of Land Management, and geologic maps produced by the United States Geological Survey.

3.3 Bankline Mapping

Banklines representing bankfull margins were digitized for each year of imagery at a scale of ~1:2,000. A tablet computer running ArcGIS and using a pen stylus was used to trace the banklines using stream mode digitizing. This methodology allowed us to capture a much more detailed bankline than using a mouse. Bankfull is defined as the stage above which flow starts to spread onto the floodplain. Although that boundary can be identified using field indicators or modeling results (Riley, 1972), digitizing banklines for CMZ development requires the interpretation of historic imagery. Therefore, we typically rely on the extent of the lower limit of perennial, woody vegetation to define channel banks (Mount & Louis, 2005). This is based on the generally accepted concept that bankfull channels are inhospitable to woody vegetation establishment. Fortunately, shrubs, trees, terraces, and bedrock generally show distinct signatures on both older black-and-white as well as newer color photography. These signatures, coupled with an understanding of riparian processes, allow for consistent bankline mapping through time and across different types of imagery.

3.4 Migration Rate Measurements

Once the banklines were digitized, they were evaluated in terms of discernable channel migration since 1957. Where migration was clear, vectors (arrows with orientation and length) were drawn in the GIS to record that change. At each site of bankline migration, measurements were collected approximately every 30 feet (Figure 41). A total of 757 migration vectors were generated for the Sun River at a scale of ~1:2,000. These measurements were then summarized by reach. The results were then used to define a reach-scale erosion buffer width to allow for likely future erosion. Results of this analysis are summarized in Section 4.2.

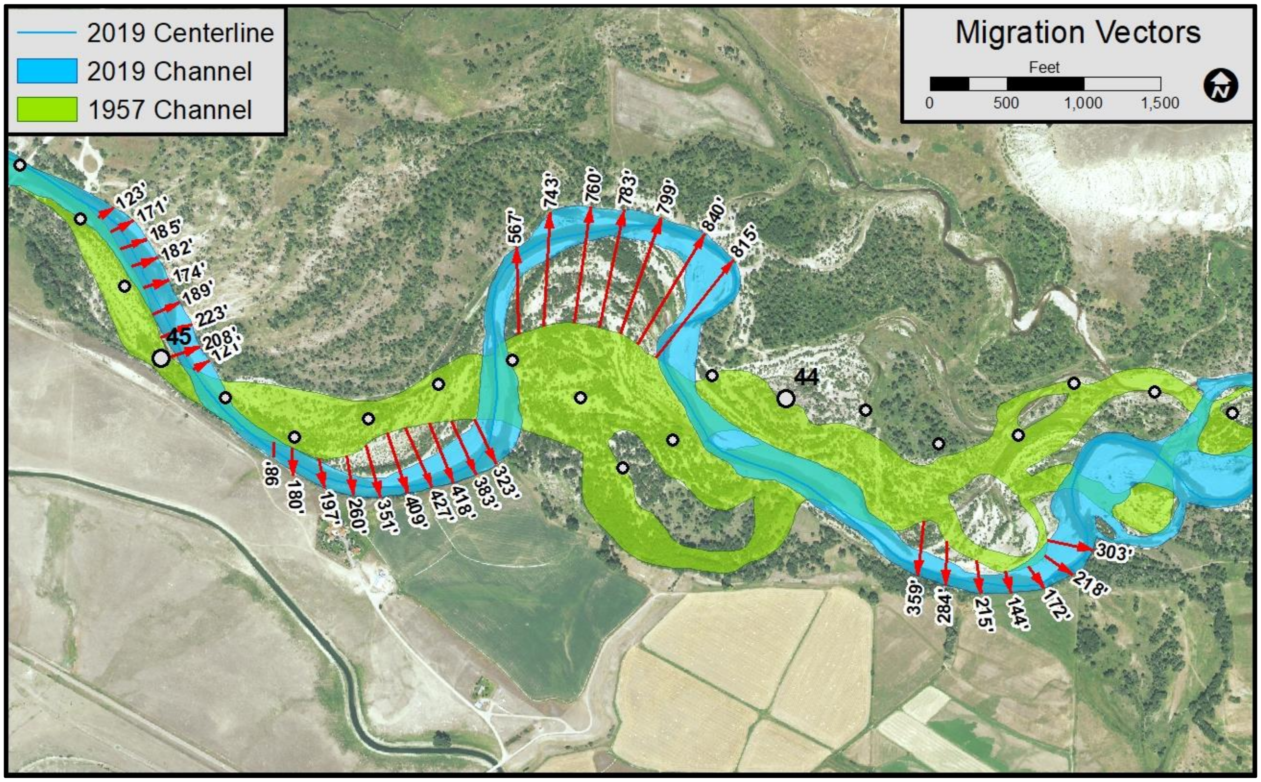


Figure 41. Example of migration measurements between 1957 and 2019 (migration distance in feet).

3.5 Avulsion Hazard Mapping

Avulsion hazards can be difficult to identify on broad floodplains, because an avulsion could occur virtually anywhere on the entire floodplain if the right conditions were to occur. As such, avulsion pathways were identified and mapped using criteria that identify a relatively high propensity for such an event. These criteria usually include the identification of high slope ratios between the floodplain and channel, tributary channels at risk of capture, and the presence of relic channels that concentrate flow during floods. Figure 42 shows several potential avulsion paths including a meander core, high flow channel, and remnant older channel (from left to right on image).

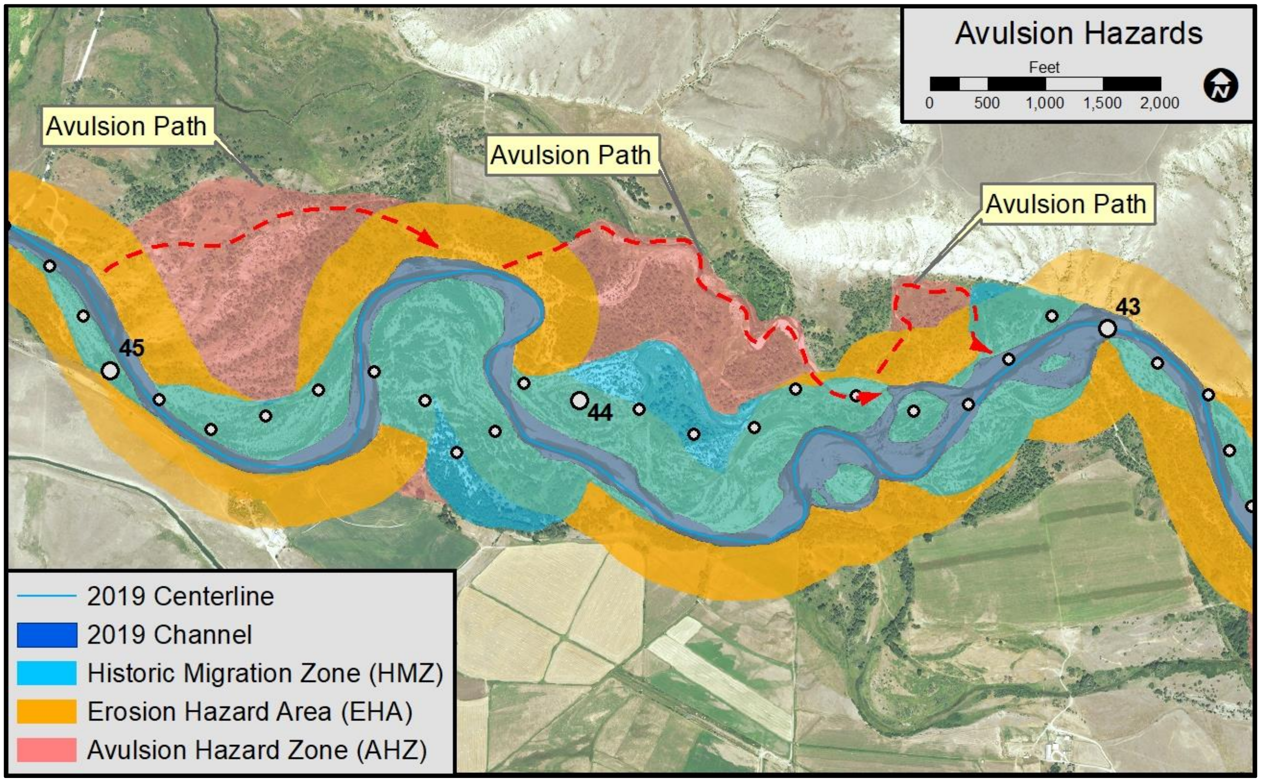


Figure 42. Example floodplain channel indicating an avulsion pathway.

4 Results

The Channel Migration Zone (CMZ) developed for the Sun River is defined as a composite area made up of the existing channel, the historic channel since 1965 (Historic Migration Zone, or HMZ), and an Erosion Hazard Area (EHA) that encompasses areas prone to channel erosion over the next 100 years. Areas beyond the EHA that pose risks of channel avulsion comprise the Avulsion Hazard Zone (AHZ). Lastly, those areas where migration has been restricted are highlighted as Restricted Migration Area (RMA).

4.1 Project Reaches

The approach to CMZ mapping used here includes a reach-scale evaluation of channel migration rates. For the 51 miles of project length, the river was broken into six reaches based on geomorphic character such as river pattern, rates of change, and geologic controls (Figure 44. The reaches range in length from 4.2 to 13.2 miles (Table 2). Average channel slope for each reach flattens in the downstream direction, with a clear drop in slope below Reach SR4 which ends at Lowry Bridge (Figure 43).

Table 2. Sun River CMZ mapping project reaches.

Reach	General Location	Upstream RM	Downstream RM	Length (mi)
SR1	Sun River to Vaughn	28.2	17.2	11
SR2	Rocky Reef Diversion to Sun River	36.8	28.2	8.6
SR3	Lowry Bridge to Rocky Reef Diversion	45.3	36.8	8.5
SR4	Just above Fort Shaw Canal to Lowry Bridge	49.5	45.3	4.2
SR5	Dry Creek to just above Fort Shaw Canal	54.9	49.5	5.4
SR6	Highway 287 to Dry Creek	68.1	54.9	13.2

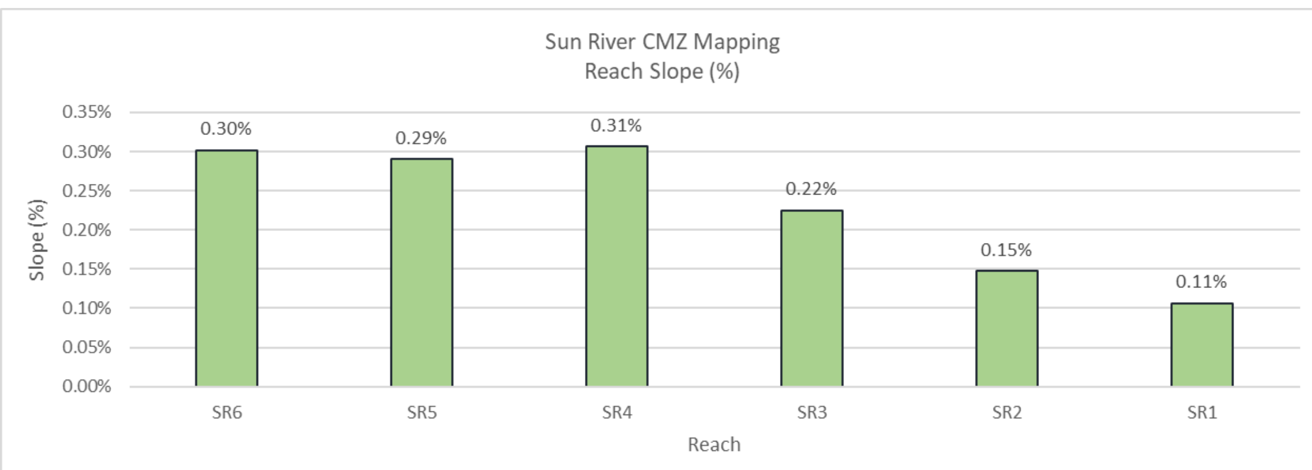


Figure 43. Average channel slope for project reaches plotted from upstream (SR6) to downstream (SR1) showing progressive loss of gradient below Reach SR4 (Lowry Bridge)

Figure 44. Sun River CMZ mapping project reaches.

4.2 The Historic Migration Zone (HMZ)

The Historic Migration Zone (HMZ) is created by combining the bankfull channel polygons into a single HMZ polygon. The bankfull channels commonly split and rejoin, creating a mosaic of channel courses with intervening islands, some of which are seasonal. The HMZ footprint includes all channels as well as any area between split flow channels. By including islands, the HMZ captures the entire footprint of the active river corridor from 1957-2019. In some settings where island areas are non-erodible, it may be appropriate to exclude these features from the CMZ. In the case of the Sun River, however, these areas have been retained in the CMZ since they are made up of young alluvial deposits that are prone to reworking or avulsion and are thus part of the active meander corridor.

Any side channels that have not shown perennial connectivity to the main channel since 1957 were not mapped as active channels and are not included in the HMZ.

For this study, the Historic Migration Zone is comprised of the total area occupied by Sun River channel locations in 1957, 1977/78, 1995, 2017 and 2019 (Figure 45). The resulting area reflects 62 years of channel occupation for the length of the Sun River study area.

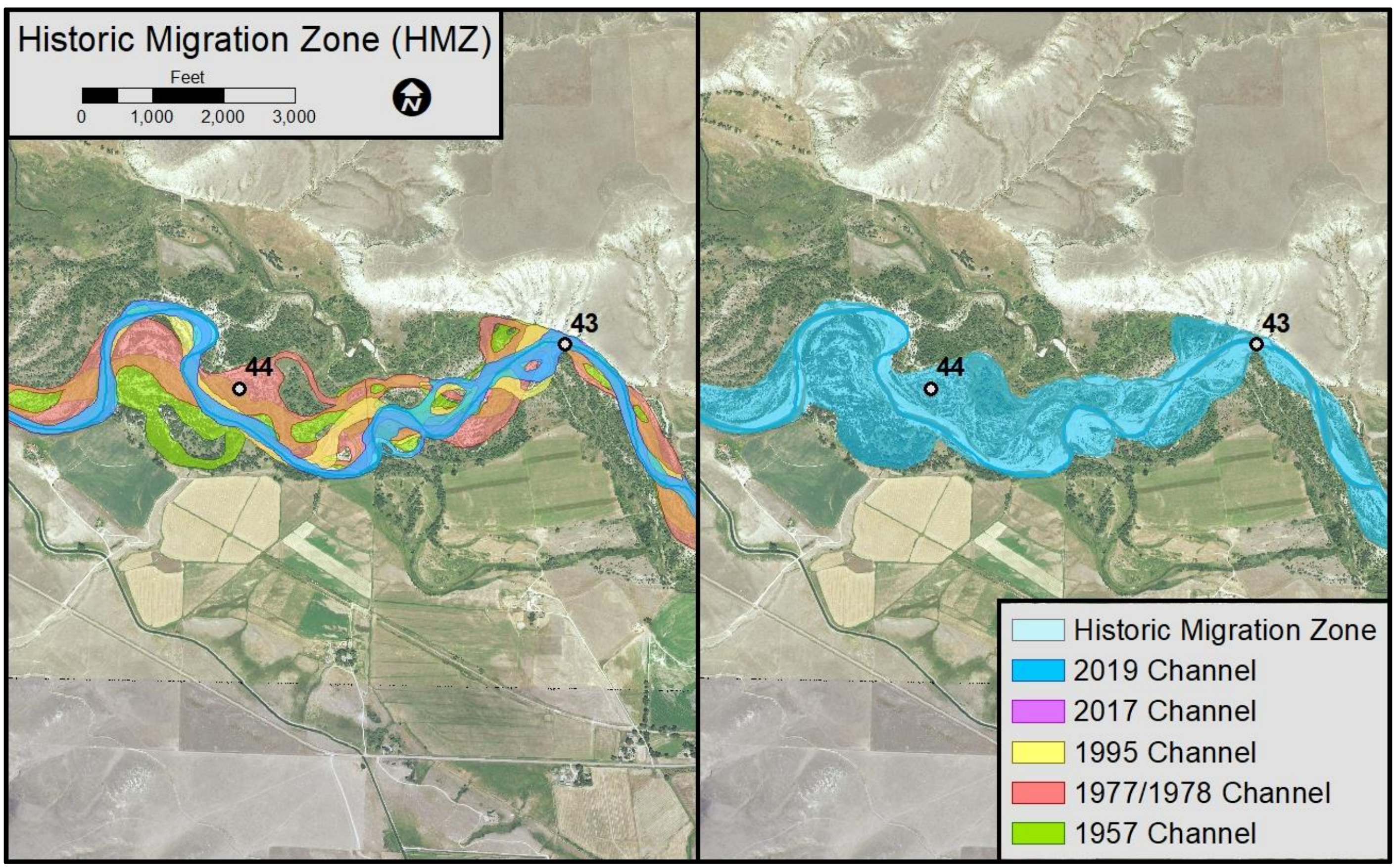


Figure 45. The Historic Migration Zone (HMZ) is the combined footprint of all mapped channel banklines.

4.3 The Erosion Hazard Area (EHA)

The Erosion Hazard Area (EHA) is based on measured migration rates, which are derived from measured migration distances. Migration distances were measured where it was clear that the channel movement was progressive lateral movement and not an avulsion. A total of 757 measurements were collected on the Sun River. The minimum distance measured is 20 feet, which proved to be an easily measurable distance that is not compromised by the resolution or spatial accuracy of the data. The 1957-2019 measured migration distances are summarized in Figure 46, and migration rates are shown in Figure 47. Migration into the terrace bankline was summarized separately, to allow the application of an erosion hazard buffer specifically to that geologic unit. Mean migration rates and EHA buffer widths are shown in Table 3 and Figure 48. The buffer width is calculated as that distance the river would move over a century's time at the mean annual rate.

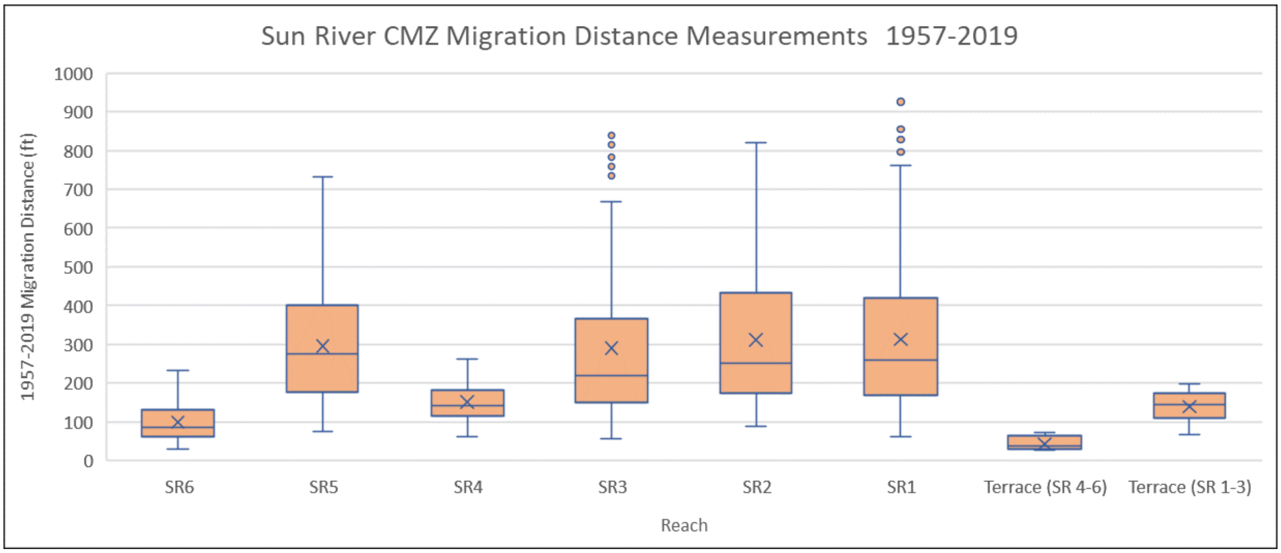


Figure 46. Box and whisker plot showing measured 1957-2019 migration distances by reach and for terraces -- reaches are plotted from upstream (left) to downstream (right). Mean values are denoted by "X".

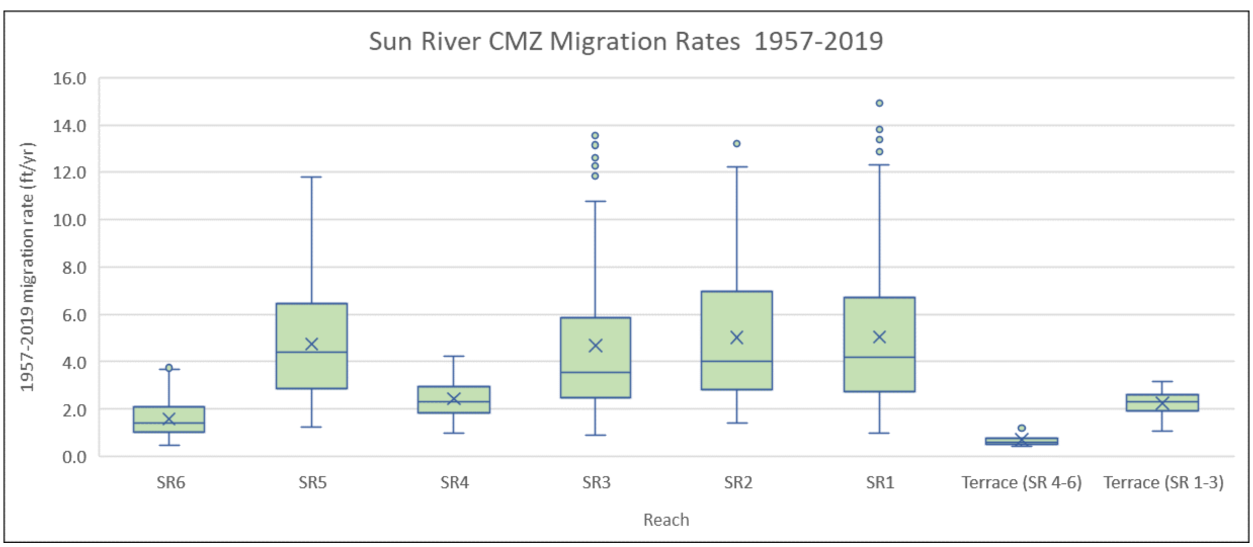


Figure 47. Box and whisker plot showing measured 1957-2019 migration rates by reach and for terraces -- reaches are plotted from upstream (left) to downstream (right). Mean values are denoted by "X".

As the *mean* migration rate is the statistic used to define the EHA buffer, the results are inherently conservative. Thus, some localized channel migration through and beyond the EHA buffer should be anticipated over the next century. Table 3 shows that in almost every reach, the 100-year erosion buffer is less than the maximum measured migration distance. Typically, however, these areas of rapid bankline movement are within the Historic Migration Zone, and thereby captured in the CMZ.

Table 3. Average migration rate and 100-year EHA buffer by reach.

Reach	Number of Measurements	Maximum Migration Distance (ft)	Average Annual Migration Rate (ft/yr)	100- Year Buffer Width (ft)
SR1	144	928	5.0	503.7
SR2	118	831	5.0	502.8
SR3	110	840	4.7	468.2
SR4	35	263	2.4	244.4
SR5	125	732	4.8	475.4
SR6	212	232	1.6	159.1
T (SR1-3)	11	188	2.2	224.8
T (SR4-6)	2	35	0.7	69.7

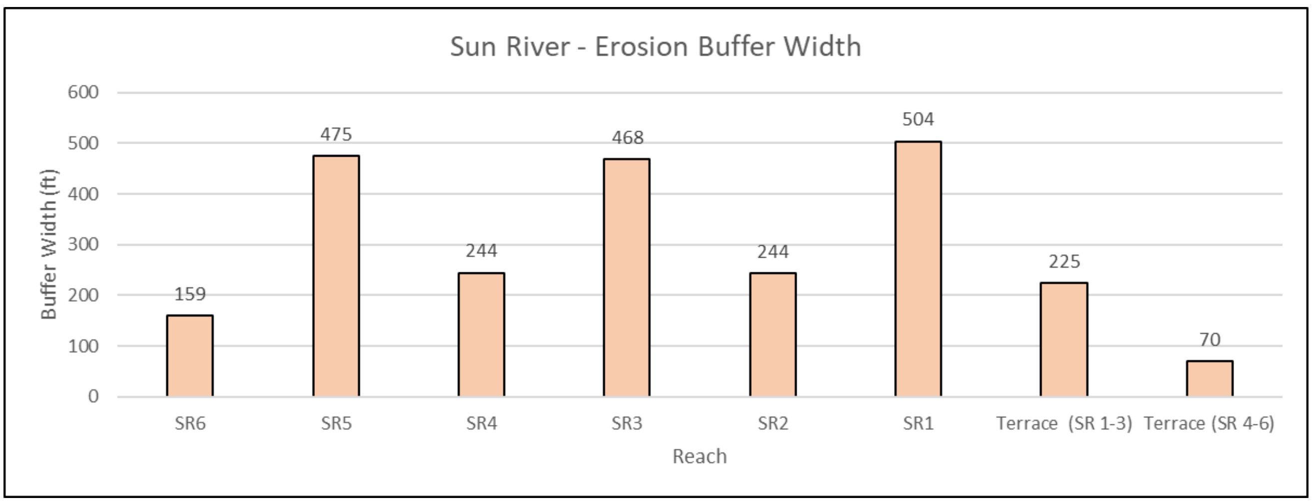


Figure 48. Mean migration rate-based EHA buffer width, Sun River-- reaches are plotted from upstream (left) to downstream (right).

The location and intensity of rapid streambank erosion shifts with time. Over a century, areas that currently show no erosion may become more active. Predicting these shifts is difficult due to the number of drivers that can cause these shifts (ice, woody debris, floods, cutoffs, etc.). As such, the erosion buffer is assigned to all banks, even those not currently eroding, to allow future bank movement at any given location. This is consistent with the Reach Scale approach outlined by the Washington State Department of Ecology (WSDE, 2010). The general approach to determining the Erosion Buffer (using the annual migration rate to define a 100-year migration distance) is similar to that used in Park County (Dalby, 2006), on the Tolt River and Raging River in King County, Washington (FEMA, 1999), and as part of the Forestry Practices of Washington State (Washington DNR, 2004).

An example of EHA mapping is shown in Figure 49. If the EHA extends into the Historic Migration Zone, it is masked by the HMZ so that areas of historic channel locations are prioritized in the mapping hierarchy. As a result, the EHA is typically discontinuous along the river.

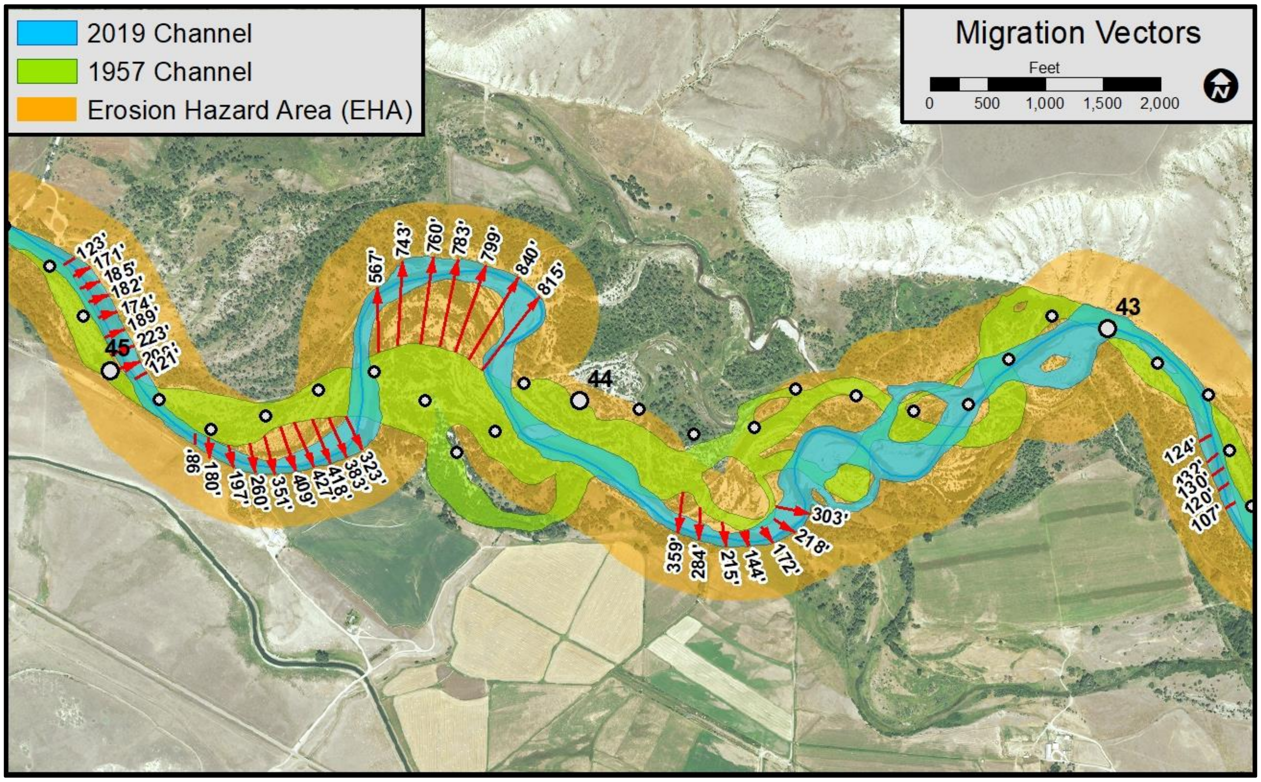


Figure 49. The Erosion Hazard Area (EHA) is a buffer placed on the 2019 banklines based on 100 years of channel migration for the reach.

4.4 The Avulsion Hazard Area (AHZ)

The Avulsion Hazard Zone (AHZ) includes the areas of the river landscape, such as secondary channels, relic channels, and swales that are at risk of channel occupation outside of the Historic Migration Zone (HMZ).

A total of 10 avulsions were mapped on the Sun River. The majority (6) of them occurred between 1957 and 1978, and two are in process. On active avulsion is shown in Figure 51; the river has migrated eastward and captured an old swale at RM 38.9 about a mile above Big Coulee. The other is the capture of Adobe Creek, which is described in Section 5.5.1. The two major types of avulsion processes on the sun river are meander cutoffs and capture of old channels/floodplain swales.

The majority of avulsions mapped on the river happened between 1957 and 1978, which would be expected due to the major floods that occurred during that time. Reach SR2 (Rocky Reef to Sun River) experienced the bulk of those avulsions.

This report refers to the flow split at the head of an avulsion as an "avulsion node".

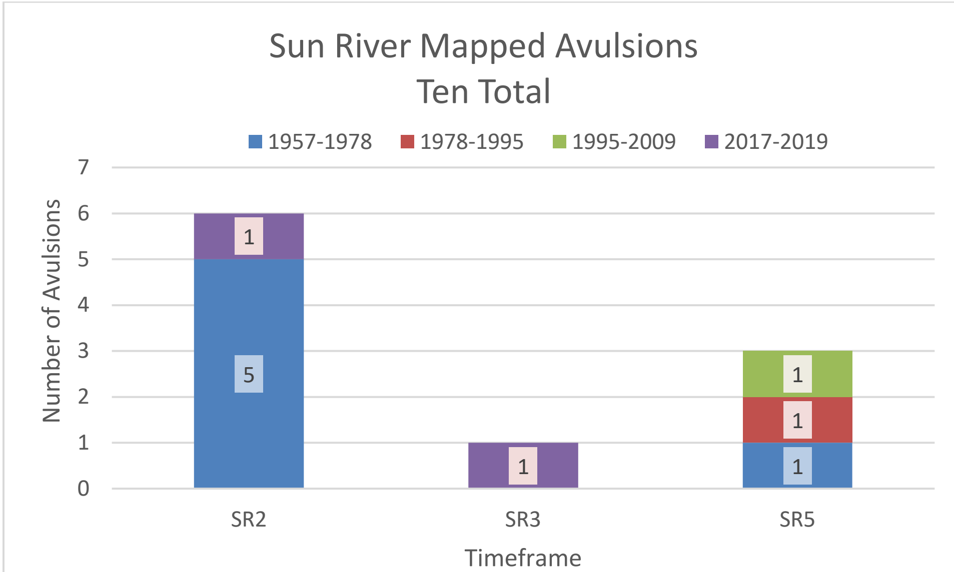


Figure 50. Number of mapped avulsions by reach, Sun River.

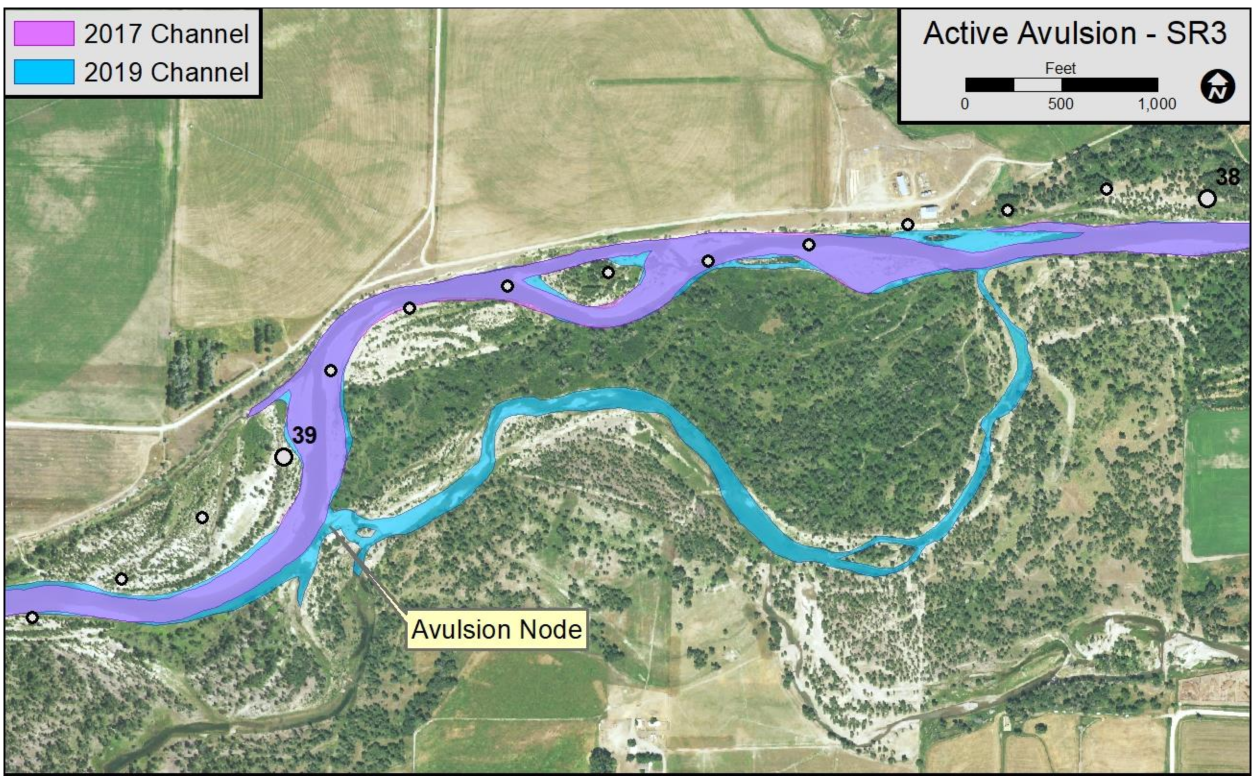


Figure 51. Active avulsion at RM 39, Reach SR3.

Considering historic patterns of avulsions, the CMZ boundaries were extended to capture similar areas that show demonstrable potential for avulsions over the next century. These mapped units capture floodplain areas that are beyond the HMZ or EHA but have side channels prone to re-occupation or meander cores prone to cutoff. It is important to recognize, however, that these events could realistically happen anywhere on the river's floodplain, and the CMZ mapping captures only the most demonstrable avulsion-prone areas.

4.5 The Restricted Migration Area (RMA)

The restricted migration area largely reflects bank protection associated with major diversions and bridges. Downstream in reach SR1 residential and suburban development begins to play a substantial role in bank armoring extents. Two dikes/levees have also restricted areas that would be otherwise exposed to channel movement.

A total of 4.7 miles of bank armor were mapped on the 51 miles of project length. Figure 52 shows that the extent of armored banks ranges from 2% to 12% of the main channel length. The densest armor is in Reach SR2, where about 10,690 feet or almost 12% of the total bankline is armored to protect agricultural fields, diversions, and developed areas. In terms of areas restricted by levees, one major 2.5 mile levee exists at Vaughn (See Section 2.6) with a smaller levee (~2600 feet) associated with a gravel pit on the south side of the river at RM 23.5.

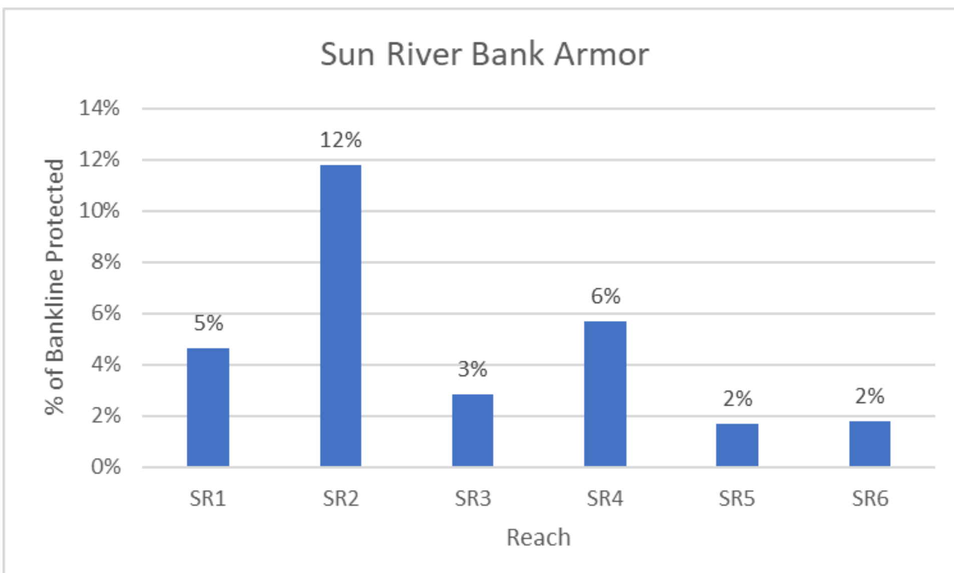


Figure 52. Percentage of bankline protected by armor by reach.

Figure 53 shows an example of Restricted Migration Areas at the city of Sun River.

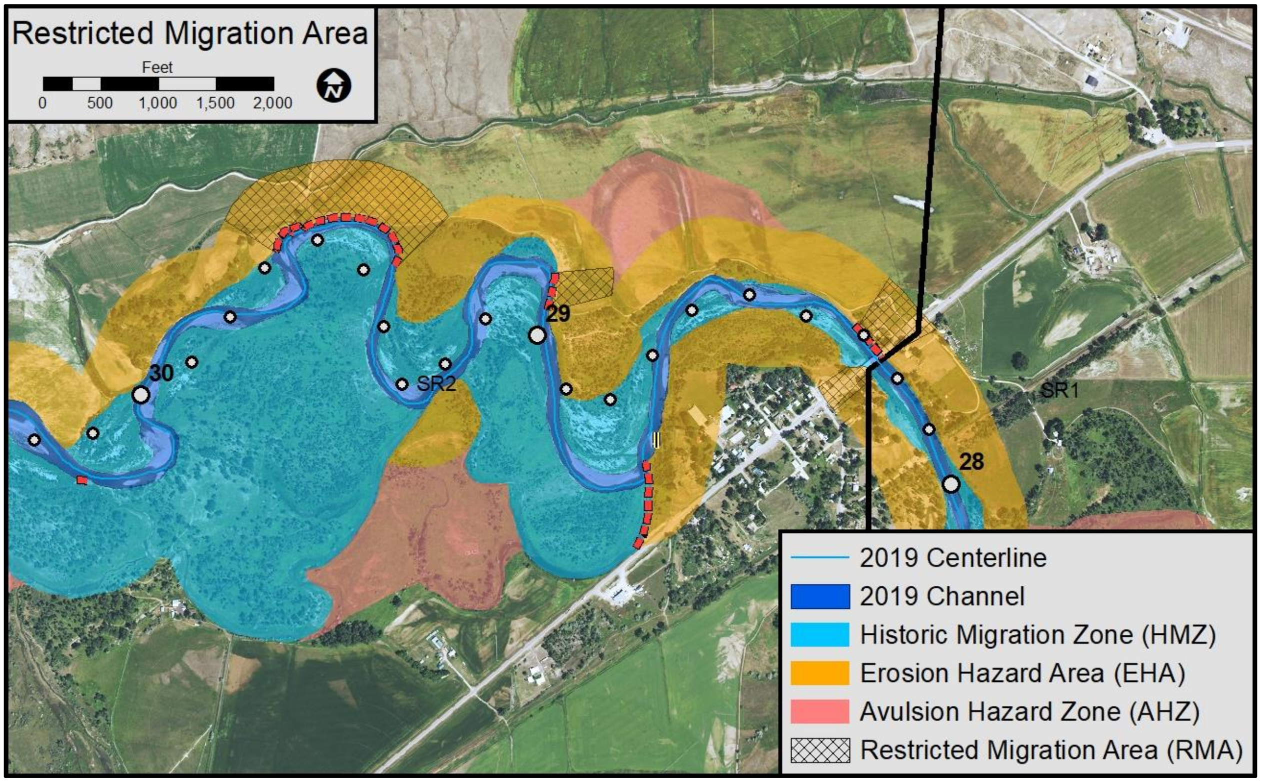


Figure 53. Restricted Migration Areas at Sun River.

Bank armoring currently restricts access to approximates 494 acres of the Channel Migration Zone. The majority of this armor is protecting irrigated agricultural land and key irrigation infrastructure at the major diversions, with the exception of approximately 159 acres of land behind levees in SR1. The amount of restricted area generally increases downstream as the river becomes less confined and development pressures promote bankline stabilization. This is especially true in reach SR1 where residential and suburban development begins to take on a major role in bank armoring and levees in the communities of Sun River and Vaughn.

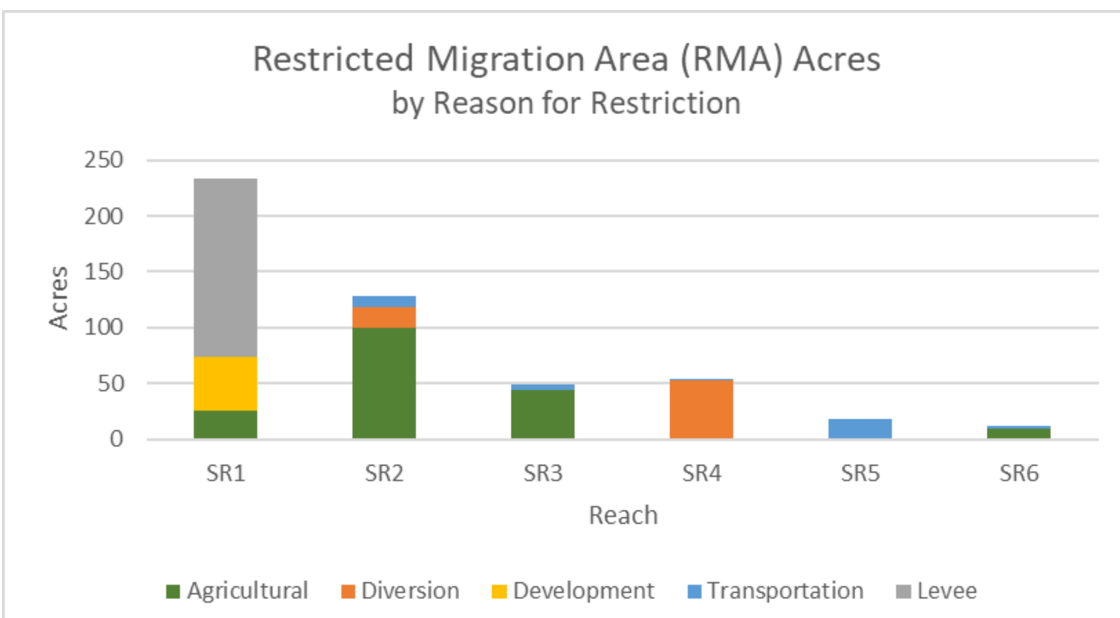


Figure 54. Acres of the CMZ mapped as restricted by reach.

4.6 Composite Map

An example portion of a composite CMZ map for a section of the Sun River project area is shown Figure 55. Each individual mapping unit developed for the CMZ has its own symbology, so that any area within the overall boundary can be identified in terms of its basis for inclusion. Over the 51 mile project reach, a total of 9,819 acres of land comprise the CMZ, or about 193 acres per mile. The mean width of the CMZ is about 1,600 feet, ranging from 730 feet in Reach SR6 upstream to 2,300 feet in Reach SR2 (Rocky Reef to Sun River).

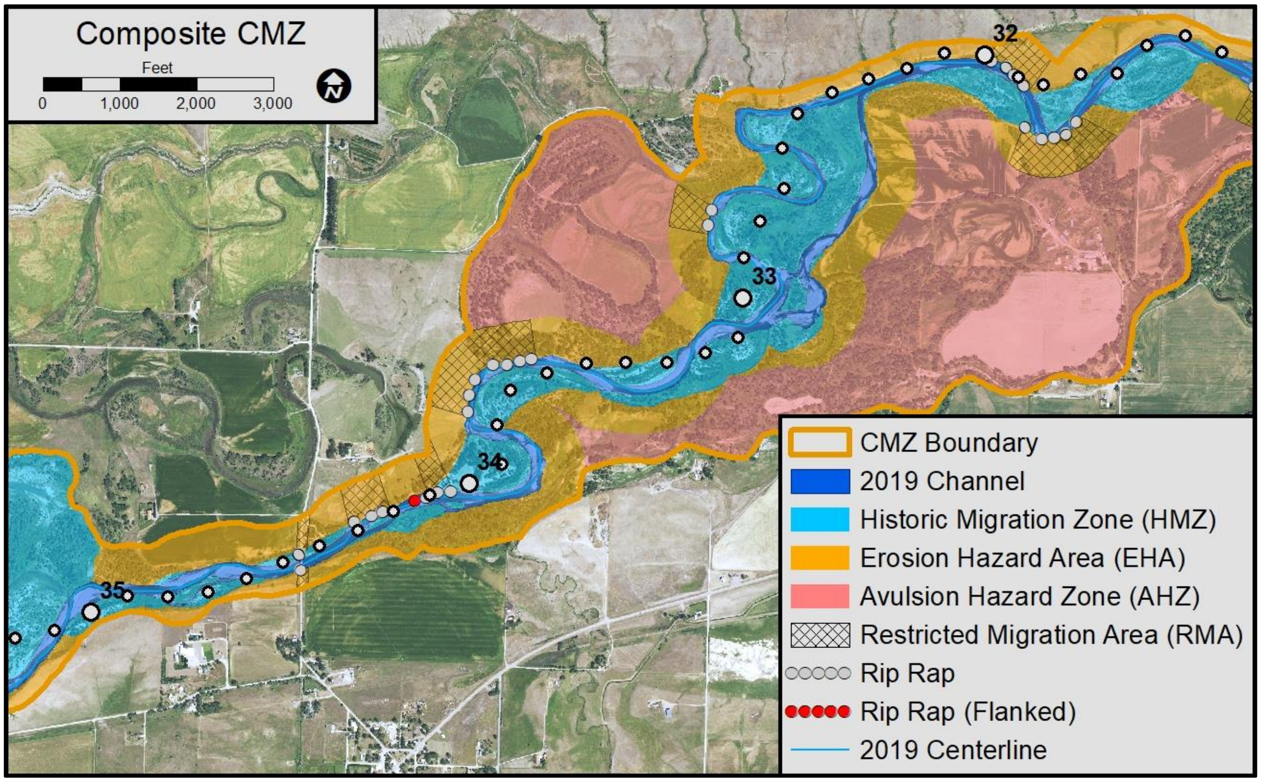


Figure 55. Composite Channel Migration Zone map.

4.7 Geologic Controls on Migration Rate

Between the Highway 287 Bridge and Vaughn, the margins of the active Sun River floodplain consist of both erodible and non-erodible terraces. The non-erodible terraces are generally comprised of Cretaceous-age sandstone overlain by a younger alluvial cap. The erodible terraces are more consistently non-bedrock, comprised of younger sediments that were shown to erode, but typically at a lower rate than the floodplain alluvium. As a result, the erosion buffer assigned to these units was narrower than those of active floodplain alluvium.

Many CMZ mapping efforts incorporate a Geotechnical Setback on valley walls, which is an area of expanded Erosion Hazard Area (EHA) against geologic units that may be prone to geotechnical failure such as landslides, slumps, or rockslides. Within the Sun River project reach, there are no mapped active landslides against the river, which suggests that the CMZ will not likely be altered by hillslope failure. Even so, confined channel segments may still be prone to rockslides may impact the river's course. Defining an appropriate setback for these processes is difficult at best and may reflect more stochastic processes than have been used to develop the CMZ. As a result, Geotechnical Setbacks have not been incorporated into the EHA, and incorporating the potential for mass failure on hillslopes was considered beyond the scope of this effort.

5 Sun River Reach Descriptions

The following sections describe each reach of the Sun River. The reaches are numbered sequentially from the downstream end of the project. To best describe the trends in geomorphology and mapping results, they are described below in the opposite order, starting with Reach SR6 just above the Highway 287 Bridge, and ending with Reach SR1 at Vaughn. The maps can be found in Appendix D.

Note: All references to River Miles (RMs) reflect the Fish Wildlife and Parks data layer that begins in Great Falls (RM0) and extends over 100 miles upstream to the confluence of the North and South Forks at the head of Gibson Reservoir (RM 102.3). River Miles are labeled on the maps in Appendix D. Wherever streambanks or floodplain areas are described as "right" or "left", that refers to the side of the river as viewed in the downstream direction. For example, "RM 16.4R" refers to the right streambank located 16.4 miles upstream of the river's mouth.

5.1 Reach SR6—Highway 287 to Dry Creek

Reach SR6 is 13.2 miles long, extending from just upstream of the Highway 287 bridge north of Augusta to the mouth of Dry Creek (Figure 56). Within this reach the river is moderately confined by bedrock and glacial outwash bluffs that limit channel movement. Bedrock outcrops are also common in the bed of the river.

Reach SR6		
Upstream/Downstream RM	68.1	54.9
Length (miles)		13.2
General Location	Highway 287 to Dry Creek	
Mean Migration Rate (ft/yr)		1.6
Max 62-year Migration Distance (ft)		232
100-year Buffer (ft)		159
100-year Terrace Buffer		70

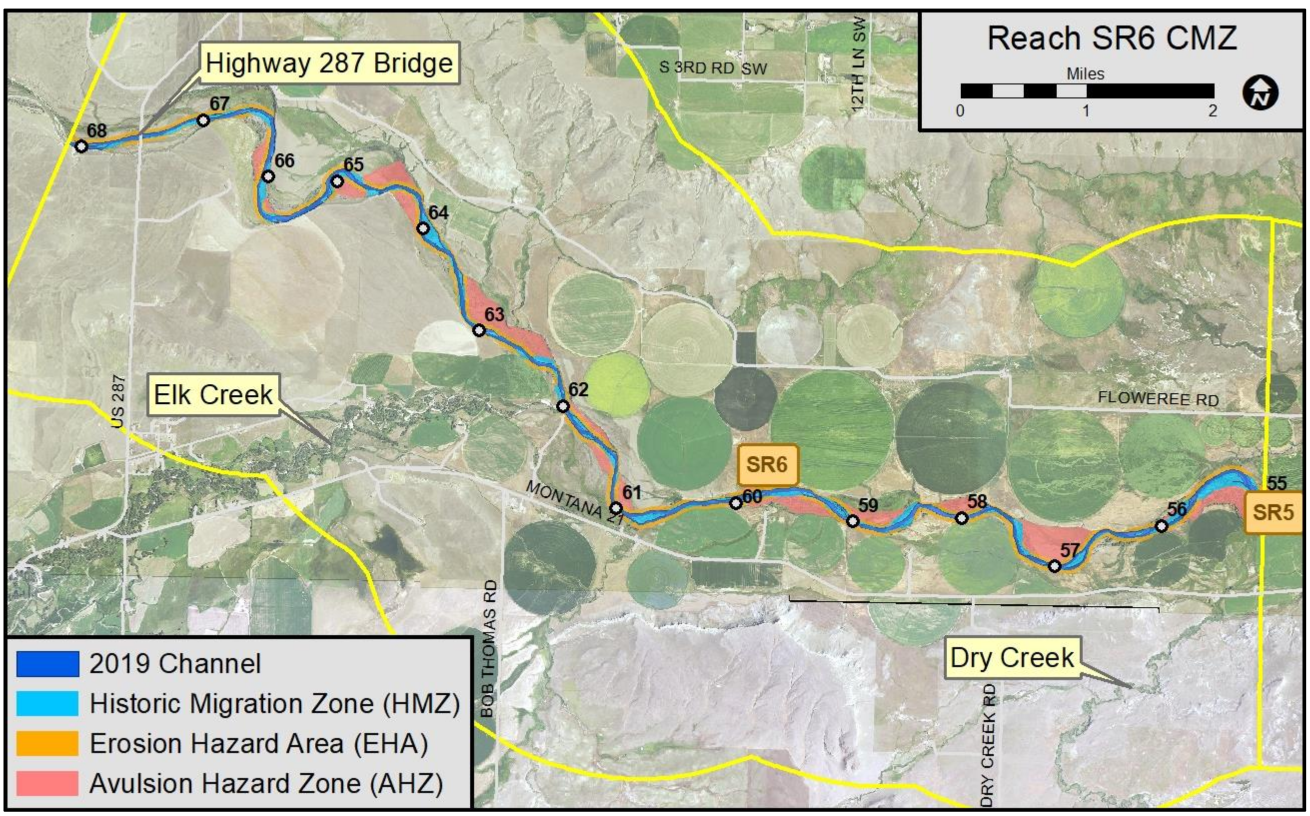


Figure 56. CMZ map for Reach SR6.

The river corridor tends to be relatively narrow in Reach SR6, and migration rates are low. Avulsion hazards are present through meander cores and where channel remnants parallel the river. Most of the bluff line in the upper portion of Reach SR6 has been clipped out of the CMZ as it appears to be highly erosion resistant, consisting of Cretaceous-age rocks overlain by outwash gravels (Figure 57). Further downstream there is no evidence of a hard rock toe on the terrace edge, and in these areas the terraces have been given a 70' wide erosion buffer width based on measured migration rates into the outwash.

The Floweree Canal closely parallels the river in the upper few miles of Reach SR6, and sometime between 2011 and 2014 there was a substantial hillslope failure along the canal that caused it to breach at RM 66.6, forming a distinct alluvial fan on the Sun River floodplain (Figure 58). Canal seepage supports numerous wetlands on the floodplain as well. In some areas such as just below the mouth of Spring Creek, the stream corridor is tightly confined between pivot fields, and in several locations the streambanks have been armored to protect those pivots (Figure 59).

The geologic confinement in Reach SR6 has resulted in a narrow CMZ with an erosion buffer width of 159 feet.

Figure 57. Sandstone bluffline clipped out of CMZ in Reach SR6 (Google Earth)

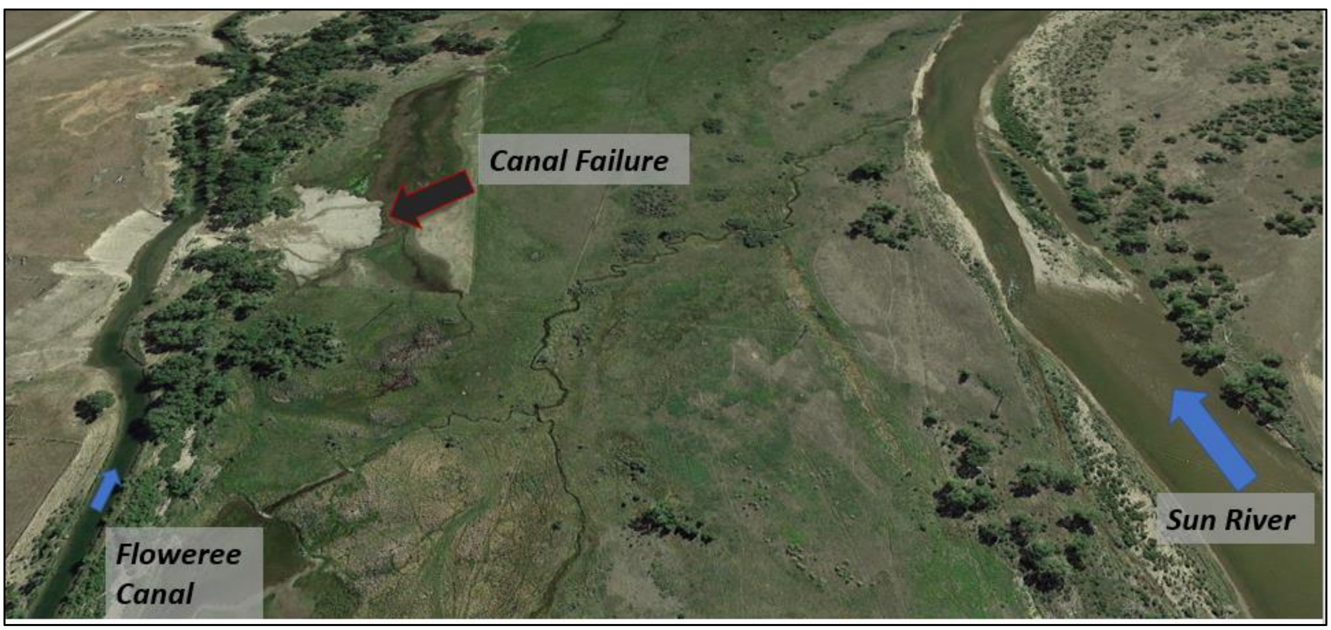


Figure 58. View downstream showing Floweree Canal breach forming alluvial fan on Sun River floodplain (Google Earth).

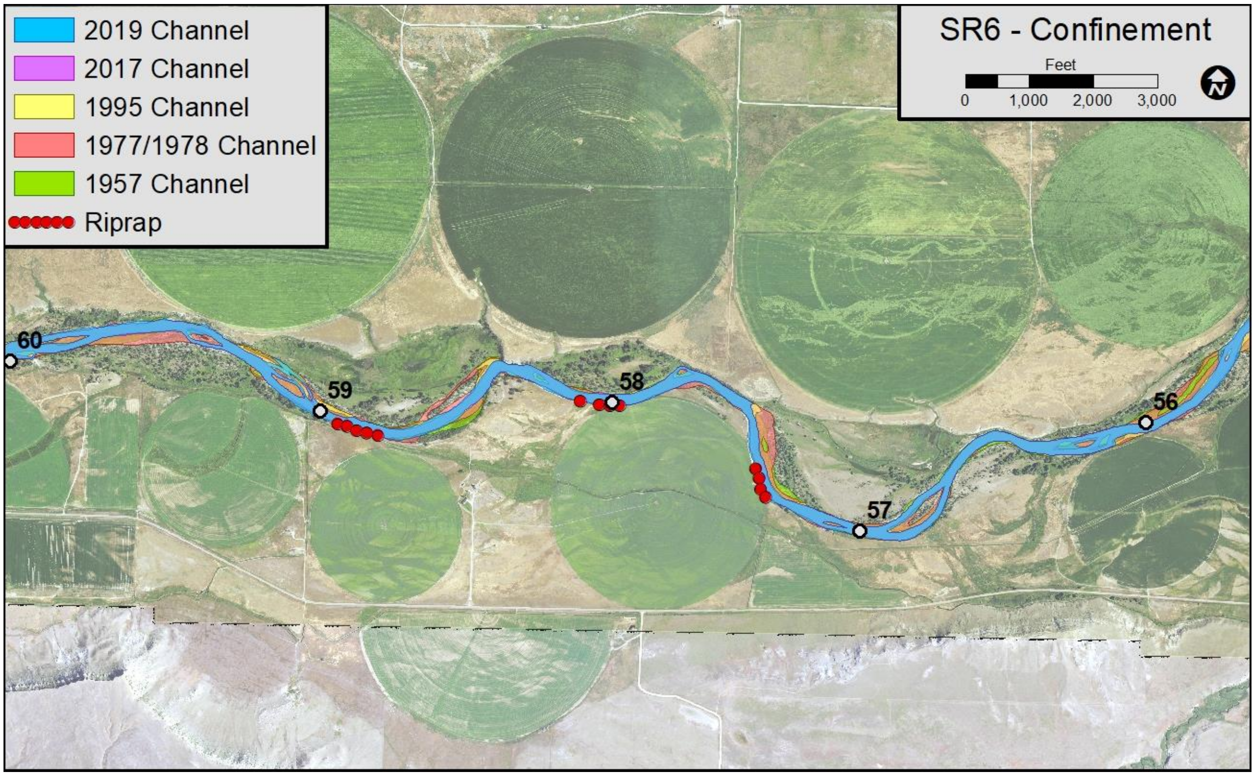


Figure 59. Bankline mapping showing armor and minimal channel movement between pivots in Reach SR6.

5.1.1 CMZ-Related Issues in Reach SR6

Issues identified with respect to infrastructure performance in this reach include the following:

1. A diversion structure at RM 60R, which is about a mile below the mouth of Spring Creek, appears to have some sedimentation issues at its entrance. A large bar has formed that but it appears that the flow split into the ditch has been effectively managed by hardening the upper face of the bar to form a deflector (Figure 60). In 1978, a rock weir extended into the river to deflect flows towards the ditch, this is probably what drove the sedimentation just downstream. The bar has been established since at least 1995. A return flow channel at the headgate will be important to maintain so the ditch is not overrun in high water. The ditch itself poses an avulsion hazard as it flows parallel to the river across a low meander, it should be monitored for that risk.

Figure 60. Bar formation at diversion, RM 60.

5.2 Reach SR5--- Dry Creek to Fort Shaw Canal

Reach SR5		
Upstream/Downstream RM	54.9	49.5
Length (miles)	5.4	
General Location	Dry Creek to just above Fort Shaw Canal	
Mean Migration Rate (ft/yr)	4.8	
Max 62-year Migration Distance (ft)	732	
100-year Buffer (ft)	475	
100-year Terrace Buffer	70	

About a mile and a half upstream of the Freeman Road Bridge at the mouth of Dry Creek, the Sun River transitions to an actively meandering channel that forms broad bendways that have migrated on the order of 500 feet since the 1950s (Figure 61 and Figure 62). This marks the shift from the relatively confined condition of Reach SR6 to a much more dynamic reach in Reach SR5. Reach SR5 is just over five miles long, extending the mouth of Dry Creek to RM 49.5 just above the Fort Shaw Canal Diversion. Within this reach, channel migration rates increase rapidly relative to upstream, with the erosion buffer width expanding from 159 feet in Reach SR6 to 475 feet in Reach SR5. Three avulsions were mapped in this reach; one of them occurred around 1999 where the river captured a swale that was carrying the lower portion of School Section Coulee (Figure 63).

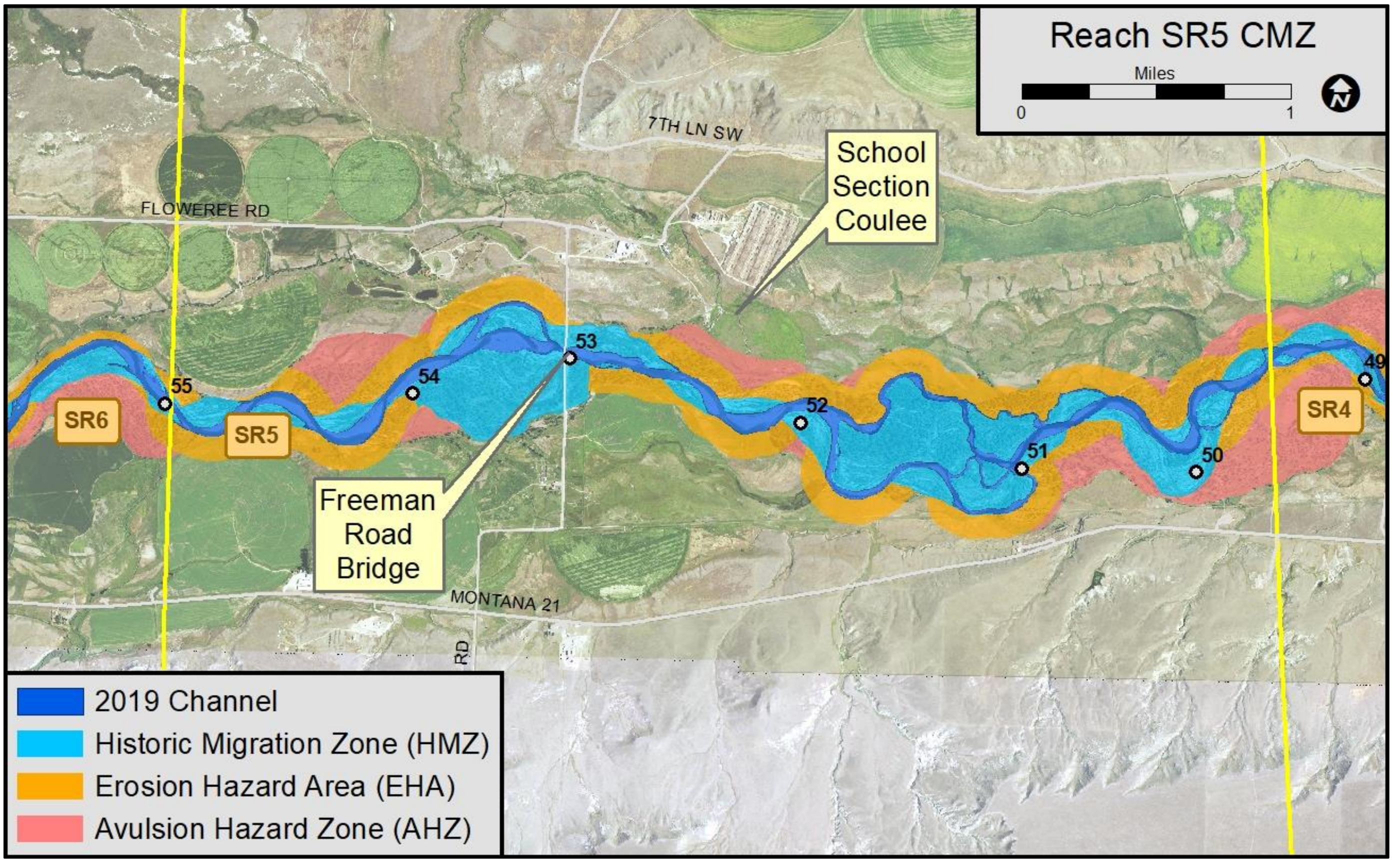


Figure 61. CMZ map for Reach SR5.

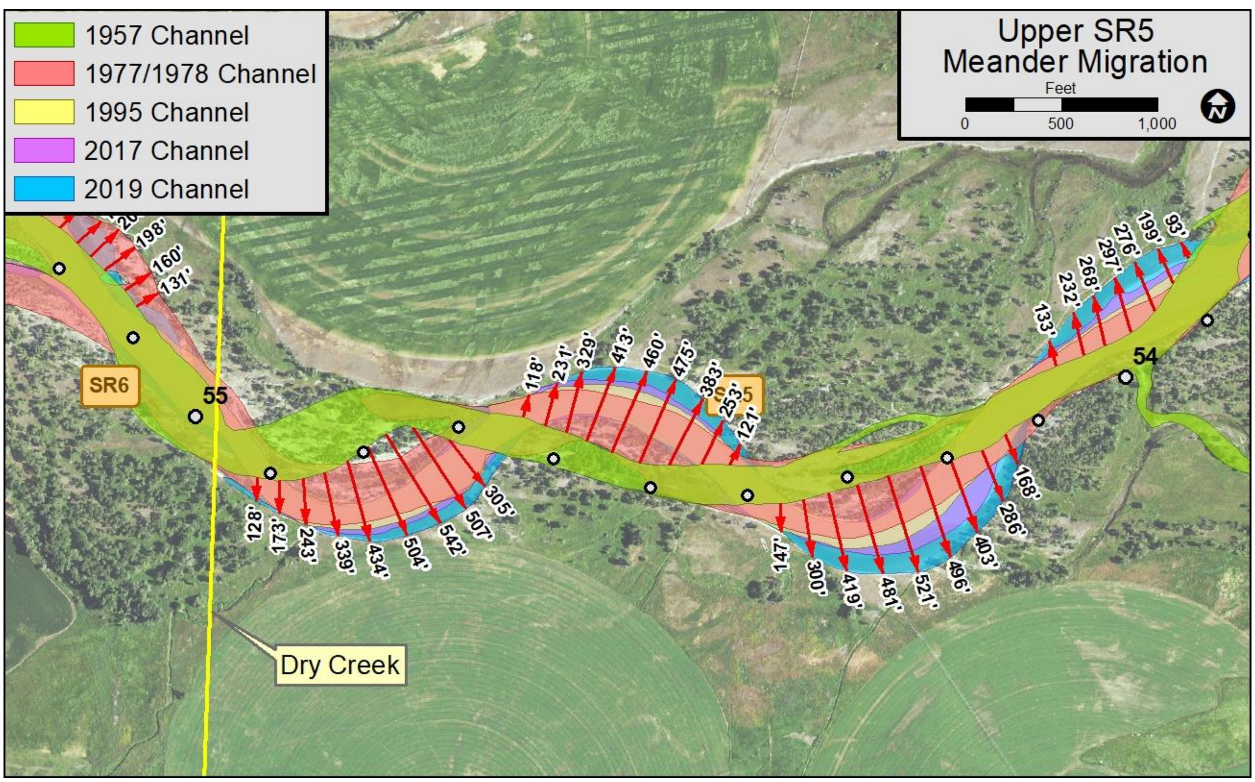


Figure 62. Meander migration in upper SR5 near the mouth of Dry Creek.

Figure 63. Sun River capture of swale that routed School Section Coulee in 1995.

5.2.1 CMZ-Related Issues in Reach SR5

1. Progressive southward bank movement immediately downstream of the mouth of Dry Creek is threatening a pivot field (Figure 62). The river was about 60 feet from the edge of the field in 2019. The banklines show that the most rapid erosion is on the downstream limb of the bend as it translates down valley to the east. This will reduce the erosive pressure on the field with time. As the river is pinned on the north side by a bluff, it will be important to provide some room for channel adjustment in this area to prevent a need for perpetual bank armor expansion. About 9 acres of the pivot field are within the mapped CMZ of the Sun River.

2. Freeman Road Bridge narrowly constricts the CMZ from over a mile wide upstream to about 250 feet at the bridge. These “hourglasses” within the CMZ can create challenges when trying to maintain a high angle approach to the bridge that is least destructive to both the bridge and road prism. It appears that the 2018 flood started to flank the right (south) bank armor at the bridge, necessitating the extension of the armor upstream (Figure 64). This project consists of a rock toe overlain by coir fabric and hundreds of willow stakes, and it performed well during recent floods (R. Sain, pers comm). Maintaining a good channel alignment is a common problem at bridges, and the best performance we have seen at such locations is a gentle tapering of the CMZ into the bridge opening. To that end, this site will require continued monitoring to ensure the upper extent of the project remains functional as the head of the taper.

3. About a half-mile downstream from Freeman Road Bridge (RM 52.4) the river has recently migrated southward into a pivot field. It appears the management response has been to reduce the pivot swing rather than to armor the river, which can be a cost-effective approach to CMZ management. That said, the pivot tower itself is at high risk of damage due to channel migration (Figure 65). Bankline maps can be used to help producers lay out pivot fields in a way that minimizes river erosion issues and associated costs.

Figure 64. Bank armor expansion above Freeman Bridge between 2017 (top) and 2019 (bottom) showing continued flanking risk south of armor.

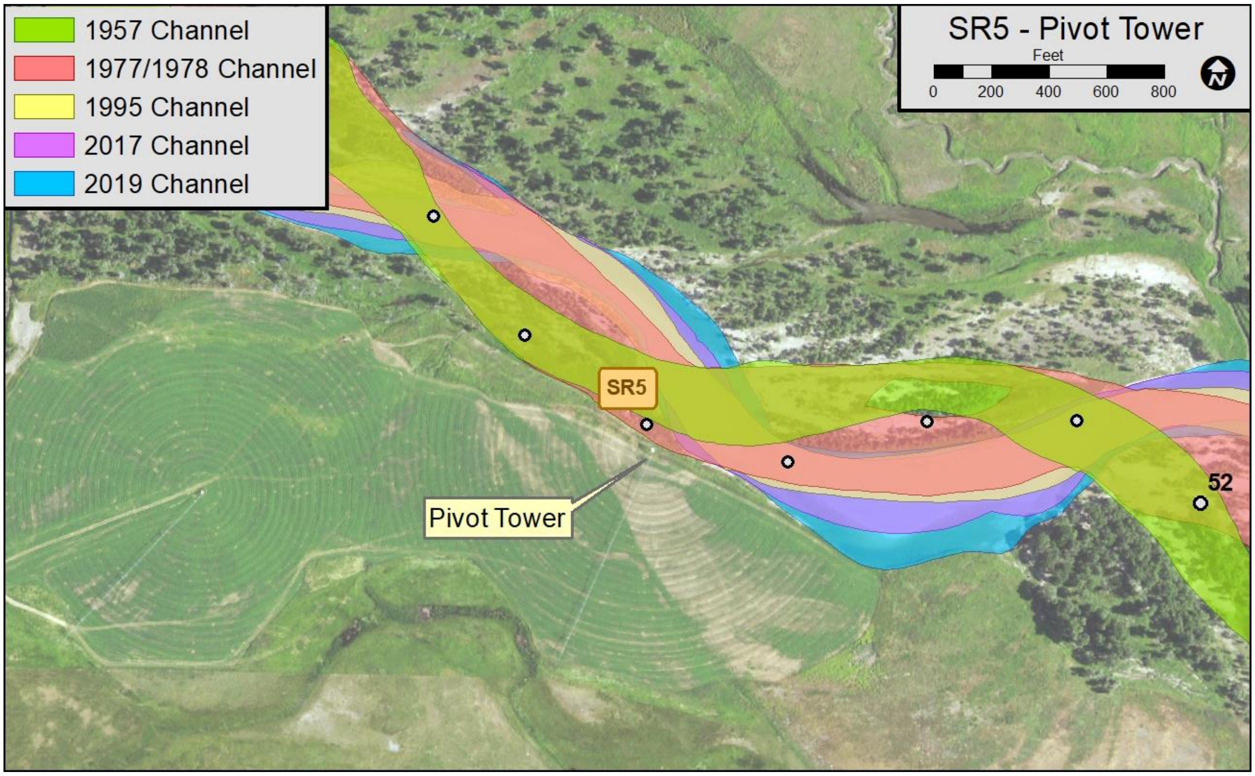


Figure 65. Pivot tower at RM 52.4R at high risk of damage due to channel migration.

5.3 Reach SR4—Fort Shaw Canal to Lowry Bridge

Reach SR4		
Upstream/Downstream RM	49.5	45.3
Length (miles)	4.2	
General Location	Just above Fort Shaw Canal to Lowry Bridge	
Mean Migration Rate (ft/yr)	2.4	
Max 62-year Migration Distance (ft)	263	
100-year Buffer (ft)	244	
100-year Terrace Buffer	70	

Reach SR4 extends from just above the Fort Shaw Canal diversion down to Lowry Bridge. The reach is 4.2 miles long. Migration rates drop in this reach relative to upstream, as the river has tended to maintain a relatively straight course with low rates of channel movement. Although the Historic Migration Zone is relatively narrow in this reach, a network of floodplain swales creates avulsion hazards on the floodplain that widen the CMZ boundaries (Figure 66).

On the order of 6% of the banklines are armored in Reach SR4, and this armor is concentrated upstream of the Fort Shaw Canal Diversion.

The maximum migration distance measured in Reach SR4 was 263 feet, and the CMZ buffer width is 244 feet.

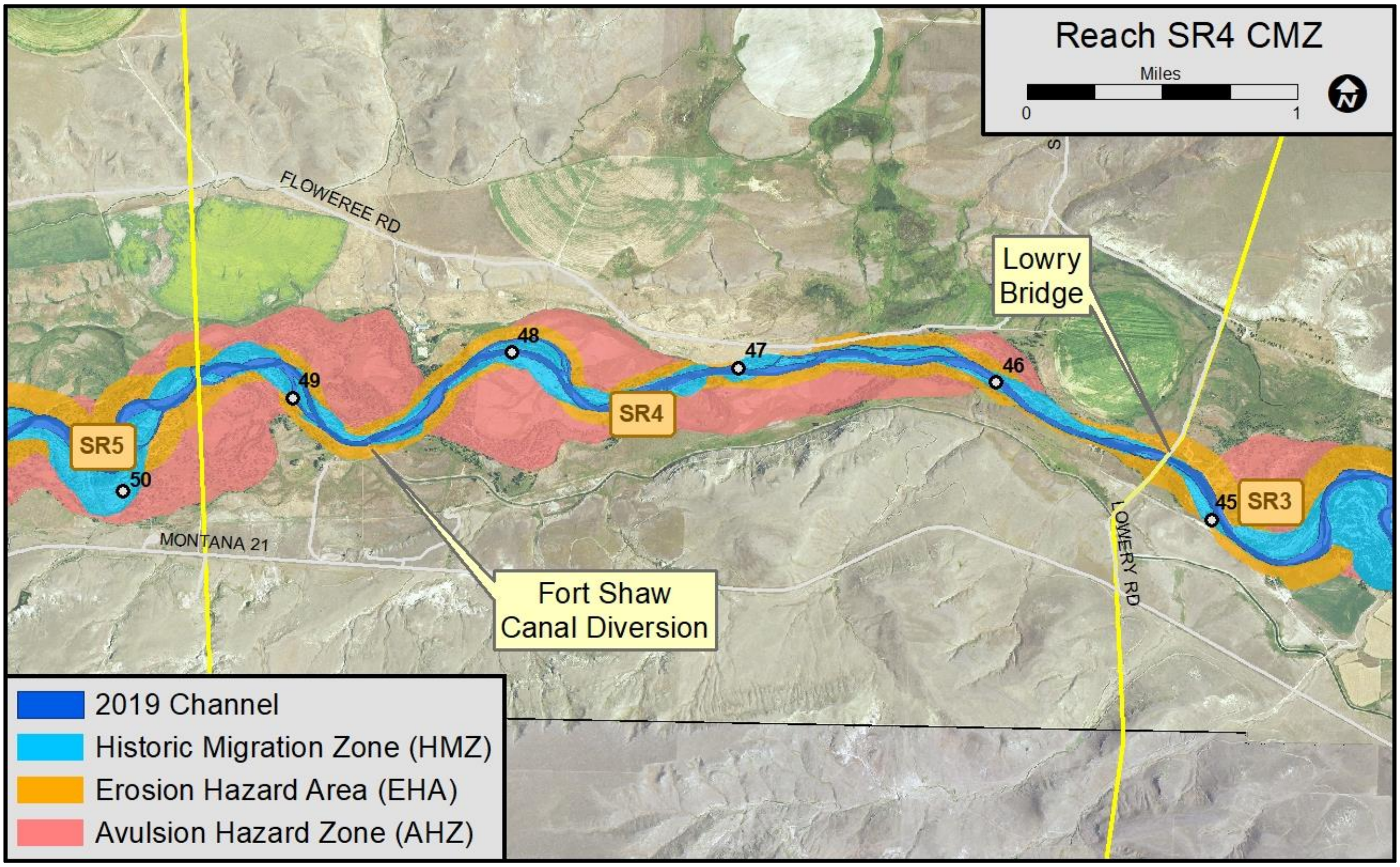


Figure 66. CMZ map for Reach SR4.

5.3.1 CMZ-Related Issues in Reach SR4

No major issues were identified in Reach SR4. There is a fair bit of bedrock control in this reach, resulting in relatively low migration rates. At the Fort Shaw Canal Diversion, the river location has changed very little since at least the 1950s due to bank armoring upstream. It appears that the river was dredged in 1957 just upstream of the diversion, probably in response to the 1955 flood. Both banks have since seen some armoring upstream of the diversion; some of that armor now sits in the floodplain about 200 feet south of the active river channel. Left bank armoring upstream of the diversion at RM 49.1 appears stable but does have some risk of flanking on its upstream end. Just below the canal there is a growing risk of an avulsion south of the river, where the channel is progressively migrating into an avulsion path made up of a well-defined historic swale of the Sun River (Figure 67).

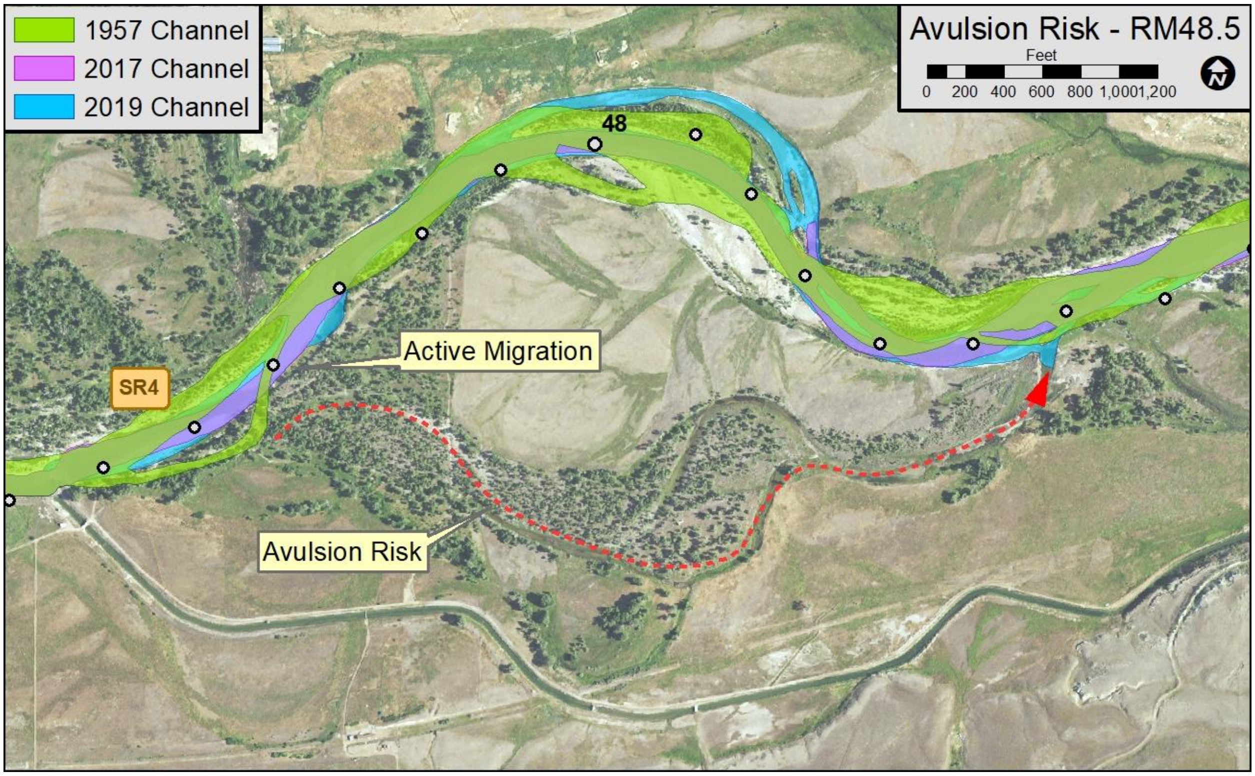


Figure 67. Example avulsion hazard through floodplain swale below Fort Shaw Canal Diversion; note how river has migrated towards upper end of avulsion path in recent years.

5.4 Reach SR3—Lowry Bridge to Rocky Reef Diversion

Reach SR3		
Upstream/Downstream RM	45.3	36.8
Length (miles)		8.5
General Location	Lowry Bridge to Rocky Reef	
Mean Migration Rate (ft/yr)		4.7
Max 62-year Migration Distance (ft)		839
100-year Buffer (ft)		468
100-year Terrace Buffer		225

Reach SR3 starts at Lowry Bridge and extends to the Rocky Reef Diversion structure (Figure 68). The reach is 8.5 miles long. A total of 110 migration measurements were collected in this reach, and the maximum 1957-2019 migration distance measured was 439 feet. Bedload remains coarse, and just below Lowry Bridge recent deposits of coarse grave/cobble was evident on the north floodplain (Figure 69). Coarse dredge spoils just upstream of the bridge suggest aggradational trends characterize reach. The 1957 imagery shows that, at that time, the river was locally highly braided with a large overall channel footprint. Since then the river has continued to evolve, creating a notably wide historic migration zone in areas (Figure 70). This wide HMZ is likely driven by the ~30% reduction in channel slope relative to upstream. In addition to a wider HMZ, the buffer width in this reach is almost double that of upstream.

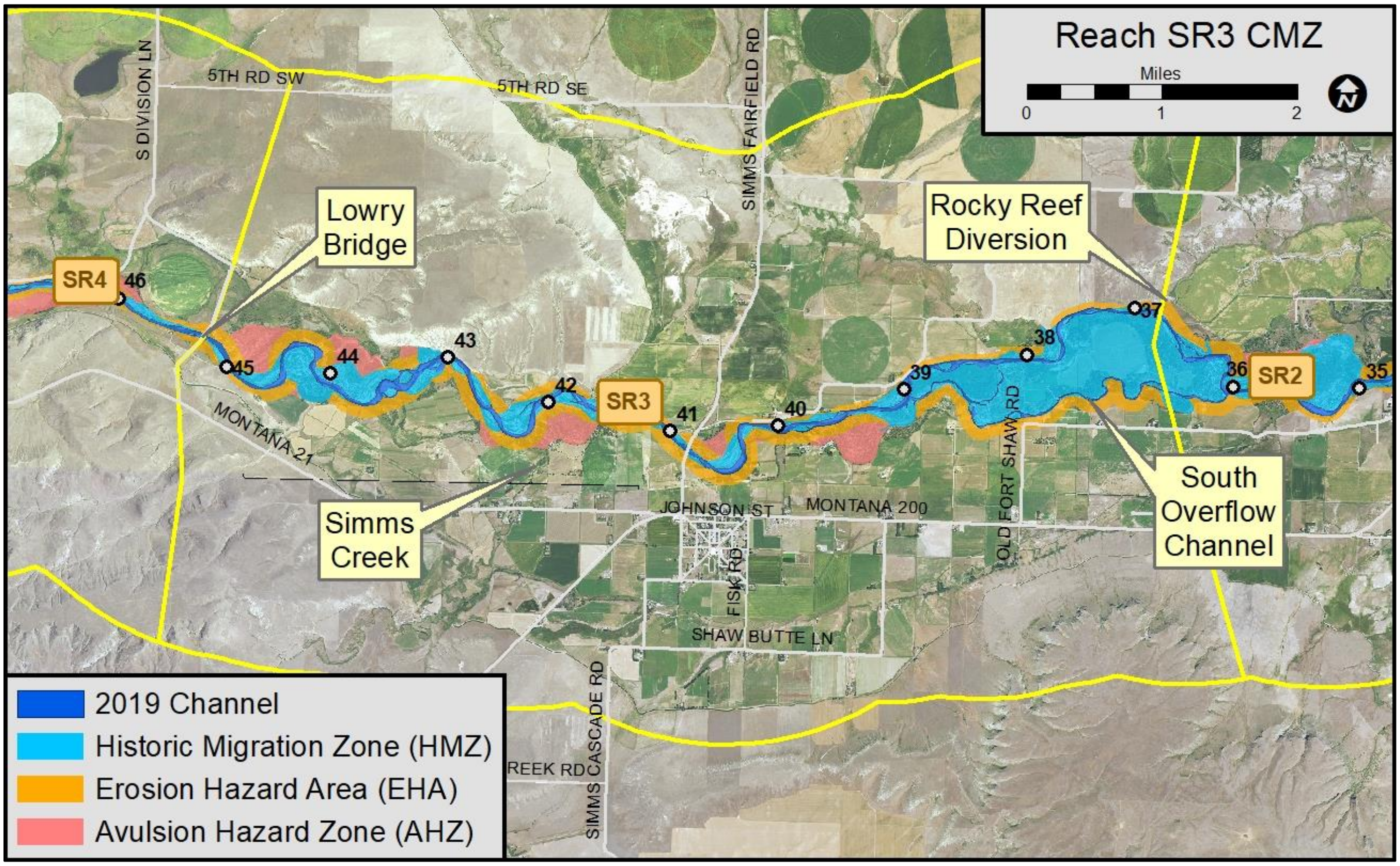


Figure 68. CMZ map for Reach SR3.

Figure 69. Coarse bedload deposition on floodplain just below Lowry Bridge.

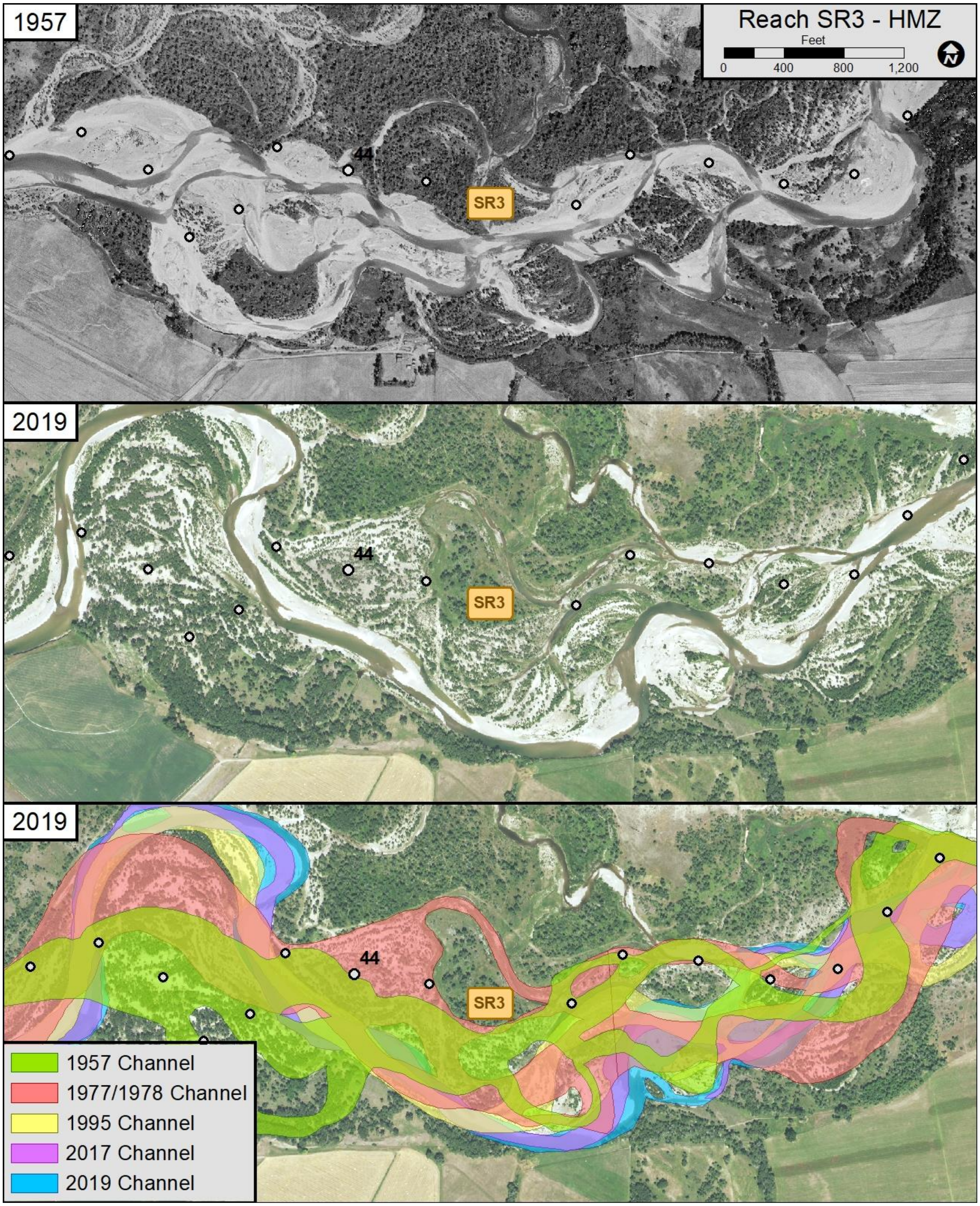


Figure 70. Upper Reach SR3 showing braided conditions in 1957 (top), some vegetation recovery by 2017 (middle). and wide, active Historic Migration Zone (bottom).

5.4.1 CMZ-Related Issues in Reach SR3

Kellogg (2014) started his assessment at Lowry Bridge which marks the start of Reach SR3. He identified Lowry Bridge as a "No Action" site, and the CMZ mapping supports that recommendation.

1. About a half-mile downstream of Lowry Bridge, there are flanked barbs on the right bank where the river has eroded into a terrace (Figure 71). Kellogg (2014) described the bank protection project at this site as follows:

> "A high terrace was shaped, nine rock flow deflectors installed, and erosion fabric laid along 1,000 feet of south river bank in late 1997. The project purpose was to stabilize the terrace and protect an irrigated hay field. Two deflectors on the upper end are intact, a third deflector is close to being flanked, and the other six have washed out. Rock from one of the flanked deflectors is exposed in mid-channel. Another deflector is buried in a large gravel point bar on the opposite side of the river. Cottonwood saplings were planted along the bank on the upper third of the project and appear to be doing well. An additional 600 feet of river bank, downstream from the flow deflectors, was shaped and covered with erosion fabric. It has subsequently washed out.
>
> During the 2011 flood, the river migrated 40 – 100 feet into the downstream end of the terrace bank. A gravel point bar on the opposite bank nearly doubled in size and is pushing the river channel into the terrace, increasing sheer stress along the terrace toe.

Recommendations for this site (Kellogg, 2014) included salvaging rock from flanked deflectors to reinforce remaining structures, monitoring for avulsions, and bank plantings.

Since 1957 about 12 acres of land have eroded at this site, the majority of which occurred between 1957 and 1978, during which time the river migrated about 410 feet to the southeast. The bank has continued to erode since the 2014 assessment, and that erosion is concentrated on the downstream end of the hayfield (Figure 71). This erosion will likely continue into the riparian corridor and lower end of the field. As this bank trends at a right angle to the river corridor (due north) it will probably require substantial maintenance and extension with time. The bendway just downstream will probably cut off in coming flood years, so the alignment in this area will be dynamic for some time. As a result, the recommendations provide by Kellogg (2014) are still valid; we would not recommend heavy bank armor investment at this location due to reach-scale dynamics.

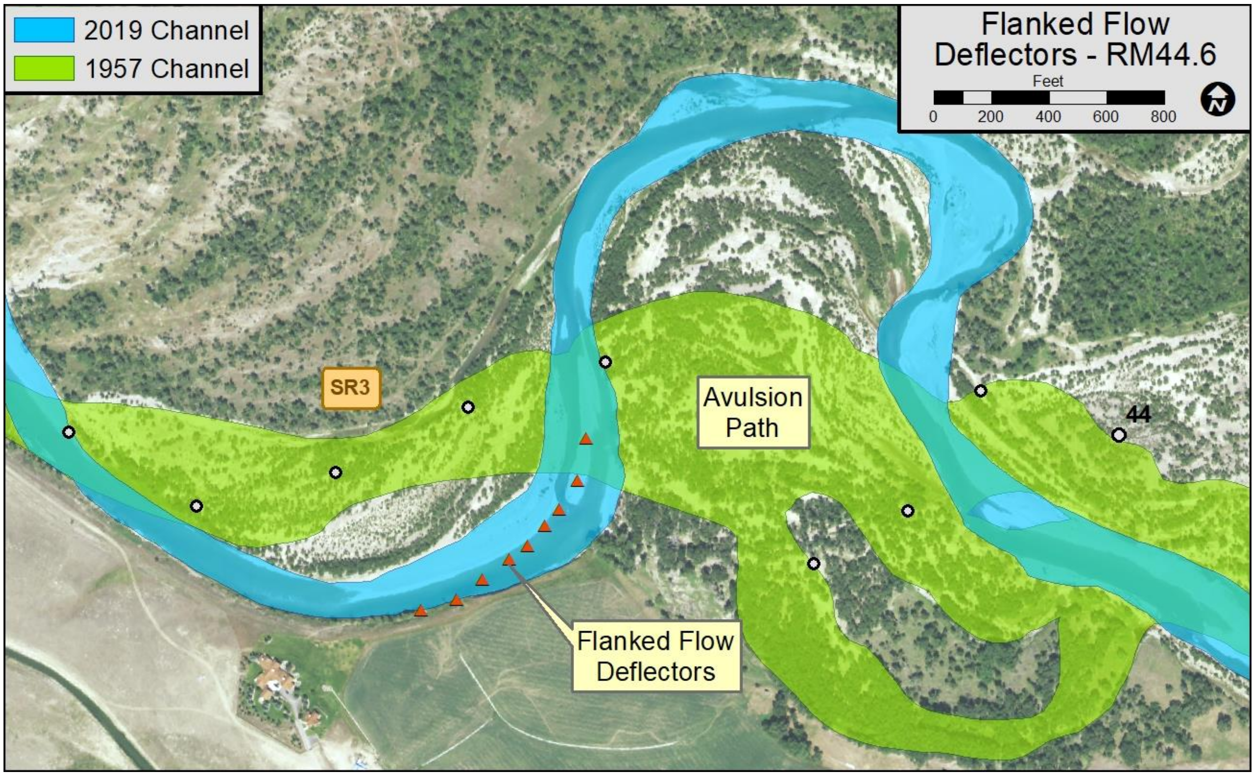


Figure 71. Channel migration at RM 44.7, site of Kellogg (2014) Site SR-3; at least five barbs have been flanked on the right bank; note avulsion path following 1957 channel route just downstream.

2. Channel migration towards the south at RM 42.3 has created a high potential for an avulsion into the lower end of Simms Creek (Figure 72).

3. At RM 41.8, a house sits on a high terrace that has actively eroded in recent years (Figure 73). This is referred to as Site SR-5 by Kellogg (2014), who described the bank stratigraphy as alluvial deposits overlying glacial lake sediments. His recommendations included water management on the terrace to reduce seepage and potentially slope stabilization. Recent bankline mapping corroborates Kellogg's 2014 observation that the river is trending essentially parallel to the bank, reducing erosive pressure at the site. Regardless, this site is a good example of how high terrace areas are not immune to bank erosion and this structures on terrace margins commonly fall into Channel Migration Zone areas and are thus at risk.

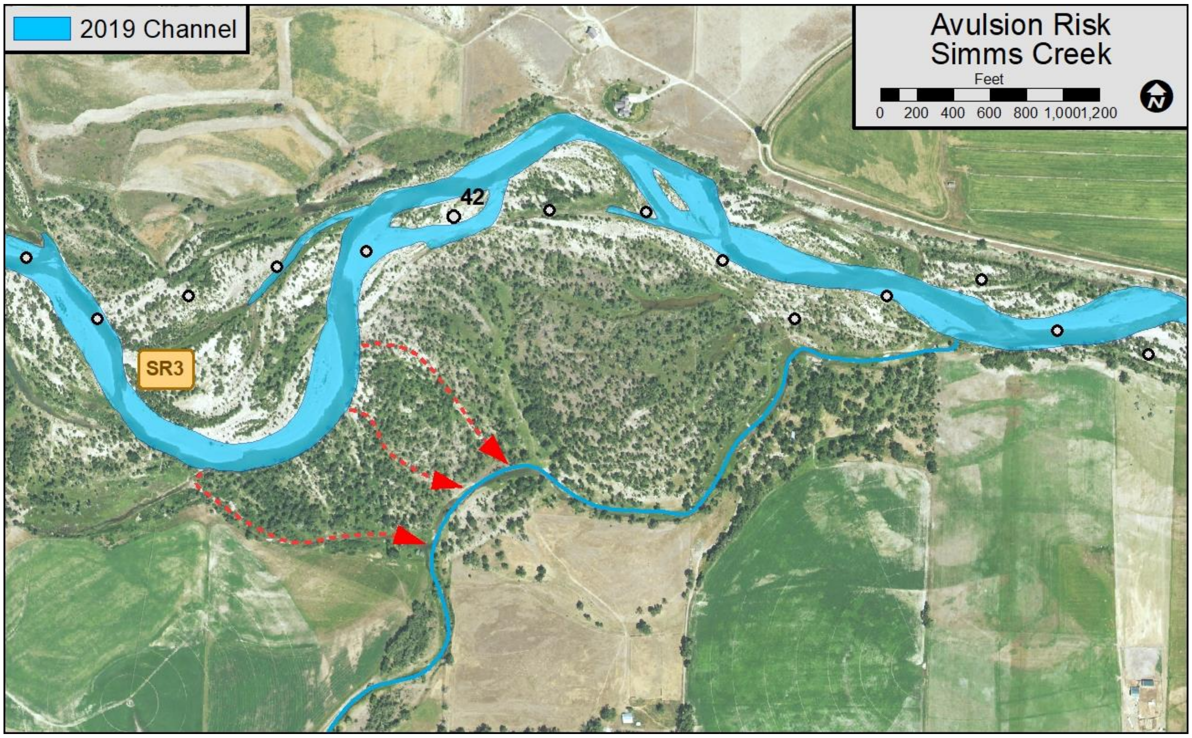


Figure 72. Multiple avulsion paths have developed from an outside bend towards Simms Creek, creating a high avulsion risk in this area.

Figure 73. Home on high terrace, RM 41.8L.

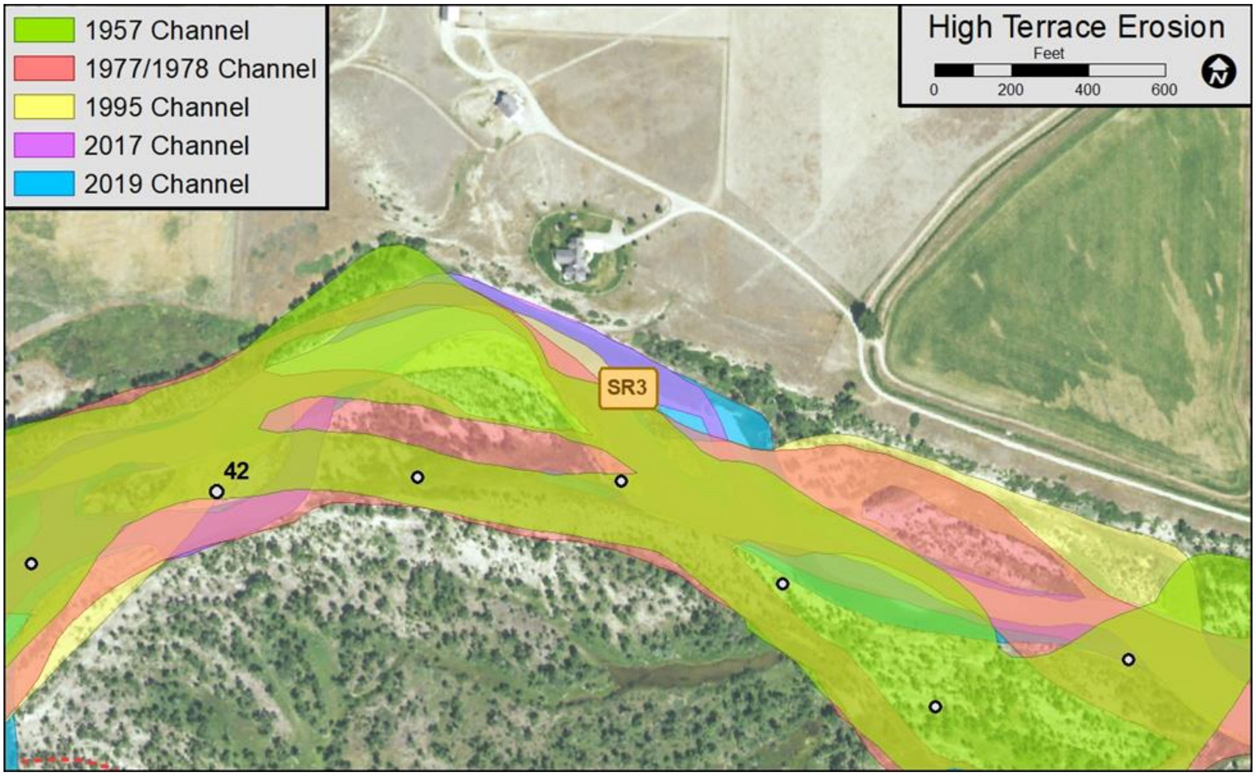


Figure 74. 1957-2019 migration pattern against high terrace at RM 41.8.

4. An active avulsion is underway at RM 38.5 (Figure 75). This avulsion is re-activating a 1957 channel route. Evidently there were efforts to prevent this from happening, including a rootwad project constructed just upstream of the avulsion node (where the river splits at the entrance to the avulsion path), and placement of a sills/berms across the relic channel to prevent its capture (Kellogg, 2014). All of these projects appear to have eroded out (Figure 76). Although a major channel relocation here will not directly bypass any major infrastructure, there is some potential of this flow shift to reactivate what Kellogg (2014) referred to as the "South Overflow Channel". If this channel were to capture a substantial portion of the river's flow it could impact water availability at the Rocky Reef Diversion at RM 36.8.

   Recommendations by Kellogg (2014) for this site included armoring the bank at the avulsion node (flow split at avulsion) to prevent the river from breaching into the avulsion path; this breaching has since occurred. In order to prevent activation of the South Overflow Channel, Kellogg (2014) recommend evaluating the head of that channel to see if structures should be built to prevent its activation. Those recommendations are still valid.

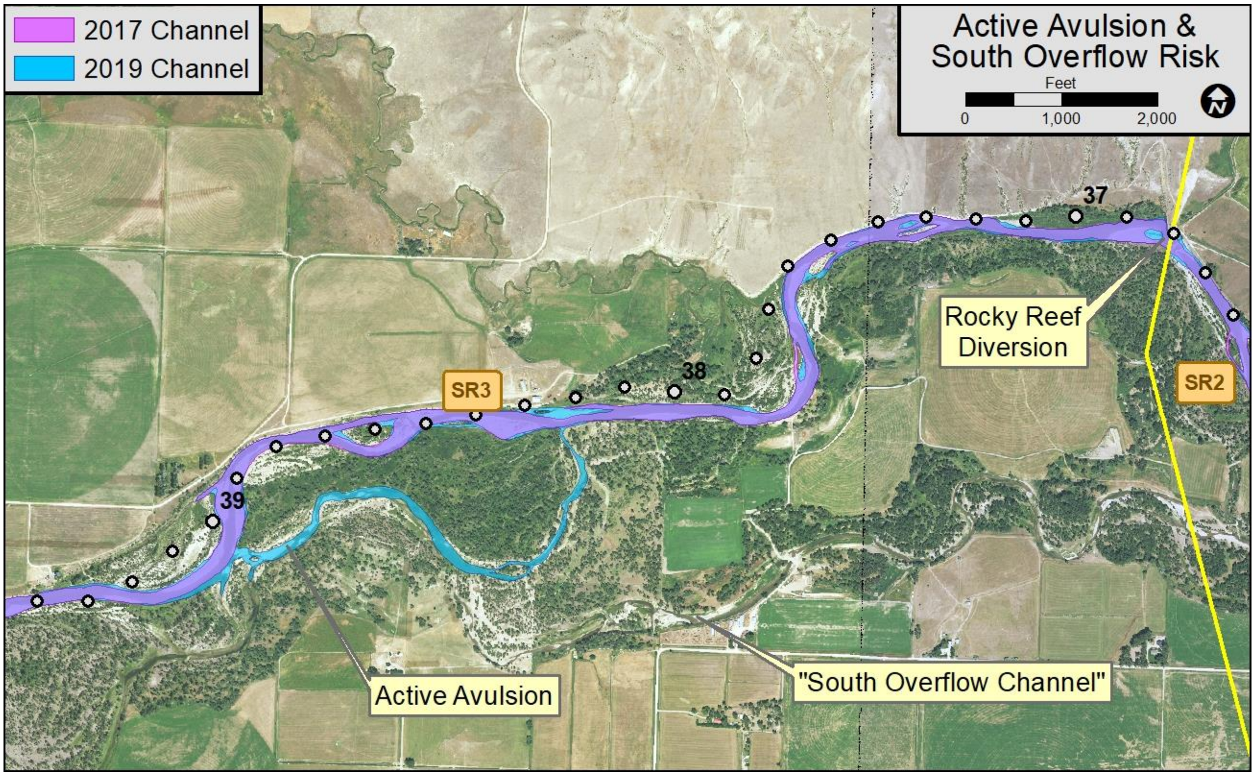


Figure 75. Active avulsion (blue 2019 path) at RM 38.5 showing potential for reactivation of South Overflow Channel that would bypass Rocky Reef Diversion.

Figure 76. Activating channels on south floodplain about 1.5 miles upstream of Rocky Reef Diversion showing breaching of cross-channel berms between 2009 and 2019.

5.5 Reach SR2—Rocky Reef Diversion to Sun River

Reach SR2 extends from Rocky Reef to the community of Sun River, a distance of 8.6 miles (Figure 77).

Figure 78 shows an example of an avulsion in Reach SR2 that occurred between 1957 and 1977. The original meander has been abandoned as an oxbow, and about a half mile of new channel has formed to the south, through a field. These types of avulsions tend to be more common through fields than in riparian areas, because riparian forests support floodplain integrity better than hay or other herbaceous crops.

Reach SR2		
Upstream/Downstream RM	36.8	28.2
Length (miles)	8.6	
General Location	Rocky Reef to Sun River	
Mean Migration Rate (ft/yr)	5	
Max 62-year Migration Distance (ft)	831	
100-year Buffer (ft)	503	
100-year Terrace Buffer	225	

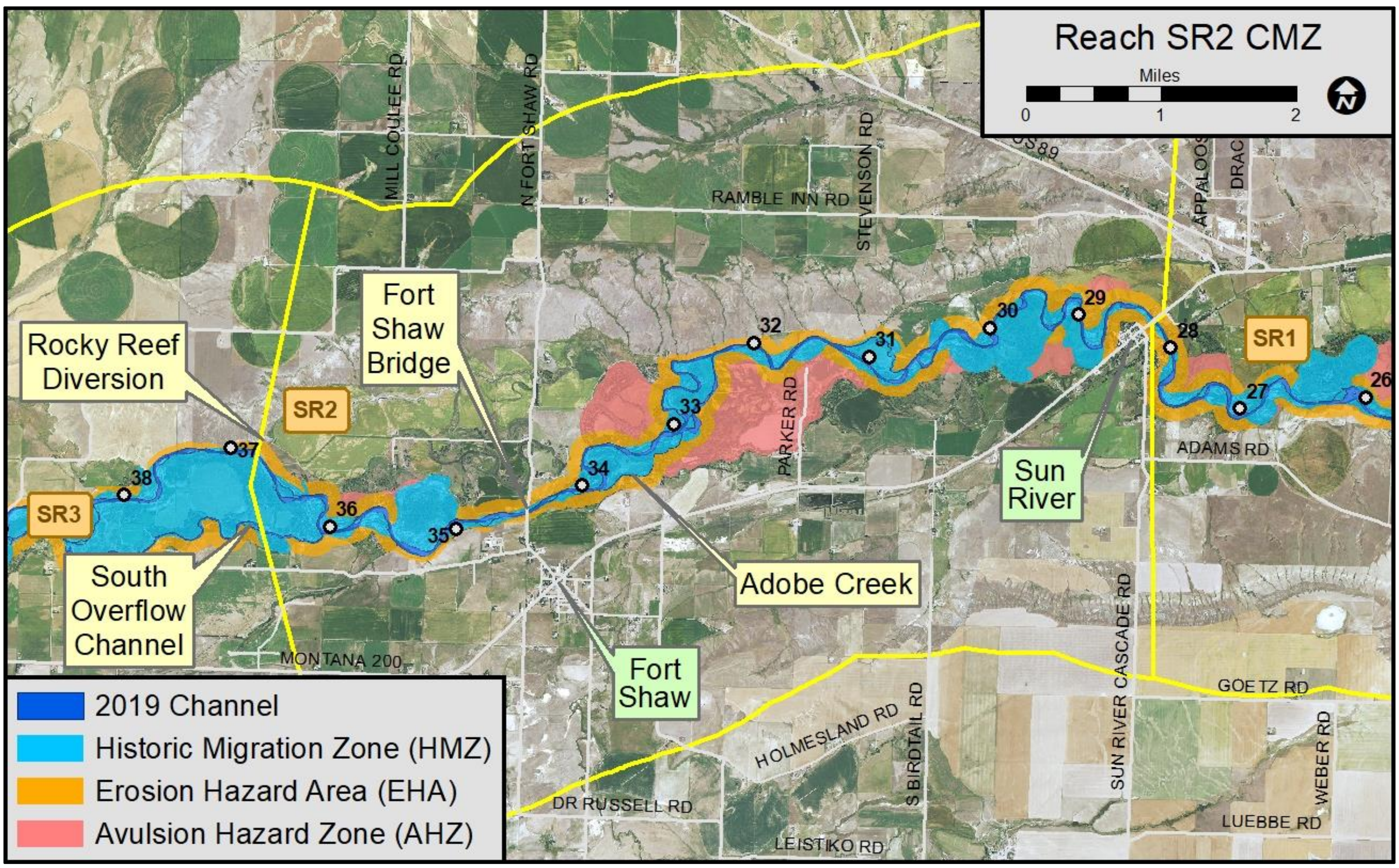


Figure 77. CMZ map for Reach SR2.

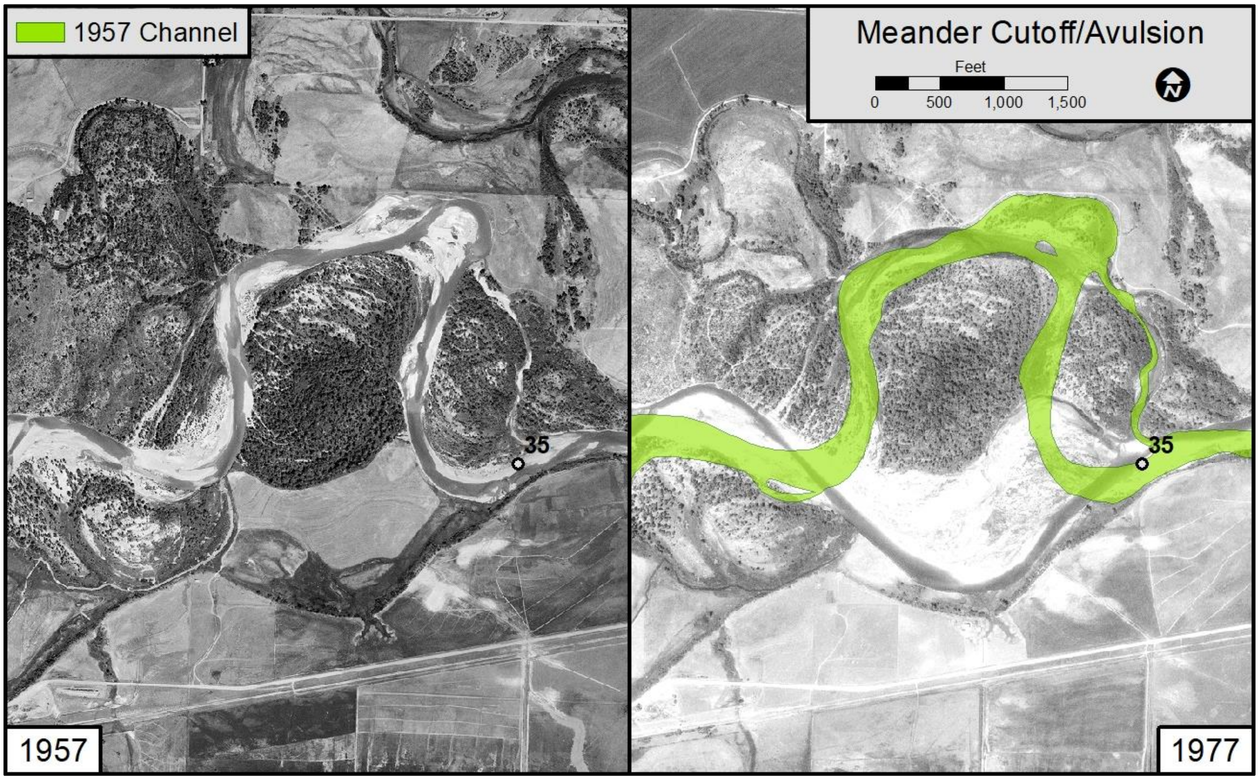


Figure 78. Meander cutoff/avulsion in Reach SR2 between 1957 and 1977.

5.5.1 CMZ-Related Issues in Reach SR2

1. An active avulsion in Reach SR2 on Adobe Creek is a current concern to landowners on lower Adobe creek. The river has migrated into a connector channel that allows Sun River flows into Adobe Creek. From the avulsion node there is about 4,300 feet of lower Adobe Creek that could potentially be activated. It is important to note that the avulsion path is about 2,000 feet shorter than the current path of the Sun River, indicating a strong topographic advantage (steeper route) for the Adobe Creek path rather than the current route of the main channel.

2. An older avulsion has established further down Adobe Creek as it flows north across the Sun River floodplain (Figure 83). This was described as High Priority Site SR-16 by Kellogg (2014) who indicated that root wads and riprap were installed over ten years ago on the right bank to prevent the river from breaching into the side channel/tributary. Recommendations were to reinforce all likely breach locations with rock riprap and flow deflectors. All treatments that were in place in recent years failed, and headcuts that had established between the river and side channel grew and allowed the river to breach into the channel.

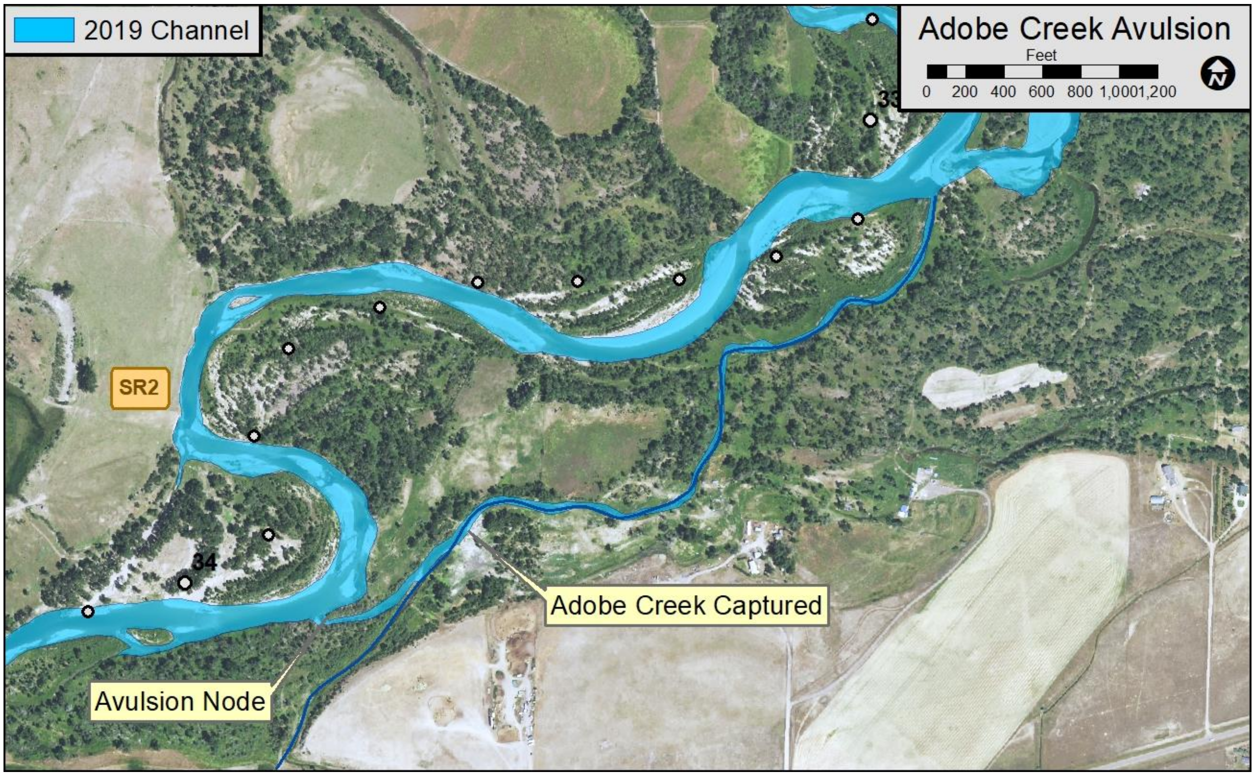


Figure 79. 2019 image showing active avulsion into lower Adobe Creek; avulsion path is about 2,000 feet shorter than the main river.

Figure 80. View down Adobe Creek above avulsion point.

Figure 81. View of Adobe Creek below avulsion point; the Sun River has captured the creek.

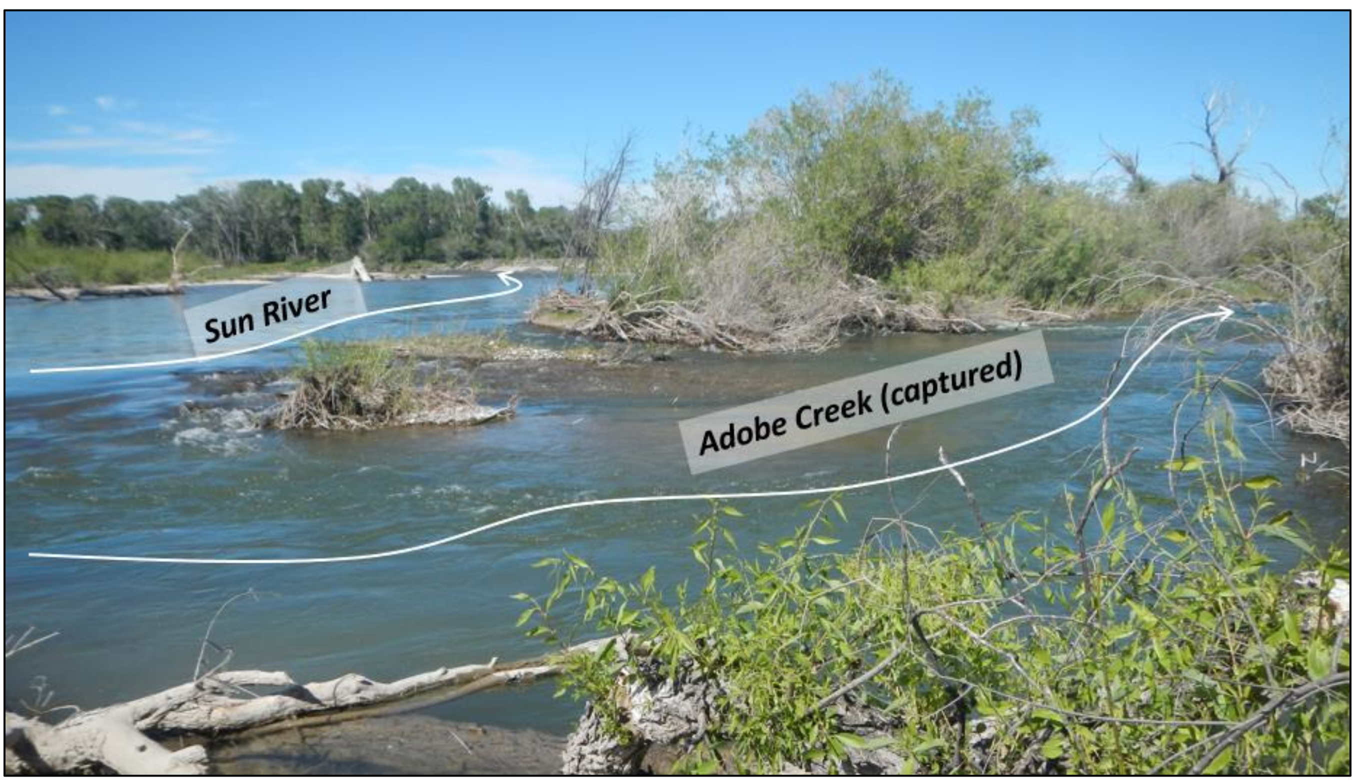


Figure 82. View downstream from avulsion node showing breach in right bank that captured swale feeding Adobe Creek.

Figure 83. Avulsion into lowermost Adobe Creek between 1995 and 2019 showing tributary capture due to bank erosion at avulsion node into old swale/creek channel.

5.6 Reach SR1—Sun River to Vaughn

Downstream of the town of Sun River Reach SR1 is characterized primarily by a long history of gravel extraction (Section 2.9). In the 1950s, the gravel mining was intensive in braided reaches, which may have been a direct response to the 1955 flood (Figure 85).

Reach SR1		
Upstream/Downstream RM	28.2	17.2
Length (miles)		11
General Location	Sun River to Vaughn	
Mean Migration Rate (ft/yr)		5
Max 62-year Migration Distance (ft)		928
100-year Buffer (ft)		504
100-year Terrace Buffer		225

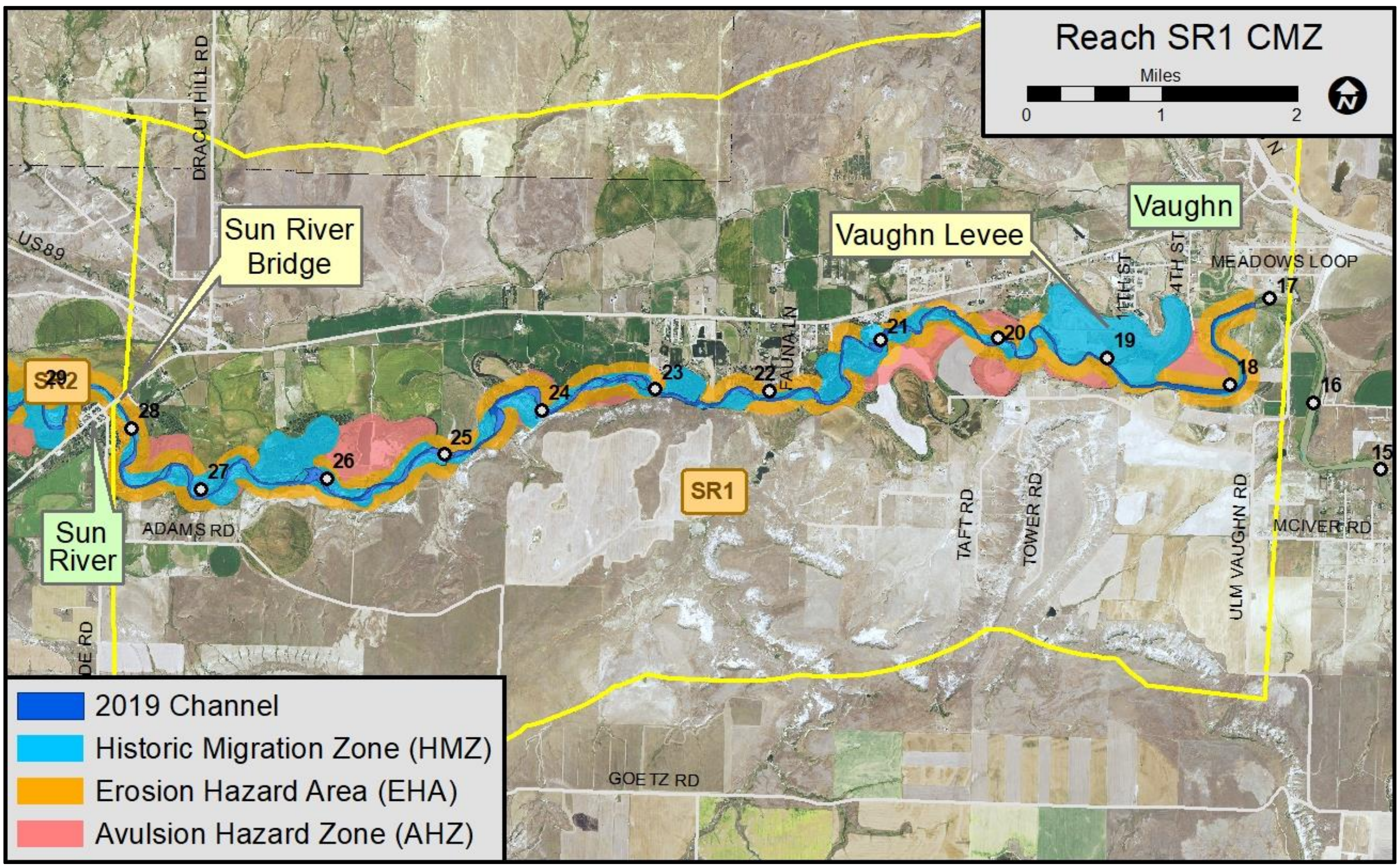


Figure 84. CMZ map for Reach SR1.

Figure 85. In-stream sand and gravel mining in 1957, Reach SR1.

5.6.1 CMZ-Related Issues in Reach SR1

The CMZ mapping shows one place of special concern in Reach SR1. It is an area of high terrace erosion on the left (north) bank at RM 20.5. The terrace has old car bodies and strap metal strewn along 1,000 feet of bank (Kellogg, 2014). Kellogg recommended that the car bodies be removed and salvaged/disposed of.

Gravel pit capture will remain an issue in Reach SR1 unless the old pits are remediated. This may not pose a major problem for channel stability, but it can create serious fisheries concerns if a breach releases non-desirable species from the pond to the river.

Figure 86. Terrace erosion at RM 20.5; green polygon shows channel location in 1957.

Figure 87. High terrace erosion at RM 20.5 (Kellogg, 2014).

6 CMZ-Related Management Considerations for the Sun River

The following section contains a summary of strategies that relate to channel migration on the Sun River.

6.1 CMZ Management and Stream Corridor Resiliency

Perhaps one of the most important results of this study is the clear documentation that the Sun River below the Highway 287 Bridge is a dynamic river corridor that naturally experiences high rates of change due to coarse sediment delivery, a flattening slope, a propensity for large rain-on-snow flood events, and a wide valley floor. The Sun River is more than a channel, it is a mosaic of active and abandoned channels on a wide floodplain that experiences major changes through time. The upper watershed delivers high volumes of coarse bedload sediment, and as the river loses slope it loses the capacity to transport that material. This deposition drives point bar formation and meander migration which will lead to bank erosion, meander cutoffs, and floodplain avulsions. Loss of sediment transport capacity in the lower project area explains in part why sand and gravel mining has been so persistent near Vaughn, where the slope of the river is about one third of that of the river upstream above Lowry Bridge.

One of the most important considerations in Sun River management is therefore how to integrate the protection of fixed infrastructure while allowing the river to naturally respond to floods, changes in sediment delivery (e.g. pulses), and topographic imbalances on the floodplain. Allowing the river to naturally adjust is important from a resiliency perspective, as local slope adjustments will help prevent chronic deposition and perching of the river above its floodplain. This means meanders will continue to grow and cut off, and the river will change its location on the floodplain, reworking sediments and minimizing topographic disparities.

The management of the river as a "corridor" is an important first application of CMZ mapping. Minimizing economic losses due to land loss, infrastructure failure, or bank amor loss should consider the following:

- Consolidate infrastructure where possible. For example, diversion headgates tend to function well below bridges, which taper the CMZ to the width of the bridge opening.
- Promote woody riparian growth in the corridor, to increase the resiliency of the floodplain during long floods that have the potential to scour floodplain channels and drive cutoffs.
- Place infrastructure such as pivot towers beyond the margins of the Erosion Hazard Area to reduce the need for near-term bank armoring.
- Carefully taper the CMZ to bridge openings using bank armor approaches that gradually narrow the stream corridor to the bridge opening.
- As possible, minimize bank armoring projects that run perpendicular to the axis of the CMZ. Any channel segments that trend across the CMZ (typically north/south) will have increased erosive pressure on the down-valley (east) side, as the armor is disrupting normal down-valley translation of bends. As such, these projects typically fail or require a higher level of maintenance than projects that trend on the edge of the CMZ in a direction parallel to the stream corridor axis.

Whereas CMZ mapping is commonly used to identify development risks, it is also important to recognize the role that channel migration plays in maintaining geomorphic stability and optimizing the ecological function of these rivers. While the Sun River has been impacted by development pressures of transportation, irrigation water delivery and residential expansion, its inherent dynamism has limited human encroachment into the CMZ footprint. As a result, there are sections on the river that show largely unimpeded channel movement and resulting complex channel forms, both spatially and temporally. The Sun River CMZ corridor is commonly over 3,000 feet wide and supports broad riparian forests of diverse age classes. The continual turnover of floodplain forest supports long term riparian health as the woody vegetation is constantly regenerating (Figure 88). Wood recruitment in more dynamic reaches is common, and entrainment of both wood and sediment through bank erosion supports to aquatic habitat development and sustenance. These conditions clearly contribute to the long-term viability of our willow/cottonwood corridors and provide geomorphically deformable river channels that can adjust to changing inputs in the future.

Figure 88. Riparian succession below Lowry Bridge; channel movement has prompted establishment of smaller cottonwood seedlings on open gravel bars on the river's edge.

6.2 Gibson Dam Operations

At one of the outreach meetings for this effort, a discussion focused on how reducing flood peaks by storing additional water in Gibson Reservoir could dampen rates of change and associated economic impacts downstream. Currently, irrigation is the only federally authorized purpose for the dam (HRC&RMS, 2013). It is common for reservoirs to provide floodwater storage and changing the water delivery patterns downstream can influence rates of river movement. This should be carefully considered on the Sun River, however, as reducing peak flows may reduce the amount of time the floodplain is inundated, but it will lengthen the time the river channel is running full. Longer durations of moderate flood levels may result in higher long-term bank erosion rates but will likely reduce avulsion frequency.

6.3 Roads and Bridges

The CMZ mapping area includes transportation features that encroach into the CMZ footprint. The main issues with bridges are twofold: 1) alignment of the river to the bridge crossing; and 2) consolidation of multiple stream channels at a bridge crossing. Bridges are typically designed at a right angle to stream flow, so that the bridge is perpendicular to flow paths. As the channels migrate laterally, this alignment can decay. It is not uncommon for poor alignments to cause problems at bridges through accelerated scour which can damage bridge piers and embankments. To that end, it is important to consider stream corridor alignment and tolerance for change in both bridge design and management. In general, managing channel alignments at bridges should be considered with CMZ concepts taken into account rather than treated as a late-stage emergency when streams dogleg through bridges, causing scour or deposition problems. The maps can help identify optimal bridge locations and define anticipated future alignment issues so support cost-effective risk mitigation.

6.4 Development Pressures

In developing CMZ maps across Montana, it is always striking to see how many structures are at risk of damage due to bank erosion. In our public outreach meetings, both for this study and throughout Montana, we have heard numerous testimonies in which landowners have described their anxiety over river movement and financial stresses of property protection. Bank armoring typically costs on the order of $90-$120 per linear foot of bank, so protection of structures on these rivers can easily cost over $100,000. Yet structures are still constructed close to actively migrating channels. We sincerely hope that this analysis will help landowners make cost-effective decisions in siting homes or irrigation structures. On the Big Hole River, one landowner moved his house 100 feet back from the top of a terrace edge based on the mapping; subsequent erosion of that terrace has proven that decision to be a major cost saving move.

6.5 Riparian Clearing

The CMZ mapping has revealed some riparian degradation on the Sun River. The cause of this degradation is probably active clearing to improve agricultural lands (Figure 89). However, the continued persistence of a robust riparian corridor on segments of the Sun River indicates that riparian restoration could be an effective means of improving floodplain/bankline resilience, and possibly reducing bank migration rates.

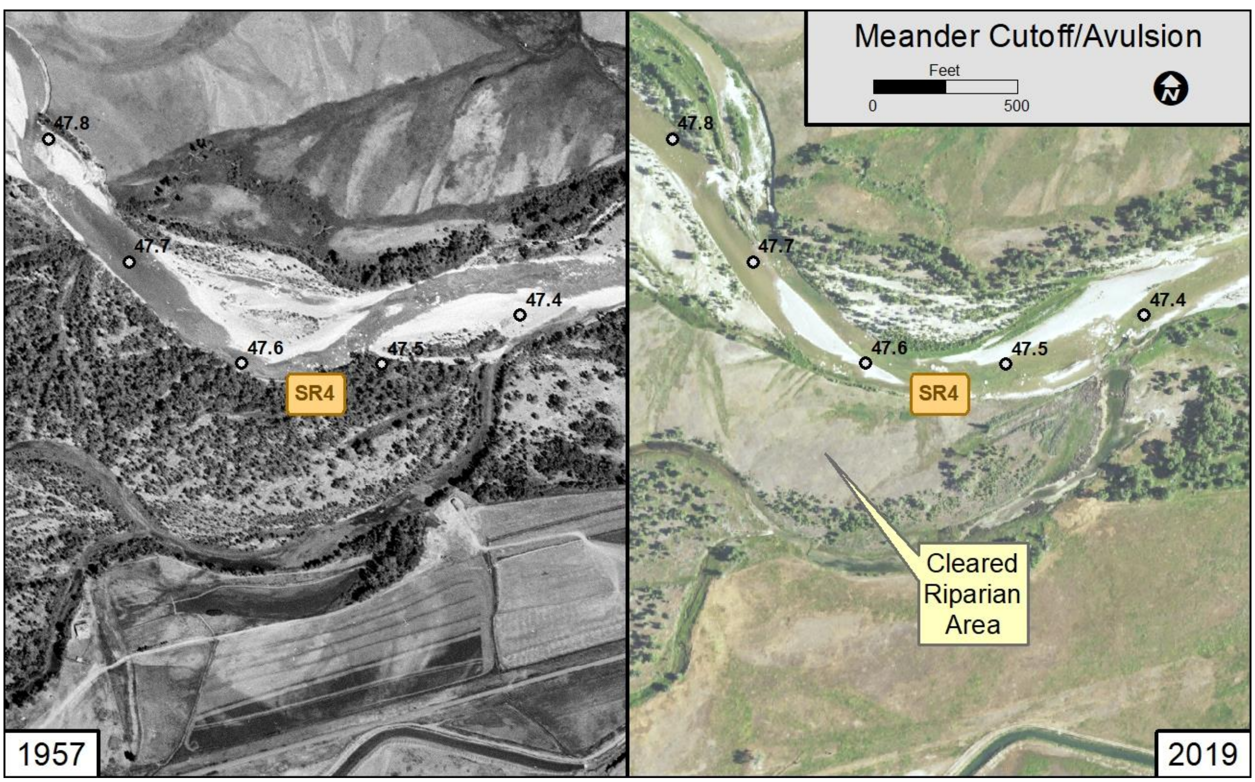


Figure 89. Riparian clearing on Sun River floodplain between 1957 (left) and 2019) right, Reach SR4.

7 Project Considerations for Specific Issues

This section describes some mitigation strategies for CMZ-related issues on the Sun River. These issues include avulsions, accelerated bank erosion, terrace erosion, and failed infrastructure that is in the channel.

7.1 Avulsions

An avulsion is the creation of a new river channel away from the main thread. On the Sun River, this may occur where the river captures a tributary, due to a meander cutoff, or where an old swale is captured. It may relocate the whole river or create a secondary channel. Avulsions commonly occur when floodwaters flow across a floodplain surface at a steeper grade than the main channel, carving a new channel along that steeper, higher energy path. Although avulsions typically occur during floods, they can also be driven by meander migration into an old swale, which is common on the Sun River. The following recommendations relate to managing avulsions on the Sun River:

1. ***Preventing Avulsions:*** In many locations on the Sun River, avulsion risks have been managed by building berms across swales where high flows are likely to channelize and convert the swale to a perennial channel. This may reduce the energy in the swale, but these berms have been shown to erode out if they are some distance down the erosion path. If an avulsion is to be prevented, it should be addressed at the upper flow split, known as the “avulsion node”. This will require plugging and reconstructing the bankline where flows enter the avulsion path.

2. ***Managing Avulsions:*** In some cases, preventing an avulsion is nearly impossible, since they can occur unexpectedly during high water. If an avulsion occurs it may be optimal to manage the new flow path as an active channel. This may involve relocating/replacing infrastructure on the avulsion path or protecting infrastructure as the new channel develops.

3. ***Accommodating Avulsions:*** Allowing avulsions to occur where there is no direct threat to infrastructure can rejuvenate aquatic and riparian habitats while allowing slope adjustments to progressively occur. This can help prevent wholesale perching of the river over its floodplain and negate the high costs typically necessary to entirely prevent an avulsion.

It is important to secure cooperation between neighbors in managing avulsions. Stopping an avulsion in an area where the avulsion path provides a more efficient route than the main channel can be an expensive venture that requires long-term vigilance.

7.2 Accelerated Bank Erosion

Probably the most common complaint with channel migration is bank erosion. As a result, bank armoring is typically the most common means of managing river locations and rates of change. On the Sun River, Kellogg (2014) noted the following:

> River volatility makes it difficult and expensive to keep existing bank armor intact and functional. Several sections along this reach are in jeopardy of being flanked by the river. The best long-term management approach is to maintain healthy riparian vegetation and limit infrastructure development along the river. Bank stabilization may only be worthwhile

where high value infrastructure (i.e. roads, buildings, irrigation structures, etc.) requires protection.

We would concur with this recommendation. Table 4 lists the bank armor sites described by Kellogg (2014) in terms of condition and priority for additional work. His workup, only included sites below Lowry Bridge, indicates that bank armor on the Sun River is highly prone to progressive damage or complete failure. Several projects have been completely lost, including flow deflector and rootwad projects. Riprap is highly prone to flanking. Of the 24 bank armor projects he reviewed, only 9 appear to be performing as intended. Based on these observations, it appears that flow deflectors and bioengineering treatments such as rootwads have not performed well on the Sun River.

Table 4. Bank armor sites below Lowry Bridge described by Kellogg (2014) describing current performance

Kellogg (2014) Site Reference	River Mile	Treatment	Priority (2014)	Condition (2014)	Condition (2020)	Performing?
SR-3	44.6	Rock Flow Deflectors	Medium	Seven of nine deflectors flanked	Same	**No**
SR-7	39.2	Root Wads/Rocks	High	Washed out	~85 feet erosion behind treatment; high avulsion hazard	No
SR-8	37.9	Riprap	No Action	Some repairs	Lower 130 feet eroded out	Upper portion
SR-14	34.3	Riprap	No Action	Upper portion intact; lower end flanked	480 feet eroded out; upper end flanking	Partially
SR-15	33.7	Riprap/Jetties	Medium	Flanking on ends of treatment	Upper end flanking	Partially
SR-17	32.8	Root Wads/Rocks	Medium	Upper 80' washing out	Upper end flanking	Partially
SR-18	32	Riprap/Rootwads	Low	Some sloughing	Lower ~230 feet eroded out	Upper portion
SR-19	31.8	Riprap	No Action	In need of minor repair	Lower ~40 feet eroded out	Upper portion
SR-21	30.1	Flow Deflector	No Action	In need of repair	Repaired	Yes
SR-22	29.8	Riprap/Jetties	Medium	Prone to flanking	Jetty removed	Yes
SR-23	29.3	Riprap	No Action	Prone to flanking	Lower end eroded out	Yes
SR-24	29.1	Riprap	Low	Erosion just upstream	Continued erosion upstream	Yes
SR-25	28.8	Riprap	No Action	Performing well	Performing well	Yes
SR-26	28.5	Rock Jetty	Medium	Prone to flanking	Jetty flanked	No
SR-29	27.7	Riprap/Jetties	No Action	Performing well	Severe erosion between jetties; risk of upper jetty flanking	Partially
SR-30	26.3	Riprap	No Action	Performing well	Performing well	Yes
SR-32	24.5	Riprap/Jetties	Medium	Prone to flanking; upper 30' in need of repair	Completely flanked; ~100 feet of erosion behind	No

Kellogg (2014) Site Reference	River Mile	Treatment	Priority (2014)	Condition (2014)	Condition (2020)	Performing?
SR-35	23.2	Rootwads/Rubble	Medium	Rootwads okay, rubble non-functional, public hazard	Lower 100 feet eroded out since-2017	Upper portion
SR-38	21.2	Rootwads/Riprap	Medium	Rootwads from 2002 washed out.	Jetty and rootwads eroded out; 160 feet of migration since 1995	No
SR-39	21	Root Wads	No Action	Performing well	Tight bend; performing ok	Yes
SR-40	21	Car Bodies	No Action	Performing well	Performing well	Yes
SR-41	20.5	Car Bodies	High	Public hazard	Public Hazard	No
SR-42	20.4	Car Bodies	Medium	Public hazard	Public Hazard	Yes
SR-43	19.6	Riprap	High	Failed barbs/riprap disrepair	Performing well	Yes

7.3 Accelerated Terrace Erosion

High terrace erosion is a distinct characteristic of the Sun River due to the erodible nature of the terrace deposits below Lowry Bridge. The erosion mechanism for these units can be related to several factors, including river erosion, mass wasting/slumping of a high vertical bank, and saturation of those terrace sediments due to irrigation on top. For the purposes of this study, the geotechnical aspects of the terraces were not individually assessed, and as such factors such as geotechnical failure or saturation-driven failure should be considered carefully at each site. As far as river erosion goes, however, the primary technique generally applied to high banks is to construct a low armored bench at the base of the terrace to provide a buffer between the river and the high valley margin, and to densely vegetate that surface to provide some erosion resistance.

7.4 Debris in Channel

Kellogg (2014) noted several locations were old man-made features are sitting in the middle of the channel (Figure 90). These features were commonly identified as public hazards. These features can also cause unusual locations and rates of channel movement due to the complex hydraulic fields they create at high water. As a result, removing these features from the active channel is recommended as funding allows.

Figure 90. Bridge abutments in channel approximately 1.5 miles downstream from Largent's Bend Fishing Access Site (Kellogg, 2014).

8 Discussion

Prior to human development, the Sun River probably hosted a complex mosaic of active channels flowing within a densely vegetated floodplain. These conditions, which were typical of major Upper Missouri River tributaries, allow floodwaters to spread through multiple channels and across a rough floodplain surface. The first major human impact to the river was likely beaver trapping. In the early 1800s beaver trappers explored the Upper Missouri watershed and beaver populations plummeted. Beaver eradication 200 years ago has been generally recognized across Montana as a profound driver of change in our rivers and streams. This change was dominated by a conversion from multi thread channel/wetland complexes to much more efficient and energetic single thread channels. Further development of stream corridors beginning in the late 1800s generally included consolidation of river channels to facilitate water use and riparian clearing to expand agricultural lands.

It is difficult to say if the Sun River was more active historically than it is today. The consolidation of flows into larger channels would tend to increase in-stream energy and associated bank erosion rates in the last century. However, the system has also been altered by flow diversions and reservoirs, which would tend to reduce in-stream energy and associated bank erosion rates. Gibson Dam was built in the upper watershed in the late 1920s, no doubt altering natural patterns of flow and sediment delivery to the river. Imagery used in this analysis shows broad expanses of open gravel bars in the 1950s and 1970s; these features may reflect short-term influences of floods, or alternatively may reflect a historic condition that has been changing since. As the influence of Gibson Reservoir includes starving the river of coarse sediment, the impacts would be initiated below the dam and then extend downstream with time. It is possible that sediment loads to the reach were naturally higher into the 1970s and that those loads are beginning to drop off as the project reach begins to experience the influence of sediment trapping upstream. An assessment of these broader historic trends was generally beyond the scope of this effort but considering them may provide some insight as to the state of the river today.

This assessment of channel migration rates and patterns on the Sun River indicates that this system has maintained a strong propensity for rapid lateral migration as well as avulsions (wholesale channel relocations). This is due to the combination of coarse bedload delivery and flattening slopes, amplified by occasional large rain-on-snow driven floods. As the river flows off of the glaciated Rocky Mountain Front towards the low gradient areas around Great Falls, stream energy naturally drops and coarse sediment is deposited as point bars and in stream deposits. This sediment drives lateral bank erosion through point bar/meander development as well as avulsions via channel perching and breaching into older swales. As a result, the floodplain currently hosts a complex mosaic of active and inactive channels, all of which have the potential for some level of dynamism.

Considering the costs associated with managing lateral migration on a river such as the Sun, stakeholders in this river corridor are relatively fortunate due to the use of a larger bench canal system to support irrigation needs. As a result, there are only a few primary diversion structures on the river and development encroachment into the stream corridor has been relatively tepid. The fairly low concentration of key infrastructure elements on the river is commendable and, if maintained, will both save money and preserve important stream functions into the future. Our attempt with this analysis is to document/demonstrate the nature of channel movement on the Sun River, to help develop effective management strategies that both support local economies while minimizing river corridor impacts that prove to be costly and ineffective.

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Appendix A: 11X17 CMZ Maps (Separate Document)