Final Report

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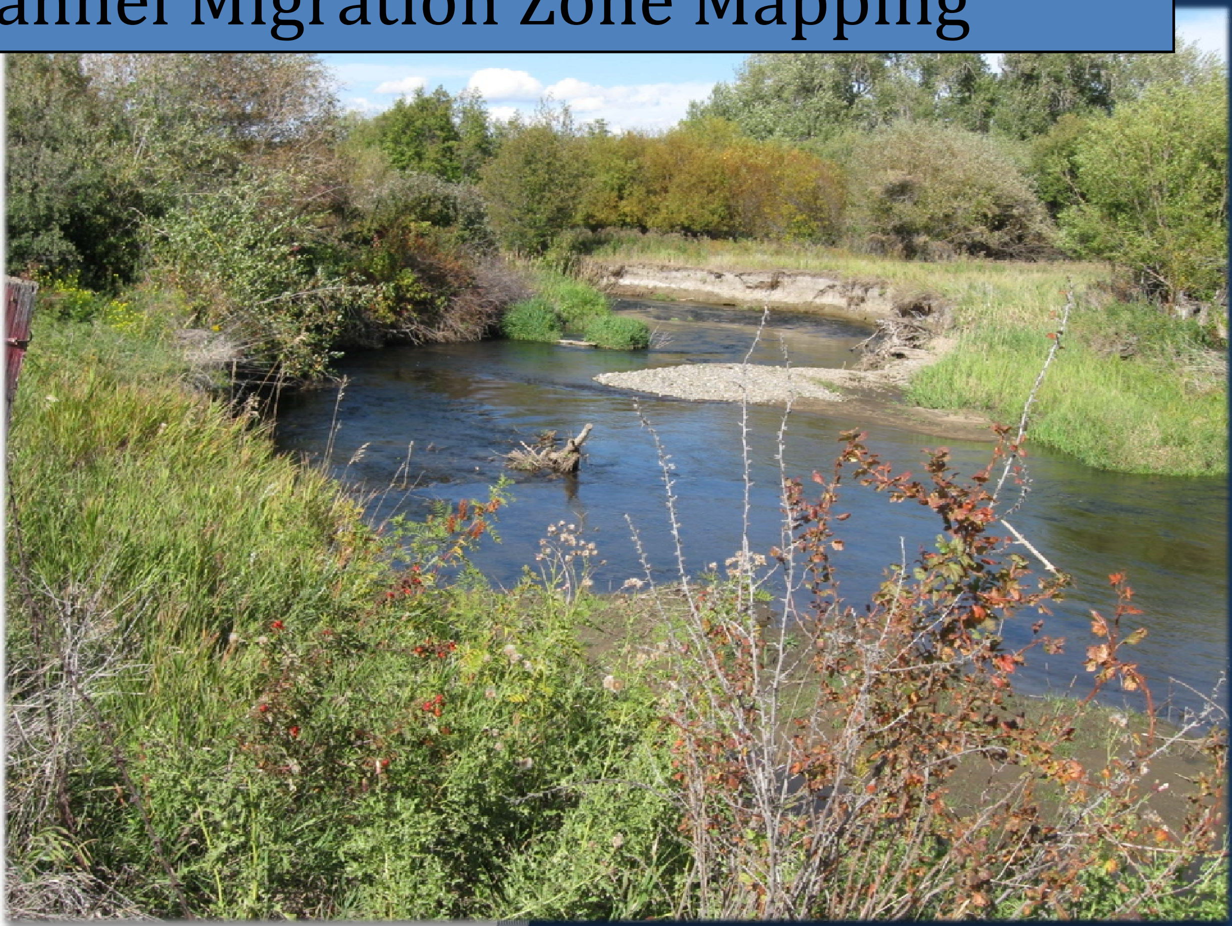
Prickly Pear / Tenmile Creeks Channel Migration Zone Mapping



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1 Introduction

This report describes the development of a Channel Migration Zone (CMZ) map for Prickly Pear Creek from Lake Helena, upstream to the Lewis and Clark County Line (14.8 miles); and Tenmile Creek from its confluence with Prickly Pear Creek, upstream to Interstate 15 (3.4 miles). The project was performed under a contract dated May 13, 2010 between Lewis and Clark County and DTM Consulting, Inc (DTM). DTM teamed with Applied Geomorphology, Inc. (AGI) to perform this work. Funding was provided by the Montana Department of Environmental Quality.

The contracted Scope of Work is to perform a Channel Migration Zone Study and develop maps to assess channel migration and river bank erosion for Prickly Pear and Tenmile Creeks within the project area.

The following report describes the process used in developing a final map product, including data acquisition, data development, analysis, interpretation, map formulation, and recommendations for further analysis in support of management efforts in the Helena Valley.

1.1 Channel Migration and Avulsion Processes

Both Prickly Pear Creek and Tenmile Creek are naturally alluvial channels, although several reaches have been highly modified by channelization. Alluvial channels flow through sediment that has been deposited by the river itself, and as such they are in a constant state of sediment reworking, building bars, eroding banks, and conveying sediment downstream. On dynamic streams such as Prickly Pear and Tenmile Creeks, these geomorphic processes are critically important for riparian vegetation communities, as the new bar surfaces provide areas for colonization by riparian species such as cottonwoods (Figure 1). Bank erosion also results in the recruitment of woody debris, which contributes to fish habitat quality and complexity. Actively eroding undercut banks also provide shade and cover for aquatic species.

Over a given timeframe, Prickly Pear and Tenmile Creeks occupy a corridor that extends beyond its current channel boundaries (Figure 2). The width of this corridor reflects rates of lateral migration. Some banks migrate relatively slowly due to low stream energy or erosion-resistant perimeter materials. Conversely, some banks migrate rapidly where the stream energy and sediment loads are relatively high and the erosion resistance of the channel perimeter is low (Figure 3).

Figure 1. Bar formation, wood recruitment, and riparian vegetation succession, Prickly Pear Creek.

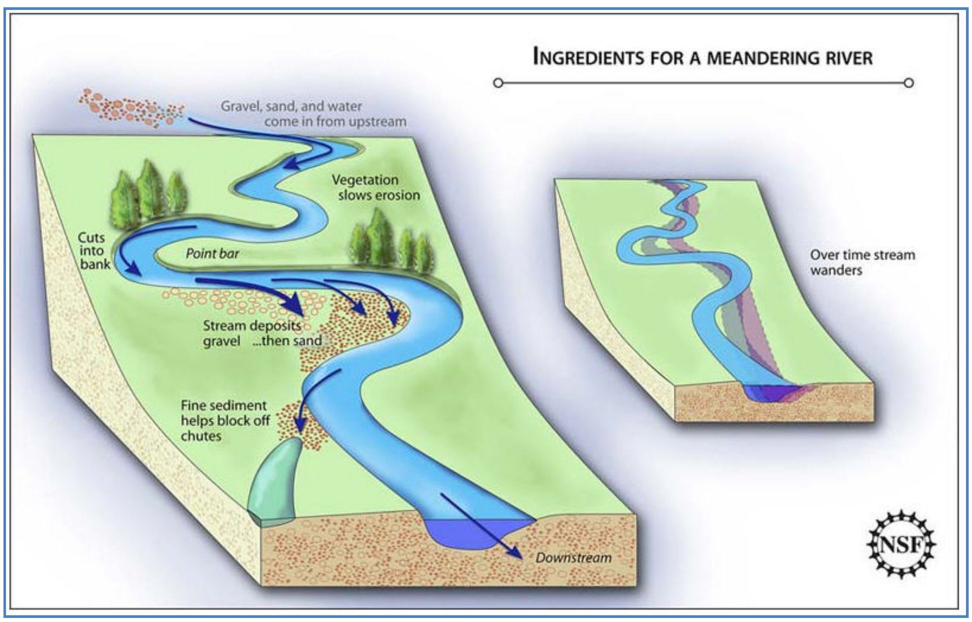

Figure 2. Schematic drawing showing the meandering river migration concept (www.berkeley.edu).

Figure 3. Active bank erosion and channel migration, Prickly Pear Creek (September 2010).

Whereas channel migration refers to the process of progressive lateral channel movement, avulsion refers to the capture of flow by a newly formed or previously abandoned channel segment. This process typically occurs during flood events, when overbank flows occupy and rapidly develop a new channel course. One example of avulsion is meander bend cutoff (Figure 4). Meander bends can cut off either due to migration, where the two limbs of a bend intersect through migration ("neck cutoff"), or by avulsion, where a new channel is excavated through the neck of the bend ("chute cutoff").

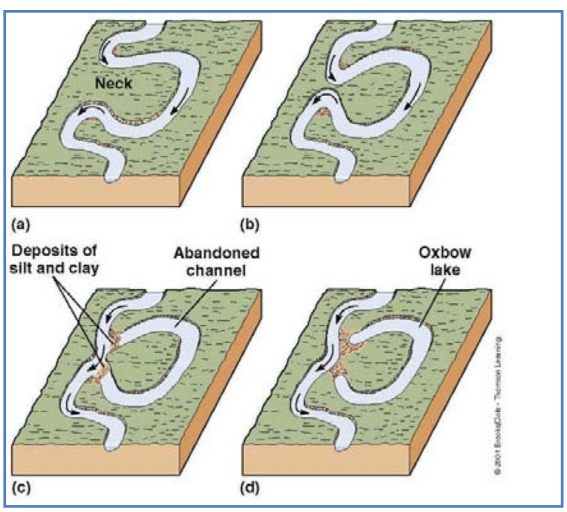

Figure 4. Schematic diagram of meander cutoff (www.uwsp.edu).

The photo shown in Figure 5 was taken from a helicopter by DNRC staff during the 2008 flood on the East Gallatin River near Bozeman, Montana. The photo shows a typical bendway on the East Gallatin, with floodwaters flowing over the core of the bend. On the downstream end of the bend (left side of photo), the overflows re-enter the main channel over a steep bank edge, creating a headcut. If the flood is large enough, or of long enough duration, the headcut will migrate up-valley through the core of the bend and excavate a cutoff channel. On this particular bend, the flood dissipated before cutoff occurred, resulting in a “failed avulsion”.

Figure 5. Example of the avulsion process, East Gallatin River, May 2008 (DNRC).

In addition to bendway cutoffs, avulsions occur where long segments of channel relocate to new areas on the floodplain. These relocations may reflect capture of an abandoned channel, a tributary channel, or creation of an entirely new channel in the floodplain. Both Tenmile Creek and Prickly Pear Creek are located on alluvial fans, where avulsions are a common geomorphic process. However, based on the evaluation of channel locations since 1955, no major avulsions have occurred within the project segments of either creek over the last 55 years.

1.2 The Channel Migration Zone Mapping Concept

Channel Migration Zone mapping is based on the understanding that rivers are dynamic and move laterally across their floodplains through time. As such, over a given time period, 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. The fundamental concept of 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. For this study, a 100-year CMZ was developed.

In general, a Channel Migration Zone is composed of the following:

- 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 or mass wasting.
- 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 (also known as the Disconnected Migration Area, or DMA).

Rapp and Abbe (2003) define the CMZ as:

$$CMZ = HMZ + AHZ + EHA – RMA$$

This general definition allows for some flexibility in terms of both component definitions and the component inclusion in the CMZ. For example, one approach identified by the State of Washington is to use meander belt width and bendway amplitude to define the EHA, rather than measured erosion rates. This approach would be appropriate in channelized reaches where natural migration is largely inhibited. Mapping the Restricted Migration Area requires a thorough inventory of bank armor and floodplain features such as dikes. In addition, whether or not the RMA is included in the CMZ requires a decision as to whether bank armor should be considered effectively managed, stable, and permanent. In our experience, where bank armor inventories are available, project stakeholders have been inclined to highlight the RMA, but not to exclude it from the CMZ as Rapp and Abbe (2003) propose. This is why the areas behind armor are called “restricted” migration areas rather than “disconnected” migration areas.

1.3 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.*

Prickly Pear and Tenmile Creeks are laterally dynamic streams that flow into the Helena Valley on alluvial fan surfaces that are prone to both lateral migration and avulsion. With potential contributing factors such as woody debris jamming, sediment slugs, or ice jams, dramatic change could potentially occur virtually anywhere on the alluvial fan surface. The goal of this mapping effort is to highlight those areas most prone to either migration or avulsion based on specific criteria developed from an assessment of historic channel behavior.

As predicted future migration is based on an assessment of historic channel behavior, the historic influences affecting channel migration are assumed to continue over the next century. In the event that the conditions experienced by the study area streams over the last 50 years change significantly over the next century, uncertainty regarding the proposed boundaries will increase. These conditions include influences imposed by system hydrology, climate, sand and gravel mining, riparian vegetation densities and extents, and channel stability. Bank armor and floodplain modifications, such as bridges, dikes, levees, could also affect map boundaries.

1.4 Relative Levels of Risk

Bankline migration and channel avulsion processes both present some level of risk to property within stream corridors. Although the quantitative probability of any area experiencing either migration or an avulsion during the next century has not been determined, their association with specific river process allows some relative comparison of the type and magnitude of associated risk. In general, the Erosion Hazard Area delineates areas that have a moderate to high risk of channel occupation due to channel migration over the next 100 years. Such bank erosion can occur across a wide range of flows. As such, the risk is not solely associated with flood events, as channel migration commonly occurs as a relatively steady process. Avulsion tends to be a flood-driven process, and as such, risks identified by the Avulsion Hazard Zone are typically associated with infrequent, relatively rapid shifts in channel course that are often difficult to predict.

1.5 Potential Applications

The CMZ maps developed for Prickly Pear and Tenmile Creeks are intended to support a myriad of applications. Potential applications for the CMZ maps include the following:

- Proactively identify future problem areas through documentation of active bankline migration;
- Provide a background tool to assess channel dynamics within any given area;
- Assist in the development of river corridor best management practices;
- Improve stakeholder understanding of the geomorphic behavior of these two creeks;
- Support planning decisions at local and county levels by identifying relative levels of erosion risk;
- Identify areas where channel migration easements would be appropriate;
- Facilitate productive discussion between regulatory, planning, and development interests active within the river corridor; and,
- Help define long-term sustainable river corridor boundaries.

1.6 Disclaimer and Limitations

The boundaries developed on the Channel Migration Zone maps 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 evolution, 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 onto the broad alluvial fan surfaces.

1.7 Acknowledgements

This project was performed for Lewis and Clark County through a contract between the Office of Community Development and Planning and the DTM Consulting/Applied Geomorphology Project Team. Rebecca Shaw from the Planning Office was instrumental in providing contract management and facilitating communication between the authors and project sponsors. Jim Wilbur (WQPD) provided technical management and field assistance, both of which were critical to the project. Kathy Chase of the USGS provided 1981 flood imagery that was very beneficial in assessing avulsion hazards. Eric Spangenberg with Lewis and Clark County GIS assisted with image acquisition and georeferencing, as well as review of the GIS products. The Technical Advisory Committee (TAC) provided feedback throughout the project and provided a thoughtful review of the document and associated data. In addition to those mentioned above, TAC members include: Steve Carpenedo (DEQ), Chuck Dalby (DNRC), Steve Granzow (citizen), Michael McHugh (Planning), Eric Roberts (MTFWP), Lynda Saul (DEQ), and Paul Spengler (LCC). The project team extends its sincere gratitude to everyone who facilitated this effort and improved the final product.

2 Physical Setting

The following summary of the project area geomorphology provides basic context regarding the physical conditions within the river corridor and the project reach in the Helena Valley. Because of the reach-scale approach to this project, it is important to consider the variability in physical conditions that control river form and process.

Prickly Pear and Tenmile Creeks are located in the Lake Helena Watershed, which is encompasses an area of approximately 620 square miles (USEPA, 2004). The western watershed boundary consists of the Continental Divide, and the Elkhorn Mountains are located to the southeast. The three major drainages in the Lake Helena Watershed are Silver, Tenmile, and Prickly Pear Creeks. These three streams all flow into Lake Helena, which is a water body impounded by Hauser Dam on the Missouri River (Figure 6).

Land uses in the project reach include urbanization (East Helena), sand and gravel mining (Prickly Pear Creek), lead smelting (East Helena), rural subdivision, rural residential, and agriculture. Surface water irrigation and ground water withdrawals in the Helena Valley have resulted in seasonal dewatering in sections of Tenmile and Prickly Pear Creek (USEPA, 2004).

The Helena Valley Irrigation District (District) was formed in 1956-58 when the Federal Government worked to replace the agricultural lands that were inundated by the construction of the Canyon Ferry Dam. The District infrastructure consists of a series of open and buried drains within the central Helena Valley constructed to lower the water table approximately 8 to 10 feet, thereby allowing mechanized farming in lands formerly characterized by muddy or boggy conditions. Several of the drains are located within the project area and discharge groundwater, irrigation return flows, and storm water into Prickly Pear Creek and Lake Helena.

Irrigation water is then delivered to the agricultural lands within the District via a pumping plant at Canyon Ferry Dam through a tunnel and canal to the Regulating Reservoir on the east side of the valley. This water is conveyed to the Helena Valley through the Helena Valley Canal, which nearly encircles the Helena Valley, crossing Prickly Pear Creek just upstream of Canyon Ferry Road. The irrigation water is then distributed through numerous laterals and ditches throughout the Helena Valley downgradient of the canal location. Annually over 80,000 acre-feet of water is delivered into the Lake Helena watershed from the Missouri River by the District.

Historic mining in the upper Prickly Pear drainage was extensive. Gold mining began in the Prickly Pear watershed in the 1860s, and extensive mining on Prickly Pear Creek took place into the 20th Century. Over 75 percent of Prickly Pear Creek has been estimated to have been subjected to stream bed modifications and dredging (Baker and Baldigo, 1985). In 1888, a large lead smelter was constructed on the banks of Prickly Pear Creek upstream of East Helena, and ASARCO operated the smelter from 1898 to 2001. This site was named by the United States Environmental Protection Agency as a superfund cleanup site in 1984, and smelting operations were suspended in 2001. On August 14, 2009, the ASARCO stacks were dynamited, marking a significant step in the smelter cleanup operations (http://helenahistory.org).

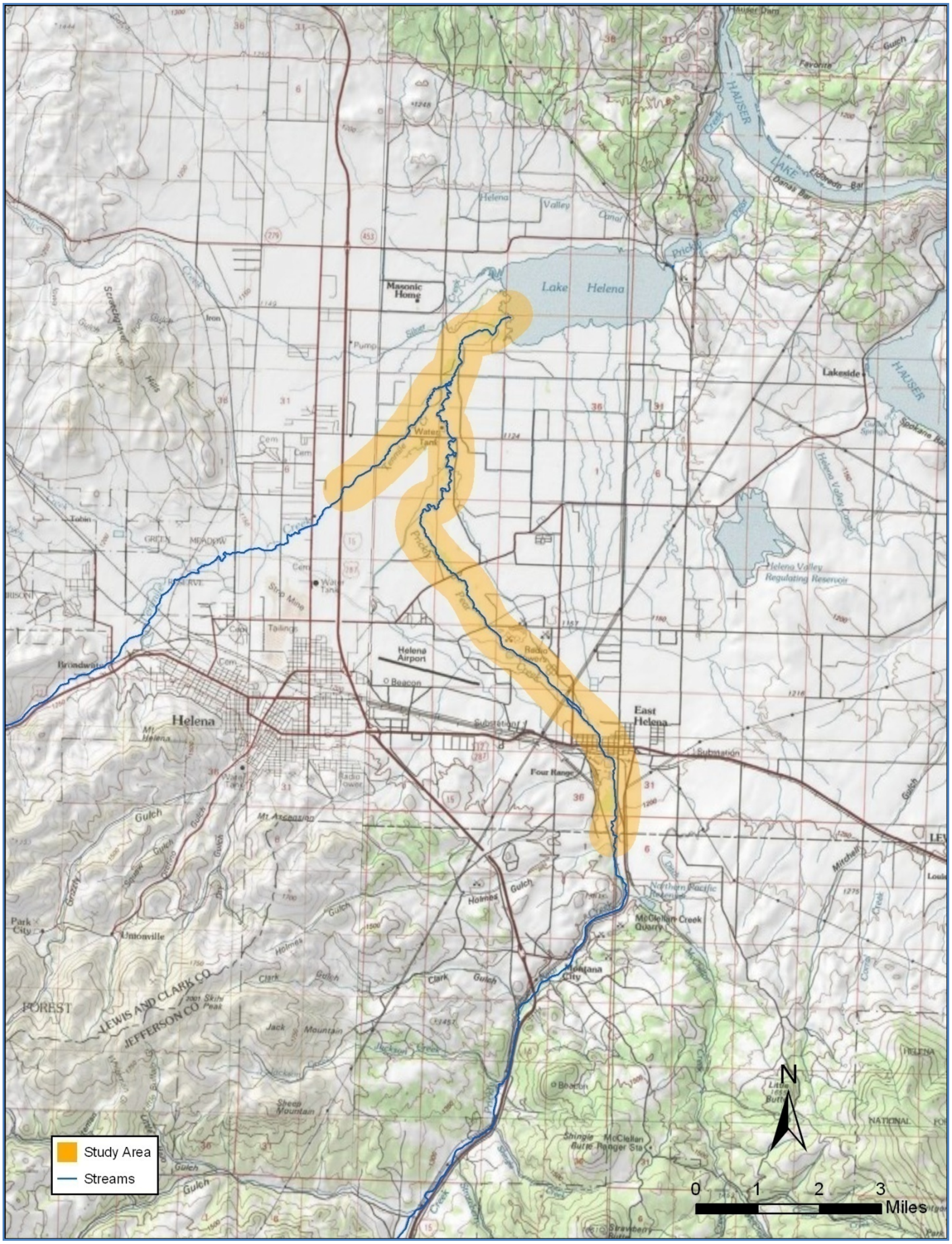

Figure 6. Prickly Pear and Tenmile Creeks in the Helena Valley, with study area highlighted.

2.1 Geology and Geomorphology

The primary geology of the upper Prickly Pear Creek watershed is the Boulder Batholith, which consists of quartz monzonite. This unit tends to naturally contribute large volumes of sand to receiving stream channels. Excessive sediment has also been contributed to Prickly Pear Creek by placer mining, as gravel tailings piles commonly line the stream banks (USEPA, 2004). Thus, natural sediment loads to Prickly Pear Creek are likely relatively high, and these loads have increased since the mid-1800s due to placer mining activities.

As Prickly Pear Creek enters the Helena Valley, it exits a narrow confined corridor and flows onto an alluvial fan at East Helena (Figure 7). This fan is a broad depositional surface that hosts numerous distributary channels to the east of the modern stream channel. Some of these channels conveyed flow during the 1981 flood event. The fan is bounded to the west by Quaternary colluvium (Qac) and to the east by Oligocene-age sedimentary rocks of the Spokane Bench. It extends northward where the modern creek and older distributary channels flow into Lake Helena. It is interesting to note that the geologic mapping indicates a small exposure of Glacial Lake Great Falls on the northeast shore of Lake Helena, indicating that this glacial lake extended into the Helena Valley (Figure 7). Glacial Lake Great Falls reached an estimated maximum depth of 600 feet at Great Falls (Alt and Hyndman, 1986).

Lake Helena is a relatively recent manmade feature. Lake Helena formed when the completion of Hauser Dam on the Missouri River in 1907 flooded the lower 8 miles of Prickly Pear Creek. General Land Office Survey maps show that prior to the completion of Hauser Dam, Prickly Pear Creek flowed in a discrete channel bounded by wetlands out of the Helena Valley to the Missouri River (Figure 8).

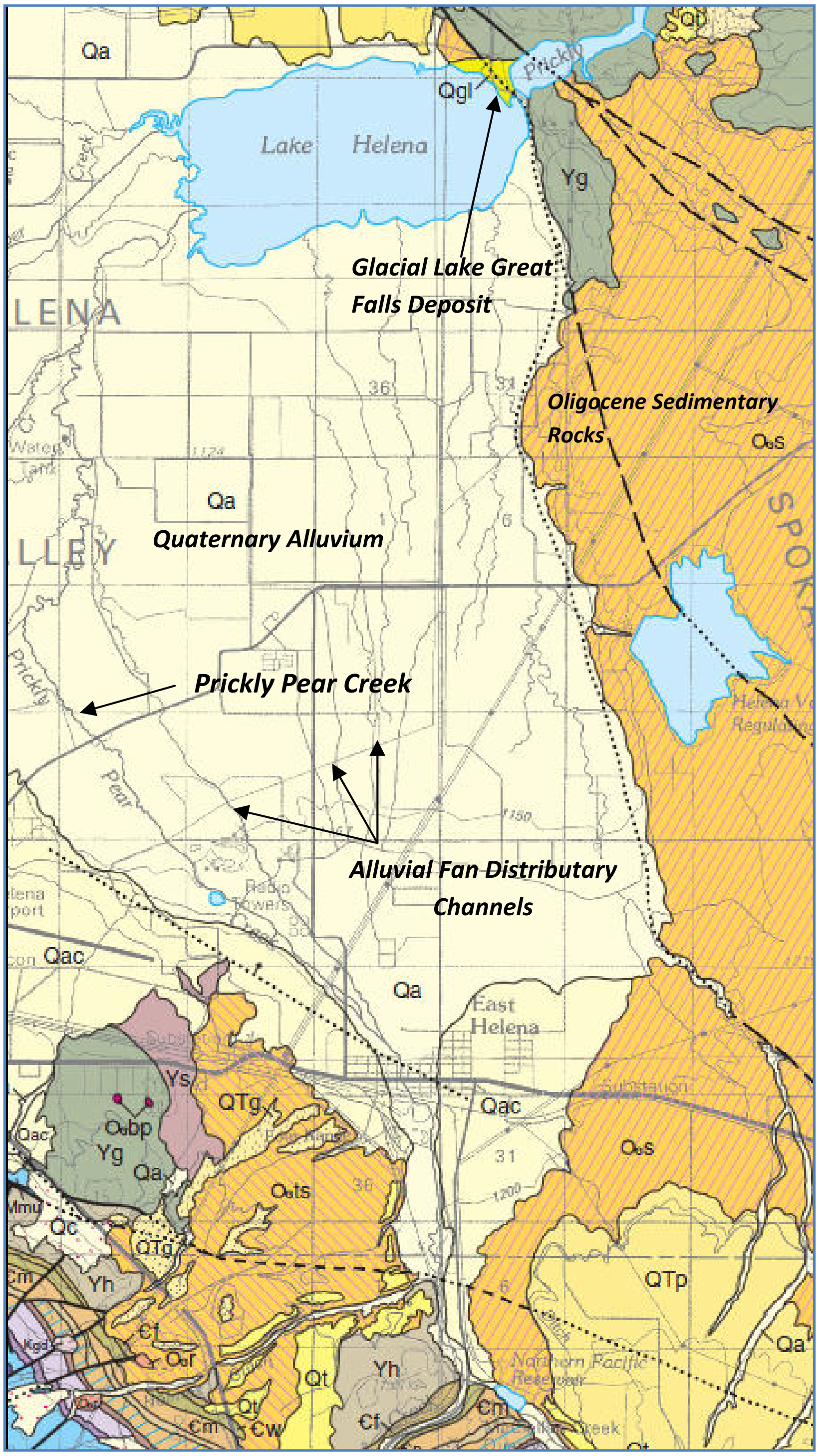

Figure 7. Geologic map of eastern portion of Helena Valley, and lower Prickly Pear Creek (Reynolds and Brandt, 2005).

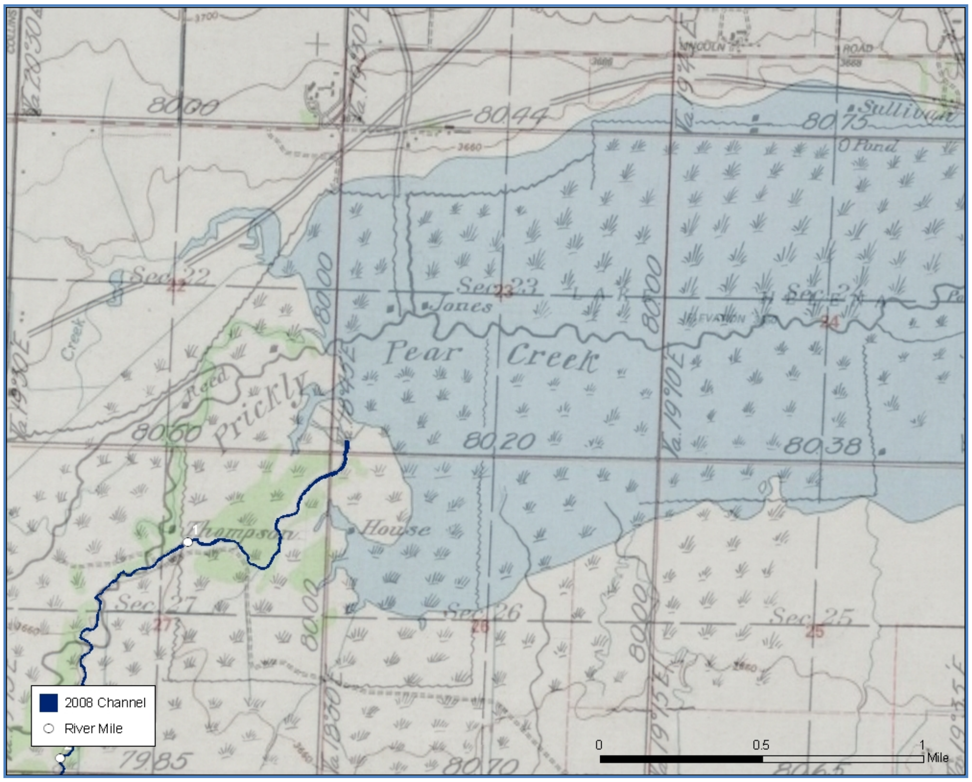

Figure 8. Pre-Hauser Dam General Land Office Survey Map overlain on USGS topographic map showing historic wetland area and Prickly Pear Creek channel that is now Lake Helena.

As Tenmile Creek flows eastward through the Helena Valley towards Lake Helena, it is bounded by numerous distributary channels that flow subparallel to the primary channel thread, similar to Prickly Pear Creek. Oblique air photos collected in 1981 show the distribution of flows into floodplain channels west of I-15 in the Helena Valley, just upstream from the CMZ project reach (Figure 9).

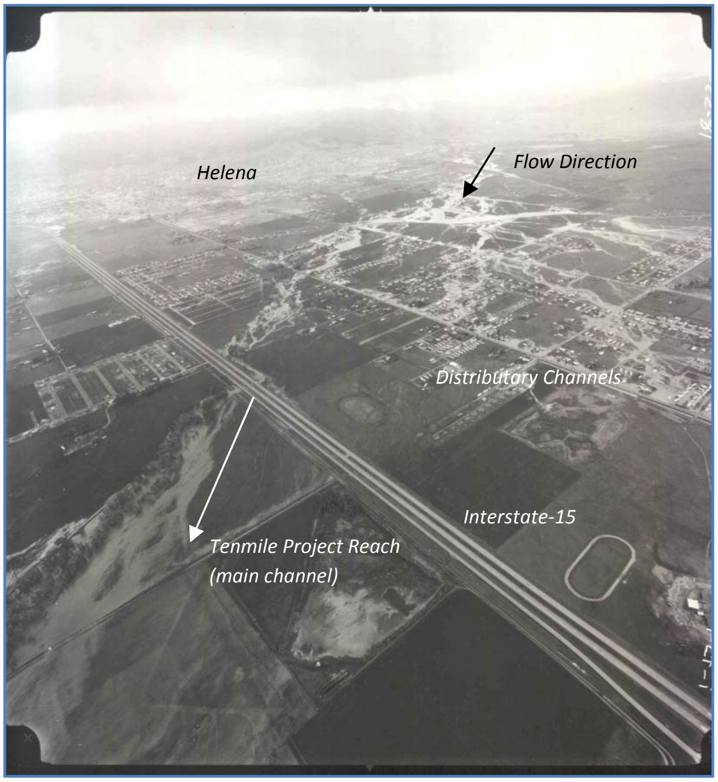

Figure 9. View to southwest towards Helena showing flooding patterns on Tenmile Creek in 1981.

Within the project reach, human influences including channelization, mining, bank armoring, irrigation, and sand and gravel mining have significantly affected the geomorphology of these streams. These impacts are discussed further in Section 3.4.

2.2 Flood History

USGS stream gages are located on Tenmile Creek near Rimini (USGS 6062500), and on Prickly Pear Creek near Clancy (USGS 6061500). These gaging stations are both located above the proposed project area, in the upper portions of the individual watersheds (Figure 10). The annual peak flow records for these two gages show similar historic flooding patterns, with the flood of record in 1981 and the second-largest event in 1975. The 1981 flood event occurred on May 22nd on both streams, and measured 3,290 cfs on Tenmile Creek and 2,300 cfs on Prickly Pear Creek. On both of these creeks, this 1981 flood event exceeded that of a 500-year flood. The 1975 event was between a 50 and 100-year flood on both creeks (http://water.usgs.gov).

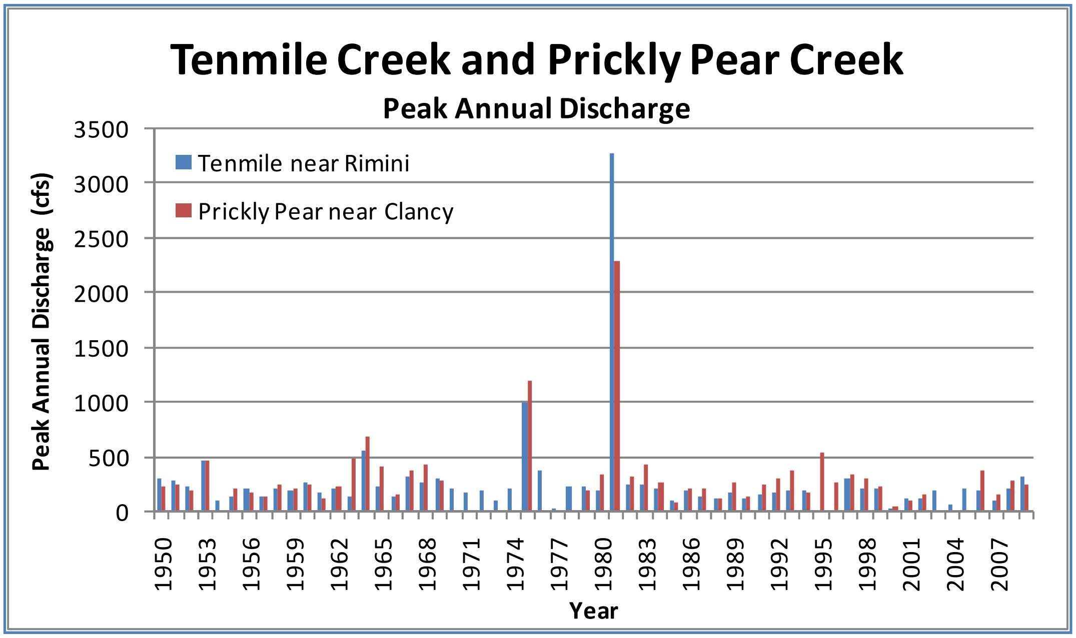

Figure 10. Annual peak discharge, Prickly Pear and Tenmile Creeks.

3 Methods

The methodology applied to the CMZ delineation is adapted from the techniques outlined in Rapp and Abbe (2003) as well as Washington Department of Natural Resources (2004). The Channel Migration Zone (CMZ) developed for Prickly Pear/Tenmile Creeks is defined as a composite area made up of the existing channel, the historic channel since 1955 (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 are identified as "Avulsion Hazard Zones" (AHZ).

The primary methods employed in developing the maps include air photo acquisition and incorporation into a GIS environment, bankline digitization, migration rate measurements, and data analysis. The mapping information and measured rates of channel shift are then utilized to define historic channel locations and apply an erosion buffer to allow for future erosion. Once this Erosion Hazard Area is established, areas beyond the buffer prone to avulsion are mapped in the GIS, using supporting information derived from air photos, Government Land Office (GLO) mapping, and inundation modeling results.

A detailed Accuracy Assessment for the input data sets is included in Appendix D.

3.1 Imagery

Imagery from 1955, 1995/97, and 2008 were used to develop the CMZ maps (Table 1). These suites were selected due to their dates, quality, and overall coverage. This 1955-2008 timeframe includes one extreme flood event (1981), and the 1975 flood which exceeded a 50-year event.

Image Series	Source	Scale	Horizontal Accuracy[1]	Notes
1955	USDA APFO	1:20,000	2.3m (within the river corridor)	7 frames, georeferenced by Lewis & Clark County GIS
1978[2]	USGS EROS	1:25,000	These images were only coarsely georeferenced and no accuracy assessment was performed.	3 frames, georeferenced by Lewis & Clark County GIS department
1995/97	USGS DOQQ Black and White	~1 meter resolution	<2.5m	Digital Download
2008	High Resolution Color	~ 1 foot resolution	<3m	Digital Download

[1]NSSDA Horizontal Accuracy (RMSE) [2]Not quantitatively used for CMZ development

Table 1. Imagery suites used in this study.

The 1955 flight was acquired from the USDA Aerial Photography Field Office (APFO) by Lewis and Clark County GIS and consists of seven black and white frames, providing complete stereographic coverage of the project area at a scale of 1:20,000. These images were georeferenced by Lewis and Clark County GIS using the Georeferencing Toolbar in ESRI ArcGIS. The resulting tiles provide spatially accurate (estimated 2.3 meter accuracy utilizing NSSDA)(FGDC, 1998) coverage of the project area through the core of the Prickly Pear and Tenmile Creek corridors. Areas outside the stream corridors show greatly decreased horizontal accuracy and should not be used for analysis purposes. The seven tiles in this dataset have a degree of overlap at the edges of the images and no precision edge-matching was attempted between adjacent images. As such, care should be taken when viewing the images in the areas of overlap. A recommended image order for display is included as a polygon layer (named 'image_use_1955') in the project database. This imagery pre-dates the construction of the Helena Valley Canal, but does show many of the primary valley drains.

The 1995/97 DOQ black and white and 2008 Color NAIP mosaics were downloaded from the Montana State Library (NRIS) and, according to the metadata, have similar spatial accuracies to the orthorectified 1955 imagery.

The 2008 imagery was procured by the USGS and provides a high-resolution (1 ft) natural-color dataset with which to view modern-day channel morphology.

The 1978 imagery suite was acquired late in the data collection process and was thus not used for analysis purposes other than for assessing the mapped avulsion hazards. This dataset was also georeferenced by Lewis and Clark County GIS using the Georeferencing Toolbar in ESRI ArcGIS. No formal accuracy assessment was performed for this imagery suite.

A series of 1981 flood photos were available for review but were not integrated into the GIS.

3.2 GIS Project

The suites of air photos were compiled within an ArcMap GIS project to provide the basis for CMZ mapping. Other data included in the GIS project include a 10-meter National Elevation Dataset DEM, digitized banklines, migration vectors, roads, stream courses as depicted in the National Hydrography Dataset, scanned General Land Office Survey Maps obtained from Bureau of Land Management, and USGS topographic maps.

The project GIS utilizes the Montana State Plane 1983 HARN spatial reference, in accordance with the Best Practices and Standards defined by the Montana Association of Geographic Information Professionals (www.magip.org, 2009). A list of GIS data layers can be found in Appendix C.

3.3 Banklines

The historic bankline locations are used to both define the cumulative historic footprint of the river, as well as for developing the migration rates for actively migrating bendways.

3.3.1 Bankline Digitizing

Banklines approximating a bankfull water condition were digitized at one of two different scales, depending on the photo resolution. On the two older image sets, a scale of 1:2,000 was used. For the high-resolution 2008 series, a scale of 1:1,500 was more appropriate. Bankfull is defined as the stage above which discharge commences to flow out onto the floodplain. There are many possible ways to delineate bankfull, including morphometric, sedimentary and discharge approaches (Riley, 1972). Despite the advantages offered by these methods, CMZ development requires identification of bankfull for past time periods where the historic ground condition can no longer be measured. Therefore, we typically rely on the extent of the lower limit of perennial, woody vegetation to define channel banks (Mount & Louis, 2005). The bankfull extent reflects those portions of channels that are likely to convey typical spring runoff, thereby preventing the establishment of woody vegetation. In addition, terrace margins and bedrock valley walls are used as boundaries. Fortunately, shrubs, trees, terraces and bedrock generally show distinctive 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. Additionally, the acquisition of modern-day banklines via field-based methods such as surveying or GPS, aside from not being feasible under typical time and budget constraints, would yield results that are not consistent with the accuracy of banklines obtained from historic photographs.

3.3.2 Bankline Digitizing Accuracy Assessment

Bankline digitizing is subject to a certain amount of positioning error associated with the digitizing scale, feature identification, and the horizontal position accuracy of the base imagery. The selected digitizing scales represent a balance between a scale at which channel migration can be reasonably detected and the appropriate scale at which the images should be used. In other words, 'zooming in' beyond these scales was not supported by the resolution of the imagery, and 'zooming out' resulted in an inability to resolve banklines locations. These scales were discovered through experimentation in ArcMap. This scale, along with the quality of the imagery, plays a role in the ability to identify features that represent the bankfull location. To assess these errors, a randomized check on the digitized banklines was performed by zooming in to select areas and evaluating the accuracy of the linework at the maximum practical scale. In all cases, the digitized line fell within approximately three meters of the actual bankline seen on the image. Since this distance is within the reported error of the imagery, this level of accuracy was deemed acceptable.

3.4 Project Reaches

The Prickly Pear Creek study area is 14.8 miles long, extending from Lake Helena to a point approximately 1.5 miles upstream of East Helena. This project reach has been subdivided into 10 reaches based on fundamental aspects of channel form including slope, sinuosity, channel pattern, and human influences (Figure 11; Table 2). The Tenmile Creek project area, which is 3.4 miles long, has been subdivided into three reaches. Air photos of each reach showing locations of measured migration are compiled in Appendix A.

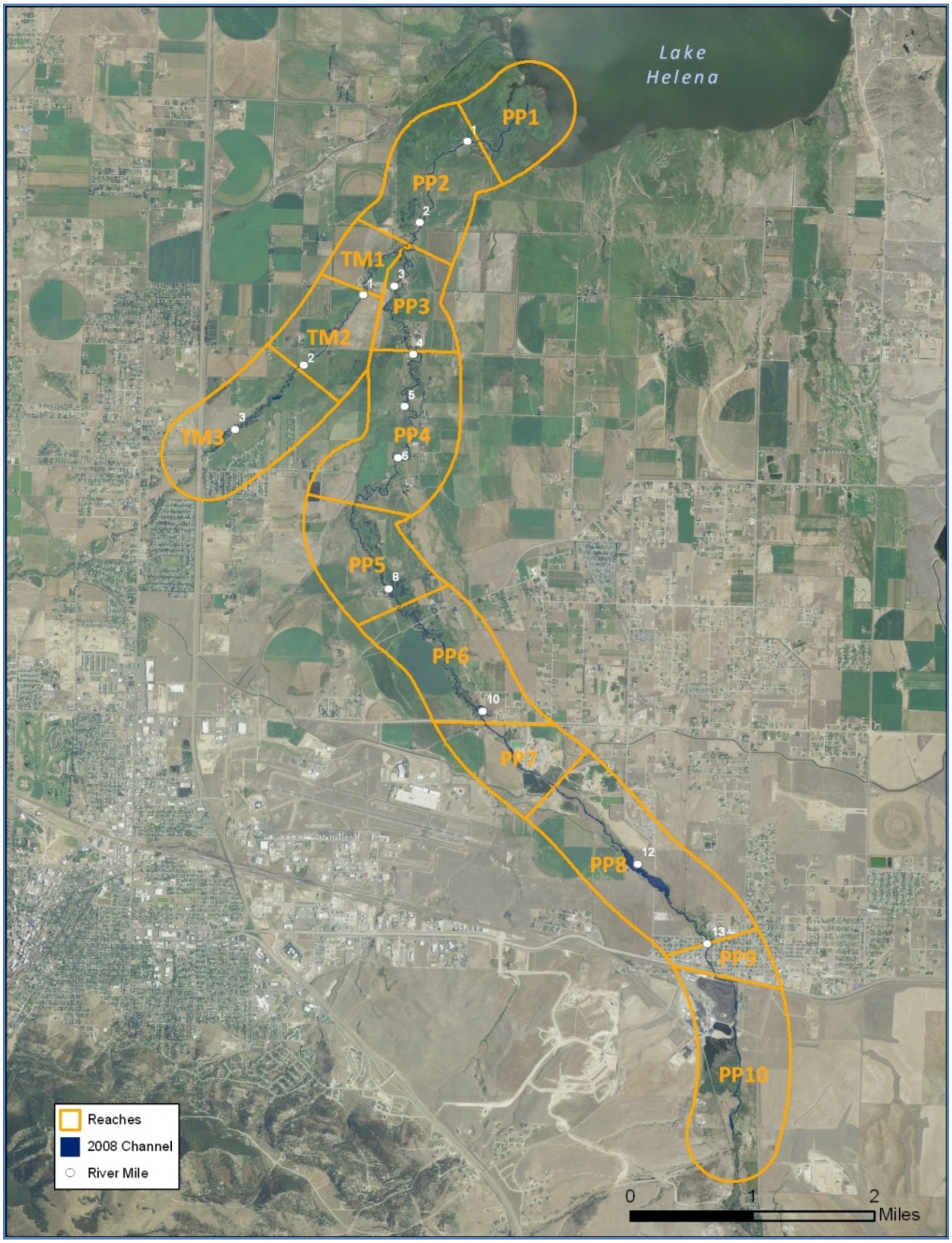

Figure 11. Project reaches, Prickly Pear (PP) and Tenmile (TM) Creeks.

Descriptor	Prickly Pear Creek										Tenmile Creek		
	PP1	PP2	PP3	PP4	PP5	PP6	PP7	PP8	PP9	PP10	TM1	TM2	TM3
River Mile	0-0.9	0.9-2.3	2.3-4.0	4.0-7.0	7.0-8.3	8.3-10.1	10.1-10.9	10.9-13.0	13.0-13.3	13.3-14.8	0-0.95	0.95-2.1	2.1-3.4
Channel Length (miles)	0.9	1.35	1.72	3.03	1.3	1.8	0.83	2.07	0.3	1.5	0.95	1.13	1.32
Valley Distance (miles)	0.7	1.1	0.96	1.4	0.95	1.21	0.77	1.8	0.3	1.41	0.57	0.84	1.06
Sinuosity	1.29	1.23	1.79	2.16	1.37	1.49	1.08	1.15	1.00	1.06	1.67	1.35	1.25
Slope (water surface slope from DEM data)	0.10	0.01	0.20	0.19	0.19	0.32	0.61	0.68	1.00	0.61	0.32	0.30	0.60
Typical Bed Material	Sand/ Gravel	Sand/ Gravel	Sand/ Gravel	Sand/ Gravel	Sand/ Gravel	Sand/ Gravel	Sand/ Gravel	Sand/ Gravel	Sand/ Gravel	Sand/ Gravel	Sand/ Gravel	Sand/ Gravel	Sand/ Gravel
Channel Type (Montgomery/ Buffington, 1993)	Pool-Riffle	Pool-Riffle	Pool-Riffle	Pool-Riffle	Pool-Riffle	Pool-Riffle	Forced Plane Bed	Forced Plane Bed	Forced Plane Bed	Forced Plane Bed	Pool-Riffle	Pool-Riffle	Pool-Riffle

Table 2. Project reach descriptions.

Channel slope and sinuosity were calculated using a channel centerline that is stationed at tenth-mile increments in the GIS. The stationing points were then intersected with Digital Elevation Model (DEM) data to create a channel profile. Prickly Pear Creek shows a fairly concave channel profile, with slope values decreasing in the downstream direction as the channel approaches Lake Helena (Figure 12). As the water surface slope lessens, channel sinuosity generally increases (Figure 13). The highest sinuosity on Prickly Pear Creek is in Reach 4, just upstream from Sierra Road.

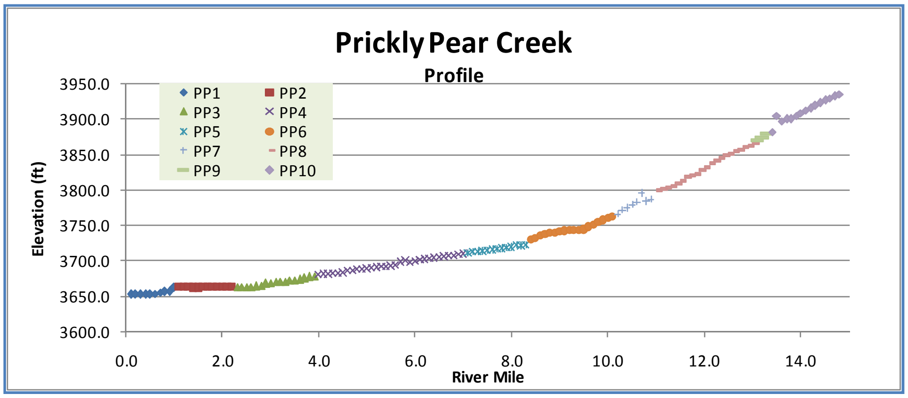

Figure 12. Water surface profile from DEM data, Prickly Pear Creek.

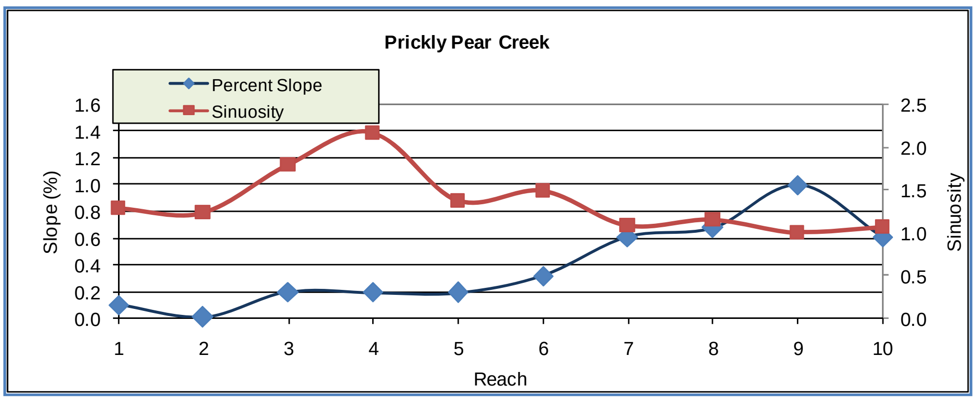

Figure 13. Channel sinuosity and slope, Prickly Pear Creek project reaches.

On Tenmile Creek, slope is more consistent through the project reach relative to Tenmile Creek (Figure 14). Sinuosity increases slightly in the downstream direction between I-15 and the confluence with Prickly Pear Creek (Figure 15).

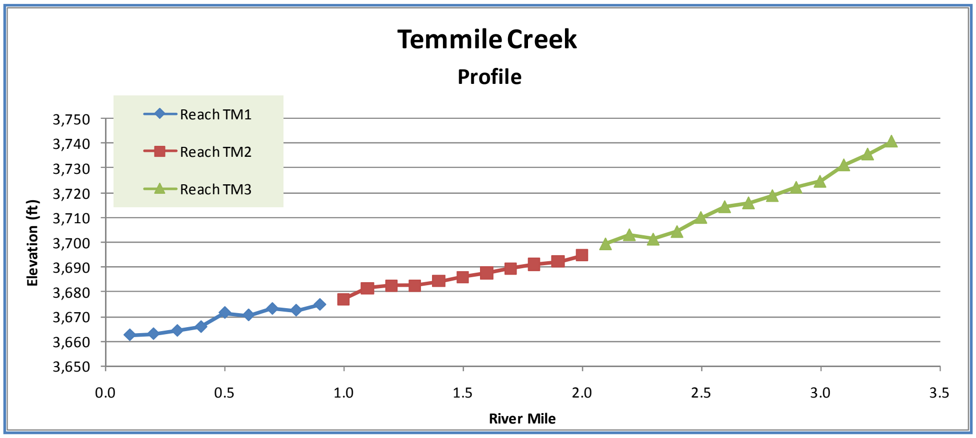

Figure 14. Water surface profile from DEM data, Tenmile Creek.

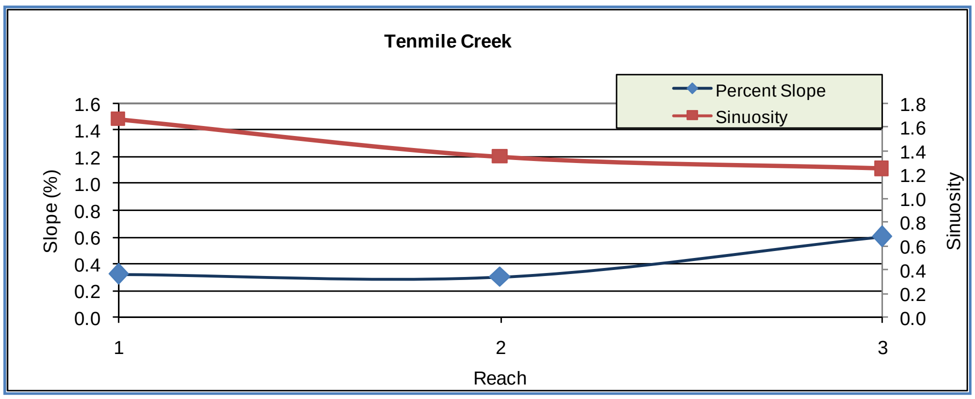

Figure 15. Channel sinuosity and slope, Tenmile Creek project reaches.

3.4.1 Reach PP1

Reach PP1 consists of the lowermost 0.9 miles of Prickly Pear Creek (Appendix A). This reach reflects the deltaic portion of Prickly Pear Creek where it enters Lake Helena. Since 1955, Prickly Pear Creek has lengthened several hundred feet through the delta area due to sediment deposition. This reach is a pool-riffle channel type. The floodplain is largely undeveloped in this reach.

3.4.2 Reach PP2

Reach PP2 extends from the upper end of the Prickly Pear delta to the Tenmile Creek confluence (Appendix A). This channel segment is characterized by moderate sinuosity, and active channel migration. Reach PP2 has a very low gradient, with a slope of 0.01% (0.5 ft/mile). Land uses in Reach PP2 are largely agricultural, and the woody riparian corridor is limited to sparse cover on the northern side of the creek.

3.4.3 Reach PP3

Reach PP3 extends from the Tenmile Confluence up to Sierra Road (Appendix A). Within this reach, the creek is sinuous and laterally dynamic. The channel is characterized by locally high eroding banks and an inset floodplain surface which suggests that the reach has incised (Figure 16). The willow corridor is locally dense, and observed bank materials are fine grained silts and sands.

Figure 16. View downstream of left bank erosion on Prickly Pear Creek, Reach PP3 (RM 3.0).

3.4.4 Reach PP4

Reach PP4 extends from Sierra Road upstream to an old dike/embankment at River Mile 7.0, just upstream of the confluence of the City of Helena wastewater treatment effluent ditch with Prickly Pear Creek. Within this reach, Prickly Pear Creek has a sinuosity (channel length to valley length ratio) of 2.16. The reach is incised, and has developed an inset floodplain surface, primarily on meander cores. Restoration activities in Reach 4 (Figure 17) have included bank lowering and inset floodplain development. The D3 drain enters Prickly Pear Creek in Reach 4 at approximately RM 4.9.

Figure 17. View downstream in Reach PP4 showing recently completed restoration project to reduce bank height and create an inset floodplain surface (RM 5.2).

3.4.5 Reach PP5

Reach 5 is approximately 1.3 miles long, extending from RM 7.0 to RM 8.3, which is just downstream from York Road (Appendix A). This reach has a moderate sinuosity and slope. Reach 5 marks a notable reduction in channel slope relative to upstream reaches, and migration rates are relatively high. Observed bank erosion includes undercutting of fine grained banks and subsequent topple failure of the upper bank (Figure 18). At approximately RM 7.4, Prickly Pear has breached a dike that separates the stream from a constructed lake/wetland complex on the right floodplain (Figure 19).

Figure 18. View downstream on Prickly Pear Creek of bank undercutting and topple failure, Reach PP5 (RM 7.8).

Figure 19. View downstream on Prickly Pear Creek showing right bank migration through constructed dike, Reach PP5 (RM 7.4).

3.4.6 Reach PP6

Reach PP6 extends from just below York Road upstream to Canyon Ferry Road. Within this reach, Prickly Pear Creek flows through a transition from the relatively steep primary fan area, to the lower slope distal fan area downstream. Field observations of coarse sediment deposition and severe bank erosion suggest that this reach is aggradational due to a reduction in sediment transport capacities on the fan surface relative to upstream. Coarse gravels and cobbles are commonly exposed in the lower banks of Reach PP6 (Figure 20).

Figure 20. Right bank erosion in Reach PP6 showing undercutting on gravel bank toe (RM 9.1).

3.4.7 Reach PP7

Reach PP7 extends from York Road upstream to the Helena Valley Canal siphon. Within this reach, Prickly Pear Creek has been channelized and encroached upon by a series of dikes that protect active and inactive gravel pits. Although the reach is channelized and diked (Figure 21), some bank migration was measured where point bars have formed, and old dike features have been flanked. This reach has been classified as a Forced Plane Bed channel type, indicating that the diking and channel straightening has converted the channel from a natural pool/riffle channel to a straight trapezoidal channel with little bedform diversity.

Figure 21. View upstream of channelized segment between the gravel pits (left) and abandoned gravel pit lake (right), Reach PP7 (RM 10.7).

3.4.8 Reach PP8

Reach 8 extends from East Helena downstream to the Helena Canal Siphon. This reach is relatively coarse grained, and has numerous functional and decrepit irrigation structures (Figure 22). Bed material reaches coarse cobble in size, and the primary geomorphic unit is a trapezoidal run. Due to the confinement associated with the irrigation structures in the reach, the reach has been classified as a Forced Plane Bed channel type, although some channel segments locally exhibit a pool/riffle morphology.

Figure 22. View downstream at the start of Reach PP8 showing coarse bed material, woody debris, and concrete structure (RM 12.9).

3.4.9 Reach PP9

Reach PP9 is the most urbanized segment of Prickly Pear Creek, consisting of a 0.3 mile long segment of urbanized channel through East Helena. This channel is primarily lined with concrete and no measureable migration occurred in this reach during the 1955-2008 timeframe.

3.4.10 Reach PP10

Reach PP10 is the upstream-most portion of the project reach, extending 1.5 miles upstream from East Helena. Within this reach, Prickly Pear Creek has been channelized as it flows along settling ponds and the ASARCO tailings. Portions of the reach were channelized prior to 1955. Migration was measured at several locations below the ponds, adjacent to the tailings.

3.4.11 Reach TM1

The lowermost 0.95 miles of Tenmile Creek are moderately sinuous, and entrenched with high banks and active bank erosion. Bank materials are fine grained and horizontally bedded suggesting deposition in a slackwater environment (Figure 23).

Figure 23. View downstream of Reach TM1, Tenmile Creek (RM 0.9).

3.4.12 Reach TM2

Reach TM2 is 1.13 miles long, and consists of an entrenched channel cross section that shows active bar development and inset floodplain development (Figure 24). Lateral migration was measureable at numerous sites in this reach.

Figure 24. View downstream showing natural inset floodplain development on meander cores, Reach TM2.

3.4.13 Reach TM3

Reach TM3 extends from River Mile 2.1 upstream to the Interstate 15 bridge at River Mile 3.4. The riparian corridor within this reach is relatively dense, and bed material consists of gravel to cobble sized material (Figure 25). The Tenmile Creek study area ends at the I-15 Frontage Road bridge. Of note in reach TM3 is a long moderate avulsion hazard running northeasterly, connecting with Prickly Pear Creek approximately 1.5 miles upstream of the current Tenmile/Prickly Pear confluence.

Figure 25. View downstream from I-15 Frontage Road bridge at the upper end of Reach TM3 and Tenmile Creek Project Area (RM 3.4).

3.5 Migration Rate Measurements

Migration rates are calculated by measuring the displacement of actively migrating bankline locations across the available period of record.

3.5.1 Migration Rate Vectors

Within the GIS, the digitized banklines were evaluated in terms of discernable channel shift between 1955 and 2008. Where migration was identifiable, vectors were drawn in the GIS to record that change. At each site of bankline migration, three measurements were collected, one in the core of the site and one on either side of the core at approximately equal spacing (Figure 26). These vectors represent the 53-year movement of a bankline for the site. The vectors are attributed with reach, eroding site identification, and line length. These measurements were then summarized by site and by reach to determine appropriate reach-specific buffer widths to accommodate future shifts in channel location.

Figure 26. Migration rate measurement vectors, Prickly Pear Creek (RM 8.0-8.6).

3.5.2 Migration Rate Vectors Accuracy Assessment

Digitizing migration vectors is subject to the same types of errors as the banklines, since both depend on interpretation of the imagery. To help mitigate this, vectors were not analyzed unless the observed migration distance was more than roughly 10 meters (32.8 feet), a value that exceeds the cumulative error of ±9 meters (29.5 feet) associated with the entire project (see Appendix D). There are banks in the study area that have moved less than this value, and, as such, these areas are not represented in the migration rate calculations. The vectors were drawn at the same scale as the banklines for each respective image series (see Section 3.1). Consequently, the amount of error in the migration vectors should not exceed 3 meters. This value was verified with a randomized check on the vectors. After the project GIS technician digitized the banklines, the vectors were drawn by the geomorphologist. This 'second look' at the banklines provided an additional level of quality assurance, and if any obvious bankline errors were discovered they were fixed prior to vector digitizing. Once digitizing was finished, the migration vector lengths were averaged by site, and then by reach, a step that helps further mitigate the feature identification errors resulting from photo misinterpretation.

3.6 Bank Armor Extents

By design, bank armor restricts the natural movement of a channel. In order to map those areas where migration is restricted ("Restricted Migration Area", or RMA), a bank armor inventory is required. There is no current data set that details these physical features for the project area. The 310 Permit Database is currently under development for Lewis and Clark County, but does not provide a complete dataset. A complete inventory and functional assessment of these floodplain features is beyond the scope of this work.

3.7 Inundation Modeling

Inundation modeling is a static model of inundation potential based upon Digital Elevation Model (DEM) data. The general technique involves creating a modeled water surface based on cross section elevations extracted from the DEM. This model surface is then intersected with the DEM to create a surface representing the deviation between the two surfaces, representing inundation depth. This is often used to approximate flood prone areas (e.g. areas where the flood surface elevations at a given stage are higher than the underlying DEM ground surface elevations are identified as flood-prone), but it also is a useful tool for identifying areas prone to avulsion (Figure 27). Areas of low elevation such as swales that may be reactivated through avulsion are highlighted in the resulting model. While anomalies in the DEM data, local structures, and the highly variable terrain complicate the model outputs, compelling results can still be developed.

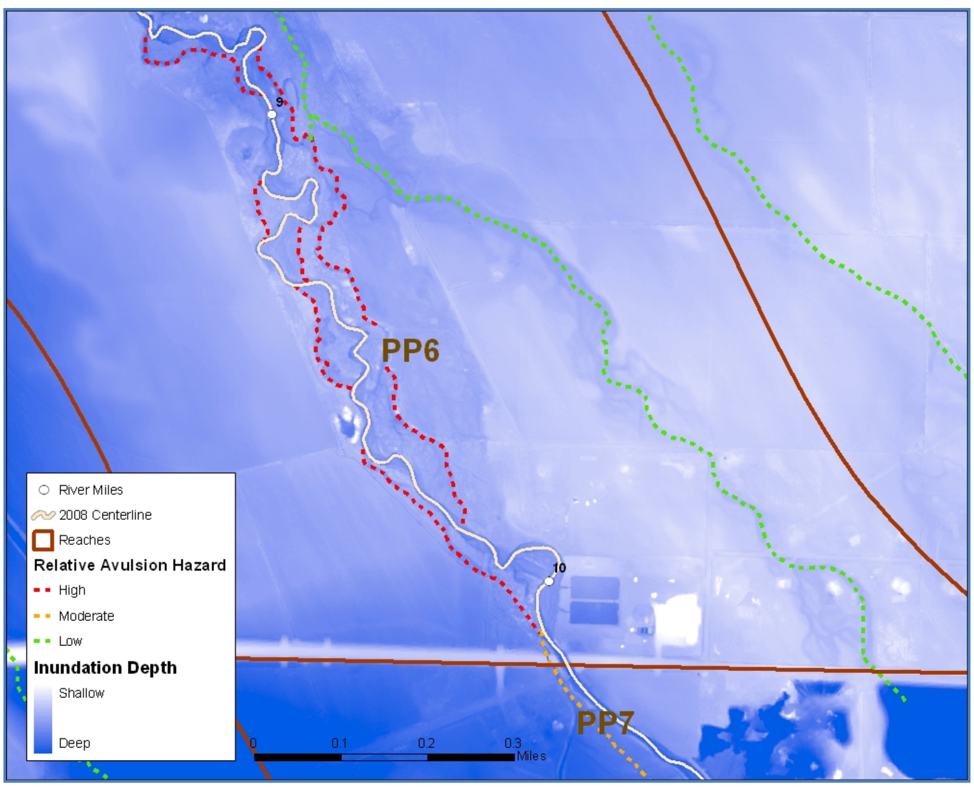

Figure 27. Inundation modeling results showing mapped avulsion pathways downstream of Canyon Ferry Road (RM 10.0).

For this study, 10 cross sections were defined along the study area. These were then intersected with the Digital Elevation Model and the minimum elevation of each cross section where it crossed the creek was used to represent the model surface at each cross section. The cross sections were then connected to create a series of inclined surfaces that represent the modeled water surface elevation. The results were used to help trace floodplain features that create potential avulsion pathways.

3.8 Avulsion Hazards

Avulsion pathways were mapped using geologic mapping, LiDAR data, inundation modeling results, and air photos. The 1981 flood photography was used to identify areas conveying flow during that event. Pathways were mapped as continuous floodplain channels, as well as bendways in the migration corridor that are prone to cutoff over the next century.

3.9 Application of Methodology to Small Streams

As the mapping methodology described above relies heavily on air photo analysis, it can only be performed in areas where the resolution of the air photos or the site conditions supports such analysis. This creates challenges on any stream were air photo resolution is poor and/or rates of movement are small. These challenges become more pronounced on small streams where migration rates tend to be relatively low, and where banklines can be completely obscured by dense vegetation. Prickly Pear Creek and Tenmile Creek, which are on the order of 30 feet wide, were the two smallest streams on which this project team has applied the CMZ mapping methodology to date.

The challenges associated with mapping relatively small channels with this methodology were recognized early in the mapping process, so the applicability issue was continually addressed throughout the project. The most difficult area to work in was the densely vegetated upper portions of Tenmile Creek, where long lengths of bankline were obscured by woody canopy cover. In these areas, the LiDAR data were invaluable in defining modern channel/floodplain boundaries. In other areas, reasonable resolution on the air photos coupled with patchy or low density vegetation allowed effective air photo analysis. Ultimately the key parameter in measuring change on these small streams was that the rates of movement that occurred between 1955 and 2008 were significant enough as to be measureable. A minimum measurement of approximately 1 channel width (30 feet) was adopted for this project, which is supported by the Accuracy Assessment in Appendix D. Using this minimum mapping unit, a total of 528 measurements were collected. If migration rates on these streams had been substantially lower, fewer measurements would have been collected, and less statistical representation would have been generated as a result. We would therefore recommend that if streams any smaller than Prickly Pear and Tenmile Creek are considered for future analysis, that only those with significant movement and high quality base data be pursued.

4 Results

The channel migration zone (CMZ) developed for the study area is defined as a composite area made up of the existing channel, the historic channel since 1955 (Historic Migration Zone, or HMZ), and an Erosion Buffer that encompasses areas prone to channel erosion over the next 100 years (Erosion Hazard Area, or EHA). Areas beyond the Erosion Buffer that pose risks of channel avulsion are identified as Avulsion Hazard Zones (AHZ).

4.1 The Historic Migration Zone (HMZ)

The HMZ for the study area consists of the collective footprint created by the 1955, 1995/97, and 2008 bankfull channel polygons (Figure 28). All islands are included within the HMZ. Any future integration of additional intermediate air photo suites (e.g. 1978) may alter the footprint of the HMZ; however, it is most likely that these changes will be entirely masked by the overlying EHA (Section 4.2).

Figure 28. A section of Prickly Pear Creek and Tenmile Creek showing the Historic Migration Zone (HMZ), a composite of 1955, 1995/97, and 2008 channel locations.

4.2 The Erosion Hazard Area (EHA)

The Erosion Hazard Area consists of an erosion buffer that allows for 100-years of future erosion based on average historic movement measured using the 1955 and 2008 banklines. This buffer is placed on the outside (landward) margins of the 2008 banklines. On a reach-scale analysis such as this, a single buffer is used for each reach, and the buffer underlies the HMZ layer. Because of this overlapping, the EHA buffer can be masked out by the HMZ where the historic footprint of the channel is relatively wide.

The general approach to determining the Erosion Buffer (100 times the mean annual migration rate) is similar to that used 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).

Bank movement was measured in the GIS directly using the digitized 1955 and 2008 banklines. At each erosion site, three linear measurements were collected to characterize channel movement. Maps of erosion site locations are shown in Appendix A, and migration measurements at each of these sites are tabulated in Appendix B. Within the study area, only those sites with a maximum channel movement in excess of 30 feet were used in the analysis. Of the 194 sites, 176 were identified for analysis, and at each site, three linear measurements were made, for a total of 528 migration measurements (393 on Prickly Pear Creek and 135 on Tenmile Creek).

Although the statistic utilized in developing the Erosion Hazard Area is the reach-scale mean migration rate, it is also instructive to consider the distribution of measured values relative to the mean. To that end, a series of statistics have been developed for each reach- scale suite of migration rate measurements. These statistics for each data series are presented in graphical form as a box and whisker plots which reflects the following statistics for each dataset: minimum, 25th percentile, mean, 75th percentile, and maximum (Figure 29). Additionally, the 90th percentile value has been added to help identify the range of the most extreme (top 10%) of rate measurements. The box can be used to visually assess the concentration of data about the mean (50% of all measurements are within the box).

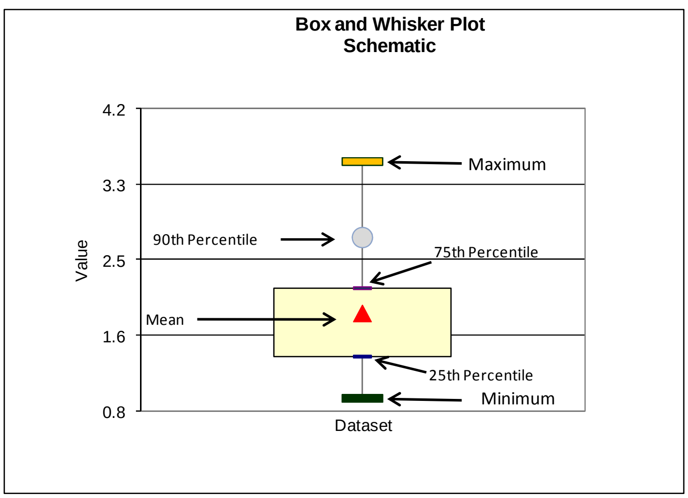

Figure 29. Box and whisker plot schematic.

A box and whisker plot of measured migration distances for Prickly Pear Creek shows that 1955-2008 site averages range from a low of 26 feet, to a maximum of 170 feet in Reach 6 (Figure 30 and Table 3). The mean values calculated for each site range from 39 feet in Reach PP1 to 66 feet in Reach PP6. In order to convert these mean 1955-2008 migration distance values to a 100-year EHA, the migration distances were converted to rates (ft/yr), and that value was then multiplied by 100. These EHA values, which are also plotted on Figure 30, range from 74 feet in Reach PP1 to 123 feet in Reach PP6.

The EHA values reflect anticipated lateral migration distances over the next 100 years on Prickly Pear Creek based on average historic rates of change. Since the average historic value is utilized, areas that migrated especially rapidly between 1955 and 2008 may not be captured by the EHA. This is depicted on Figure 30 as the EHA value (green circles) are less than the maximum measurement in Reaches PP2, PP3, and PP6. This adoption of an EHA value that does not accommodate statistical outliers recognizes that, in an effort to characterize typical rates of change, areas of exceptionally rapid change may not be fully captured by the EHA. As such, it is important to recognize that over the next century, a few sites will likely migrate completely through the EHA and Channel Migration Zone boundary.

The calculated mean 1955-2008 migration distances on Tenmile Creek range from 48 to 51 feet, indicating that the average rate of movement in all three reaches is quite similar (Figure 31 and Table 4). However, Reaches TM2 and TM3 have high maximum measurements that exceed the EHA value, in a fashion similar to Prickly Pear Creek Reaches PP2, PP3, and PP6.

The relationship between maximum migration measurements and mean-based EHA values is discussed further in 4.2.1.

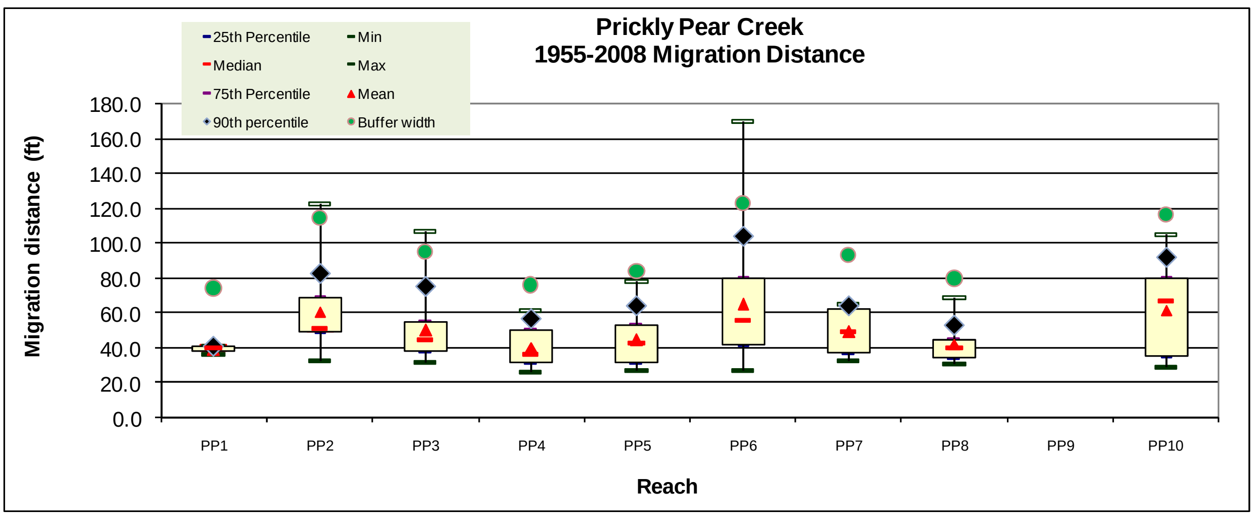

Figure 30. Box and whisker plots showing statistical summary of migration measurements, Prickly Pear Creek.

Statistic	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5	Reach 6	Reach 7	Reach 8	Reach 9	Reach 10
25th Percentile	38.5	49.2	38.3	31.6	32.0	42.2	36.8	34.8	*	35.1
Min	36.2	32.1	31.2	25.9	27.0	26.7	32.5	30.7	*	28.7
Median	39.8	51.4	44.2	36.5	42.9	55.5	49.4	40.2	*	67.0
Max	40.8	122.4	106.6	61.3	77.5	169.8	64.9	68.3	*	105.0
75th Percentile	40.4	68.8	54.7	49.7	53.4	79.6	61.7	44.2	*	80.0
N	4	9	25	29	15	24	4	12	*	9
90th Percentile	40.7	82.8	75.5	56.3	64.5	104.0	63.7	53.3	*	91.8
Mean	39.2	60.6	50.1	40.2	44.5	65.0	49.1	42.1	*	61.7
Mean Migration Distance: 100 year timeframe (feet)	74	114	95	76	84	123	93	80	*	116

**Reach 9 of Prickly Pear Creek is mostly constrained by concrete and no measurements were made.*

Table 3. Migration distance statistics, Prickly Pear Creek.

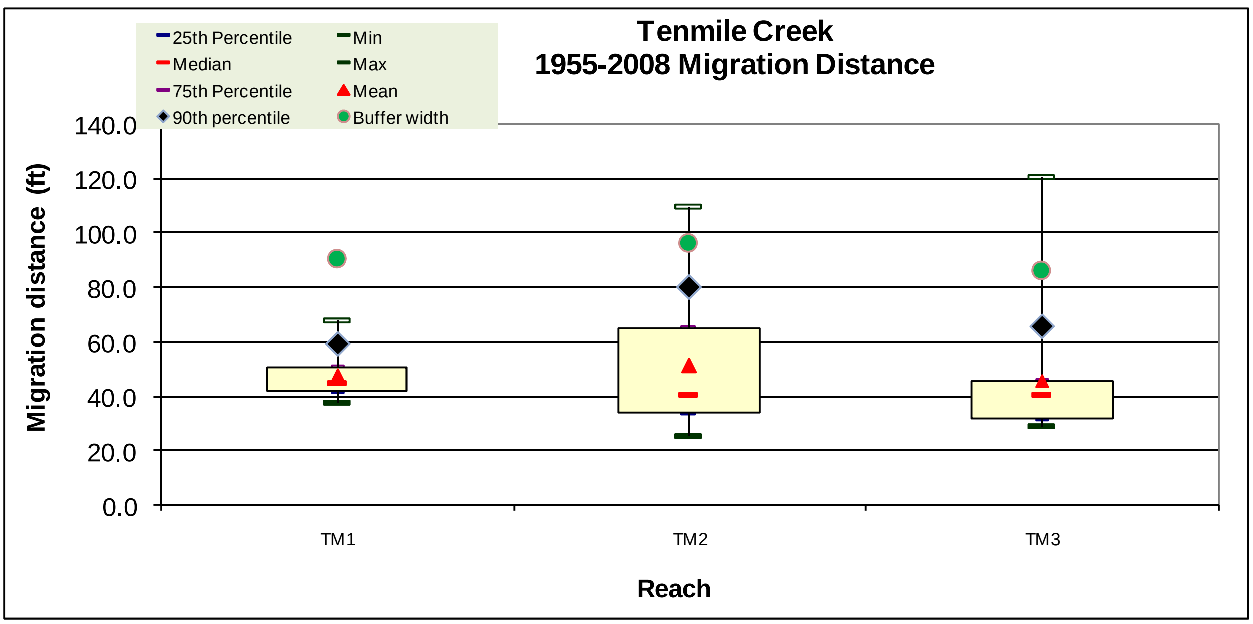

Figure 31. Box and whisker plots showing statistical summary of migration measurements, Tenmile Creek.

Statistic	*Reach 1*	*Reach 2*	*Reach 3*
25th Percentile	41.9	34.0	31.5
Min	37.9	25.5	29.0
Median	44.8	40.2	40.5
Max	67.9	109.6	120.5
75th Percentile	50.5	64.7	45.5
N	12	15	18
90th Percentile	59.2	80.1	65.4
Mean	47.9	50.9	45.7
Mean Migration Distance: 100 year timeframe (feet)	90	96	86

Table 4. Migration distance statistics, Tenmile Creek.

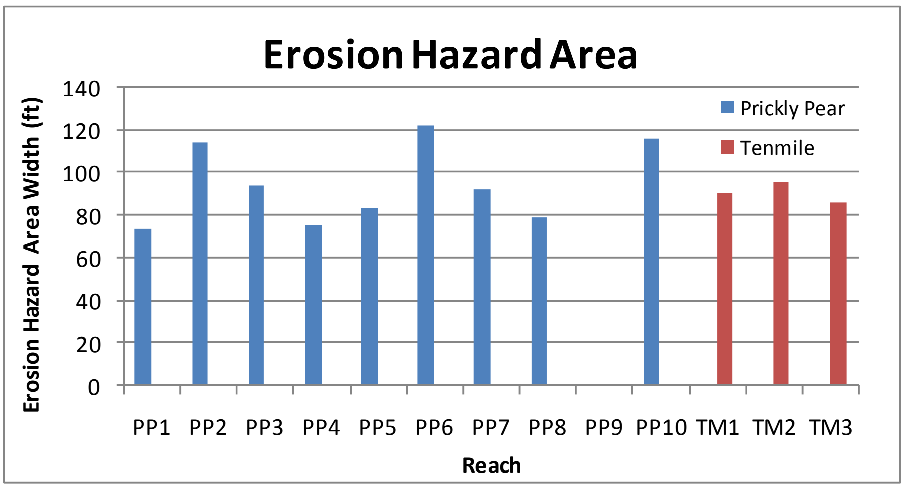

Figure 32. Erosion Hazard Area (EHA) buffers, Prickly Pear and Tenmile Creeks.

4.2.1 Outliers

A comparison of the proposed buffer widths to the maximum migration measured in each reach demonstrates a critical aspect of CMZ mapping. For the Prickly Pear/Tenmile Creek study area, the application of a mean migration rate to develop a 100-year buffer accommodates most, but not all, of the 1955-2008 movement. The plot demonstrates that the proposed buffer (green circles) exceed the 90th percentile values of the measurements in every reach, indicating that over 90% of the sites measured are accommodated by the mean-derived buffer. This is not the case with maximum values. In Reaches PP2, PP3, PP6, TM2, and TM3, the maximum migration distance experienced from 1955 to 2008 exceeds the proposed 100-year buffer width. This result is common on dynamic streams where a few sites experience extremely rapid erosion, and thus become statistical outliers. In a practical sense, it indicates that a small number of sites are likely to exceed the buffer width on a 100-year timeframe. Of the 176 erosion sites, a total of eight sites, or 4.5%, would have exceeded the buffer distance between 1955 and 2008 (Figure 33).

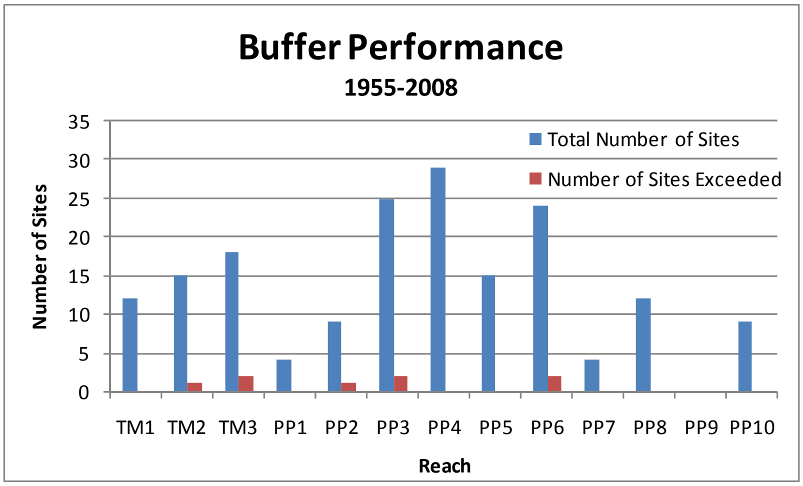

Figure 33. Number of sites where EHA buffer would have been exceeded by 1955-2008 migration.

4.2.2 Geologic Controls on Migration Rate

Through the vast majority of the project area, the streams flow through recent alluvial deposits that become finer grained in the downstream direction. The reach boundaries address these shifting downstream trends in sediment load and bank materials. In a few locations, however, the channels are eroding into low terrace deposits, such as in the lower reaches of Prickly Pear Creek. The average rates of bank erosion into the terrace margins may be different than those of the younger alluvium due to higher rates of sediment loading from the terraces (higher banks) or the presence of more erosion-resistant materials (clast size or cementation). Although this potential difference in rates is recognized, limited resources precluded the mapping and characterization of the terraces for this project. Although limited field observations indicated no major difference in geotechnical characteristics of the units, those observations are not supported by any detailed or quantitative analysis.

4.3 The Avulsion Hazard Zone (AHZ)

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. Our approach to defining avulsion pathways is to develop criteria that identify a relatively high propensity for such an event. These criteria include bendway cores that are prone to cutoff, as well as relic floodplain channels that concentrate flow during floods. Flood photos, LiDAR data, and inundation modeling results were used to help identify floodplain channels (Figure 34 through Figure 36).

Three different types of avulsion hazards have been mapped and are identified separately on the accompanying maps (Figure 37).

1. ***High Hazard***: Areas within the 100-year floodplain prone to meander cutoff.
2. ***Moderate Hazard***: Floodplain swales within the 100-year floodplain that show continuous flow paths and intersect the modern channel.

3. ***Low Hazard***: Continuous swales that are located out of the 100-year floodplain, but discernable as distributary channels on the alluvial fan.

Figure 34. 1981 flood image showing flow spreading through and downstream of East Helena.

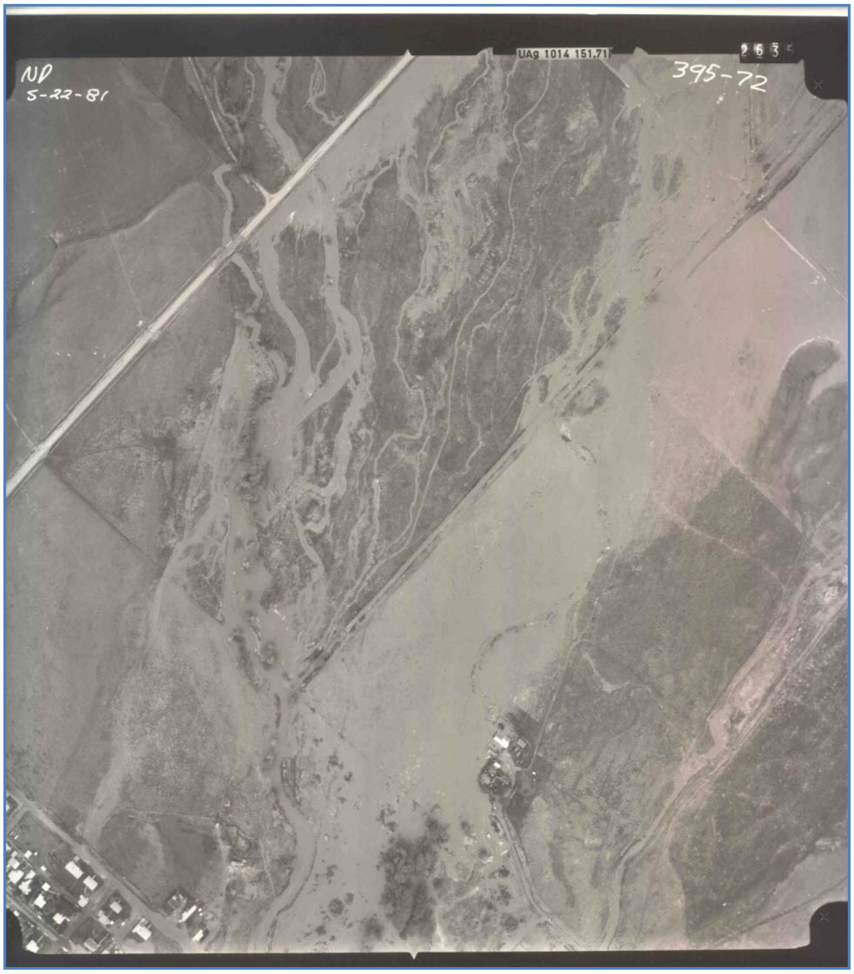

Figure 35. 1981 flood photo of Prickly Pear Creek just north of East Helena showing floodplain channel activation.

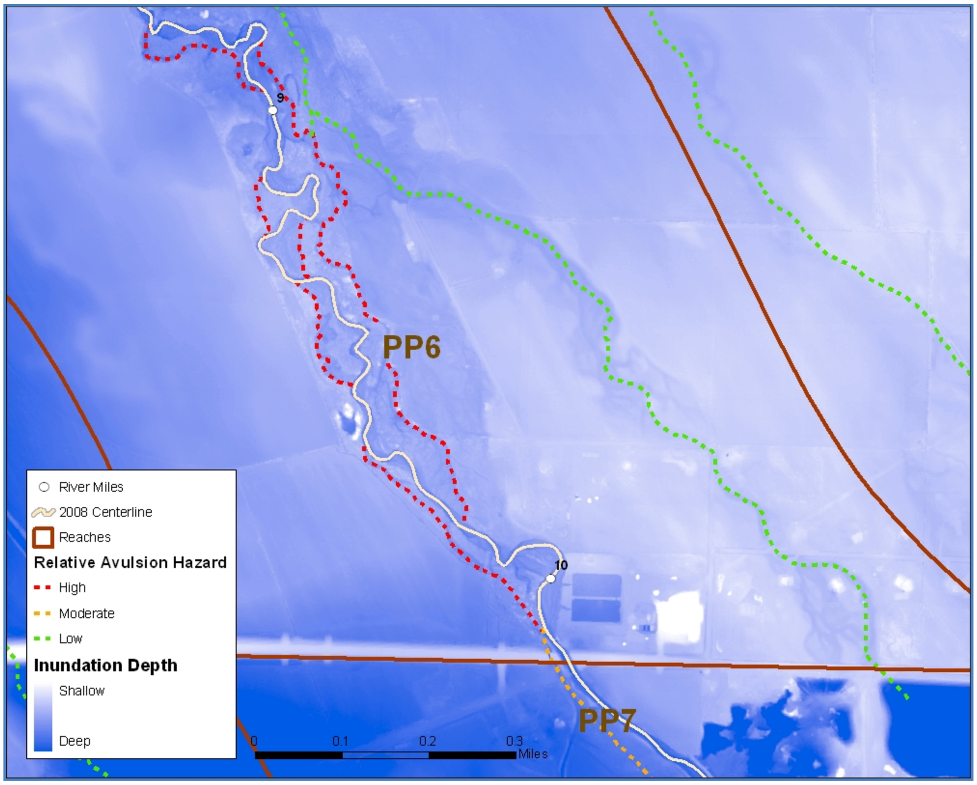

Figure 36. Inundation modeling results showing mapped avulsion pathways downstream of Canyon Ferry Road.

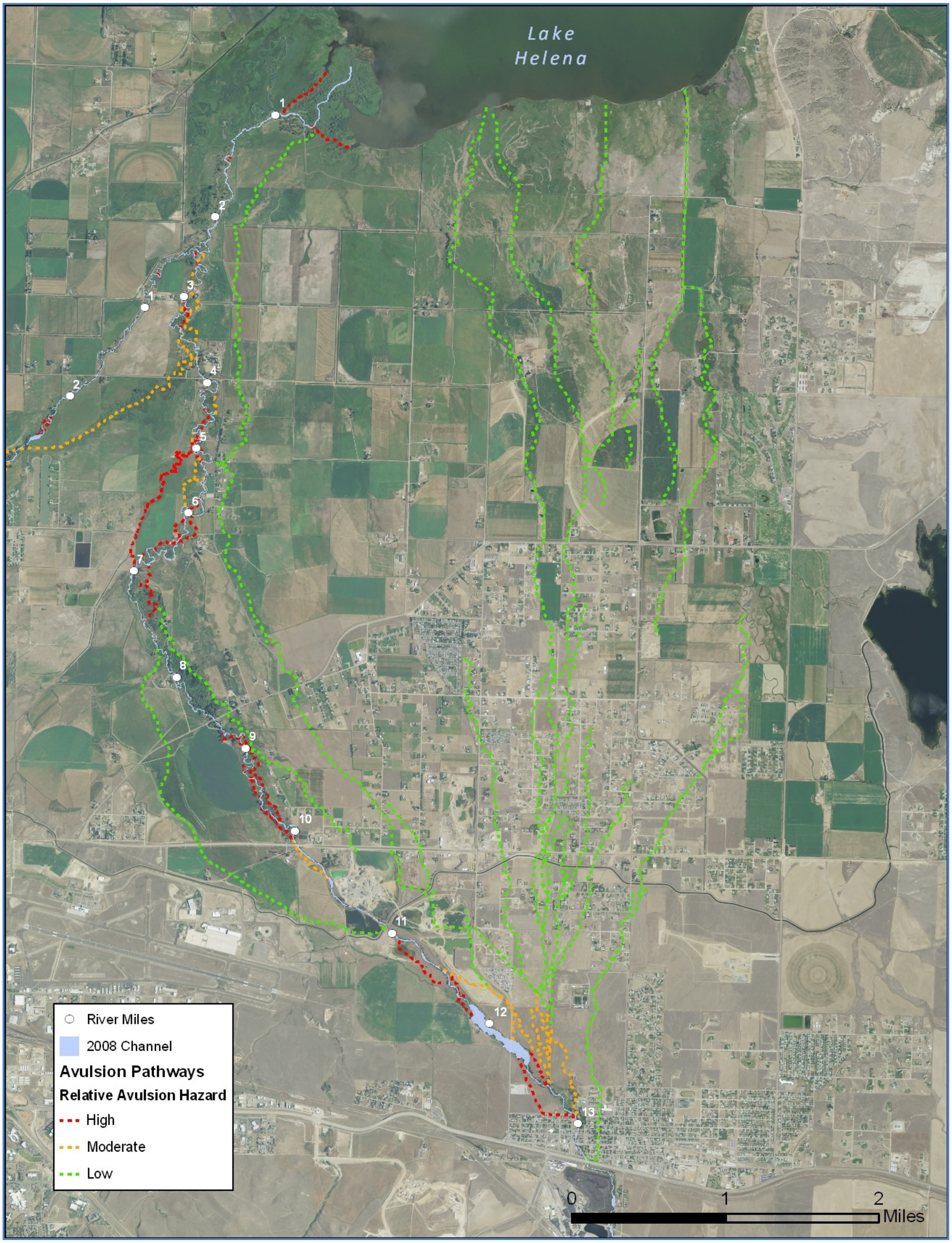

Figure 37. Mapped avulsion pathways, Prickly Pear Creek and Tenmile Creek.

4.4 The Restricted Migration Area (RMA)

The bank armor inventory for the project reach is currently incomplete. Since data are not available to consistently identify CMZ areas restricted by bank armor, this map unit has not been developed. As more detailed information becomes available, these areas can be identified on the maps and highlighted as restricted.

4.5 Composite Map

A portion of the composite CMZ map within the study area is shown in Figure 38. The final CMZ boundary includes the Historic Migration Zone (HMZ), Erosion Hazard Area (EHA), and areas of High Avulsion Hazards (AHZ). Avulsion hazards considered of moderate risk are not included within the CMZ boundaries.

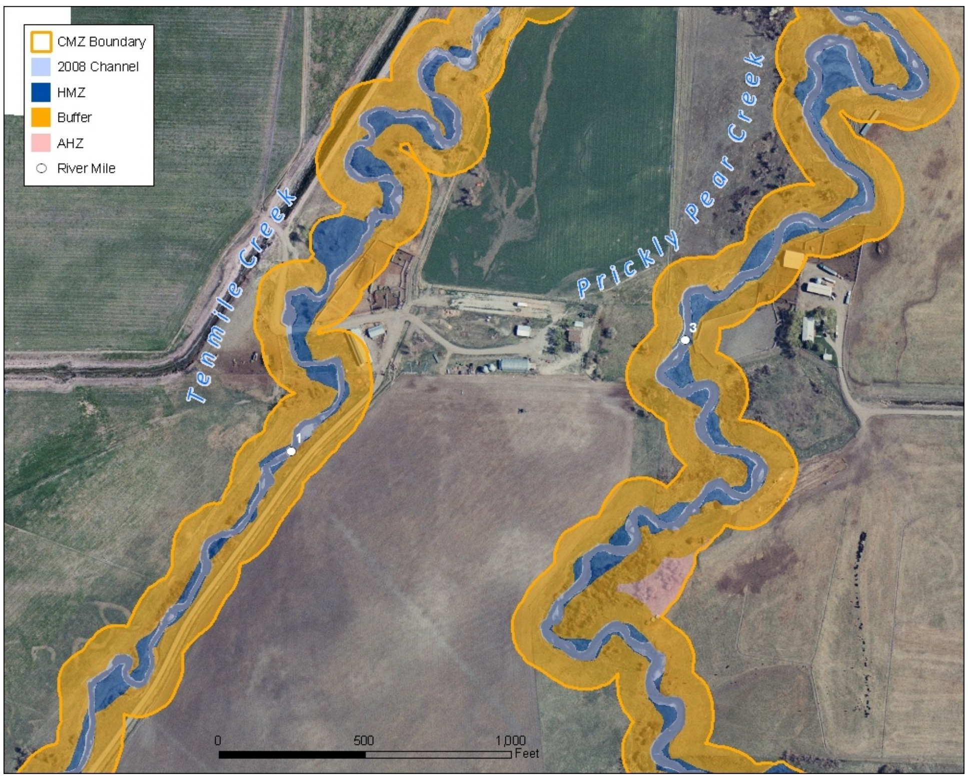

Figure 38. Composite Channel Migration Zone near the confluence of Prickly Pear Creek and Tenmile Creek shown on 2008 imagery.

4.6 Deliverables

In addition to this report, CMZ mapping products for this effort consist of GIS data and a map that delineates the Channel Migration Zone for the Prickly Pear Creek and Tenmile Creek study area. All new project data are supplied on DVD in an ESRI Personal Geodatabase, along with a PDF version of the project map and this report. Each Feature Class is accompanied by appropriate FGDC compliant metadata. All data utilize the Montana State Plane 1983 HARN meters spatial reference. A list of GIS data layers can be found in Appendix B.

5 Recommendations

The limited resources available for this project precluded the completion of a comprehensive geomorphic analysis and integration of those results into the CMZ assessment. The following section describes recommended future steps towards developing a more thorough understanding of the geomorphic behavior of Prickly Pear and Tenmile Creeks.

5.1 Individual Site Assessment using Existing Information

Because the widths of the erosion buffers are based on the average migration rate for an entire reach, the boundaries themselves do not reflect detailed, site-specific migration predictions. At a single location, migration rates will vary with time due to changes in channel planform, flow conditions, materials exposure, land use, and riparian conditions. Predicting these conditions at every eroding bank over the next century and developing site-specific rates that will accommodate those conditions is beyond the scope of this project. However, the GIS project that accompanies this report contains data generated in this effort that can assist managers in making decisions regarding the appropriateness of bank armor in a given location. With the GIS, the user can focus on an individual area and assess historic land use, planform change, and migration rates. This can be achieved using the air photos in the project to assess overall site change. Migration vectors in the project are attributed with the 1955-2008 migration distance. With this information in hand, a better understanding of individual site conditions can support 310 permit decisions.

Maps of all erosion sites and the corresponding migration measurements are included in Appendix A and Appendix B.

5.2 Additional Analysis to Support Individual Site Assessment

Individual factors that influence migration rates on the Prickly Pear Creek and Tenmile Creek are not identified in this mapping effort. Migration rates naturally vary in any river system due to influences of materials, riparian condition, hydrology, land use, etc. In order to develop a more rigorous analysis of migration rates, it would be appropriate to further attribute the migration vectors in terms of site conditions, and then a statistical analysis of those results may shed light on rate influences. This effort would require segmenting the vectors into time steps based on the suites of photography, and then attributing each time step with parameters such as geology, land use, riparian density, and hydrologic history. If the results stratify sufficiently, it would be appropriate to map these features in the valley bottom and adjust migration rate projections accordingly. However, this will require extensive mapping of historic and existing land uses and riparian cover, additional information on soils, and will not be able to accommodate future land use change.

5.3 Incorporation of a Bank Armor Inventory

No bank armor inventory was available for either Prickly Pear Creek or Tenmile Creek. Bank armor effectively restricts areas of the Channel Migration Zone, and its incorporation into the map product can provide useful information regarding the cumulative effect of bank armor on natural channel movement. We would recommend the incorporation of mapped bank armor into the GIS.

6 References

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7 Appendix A: Erosion Site Maps

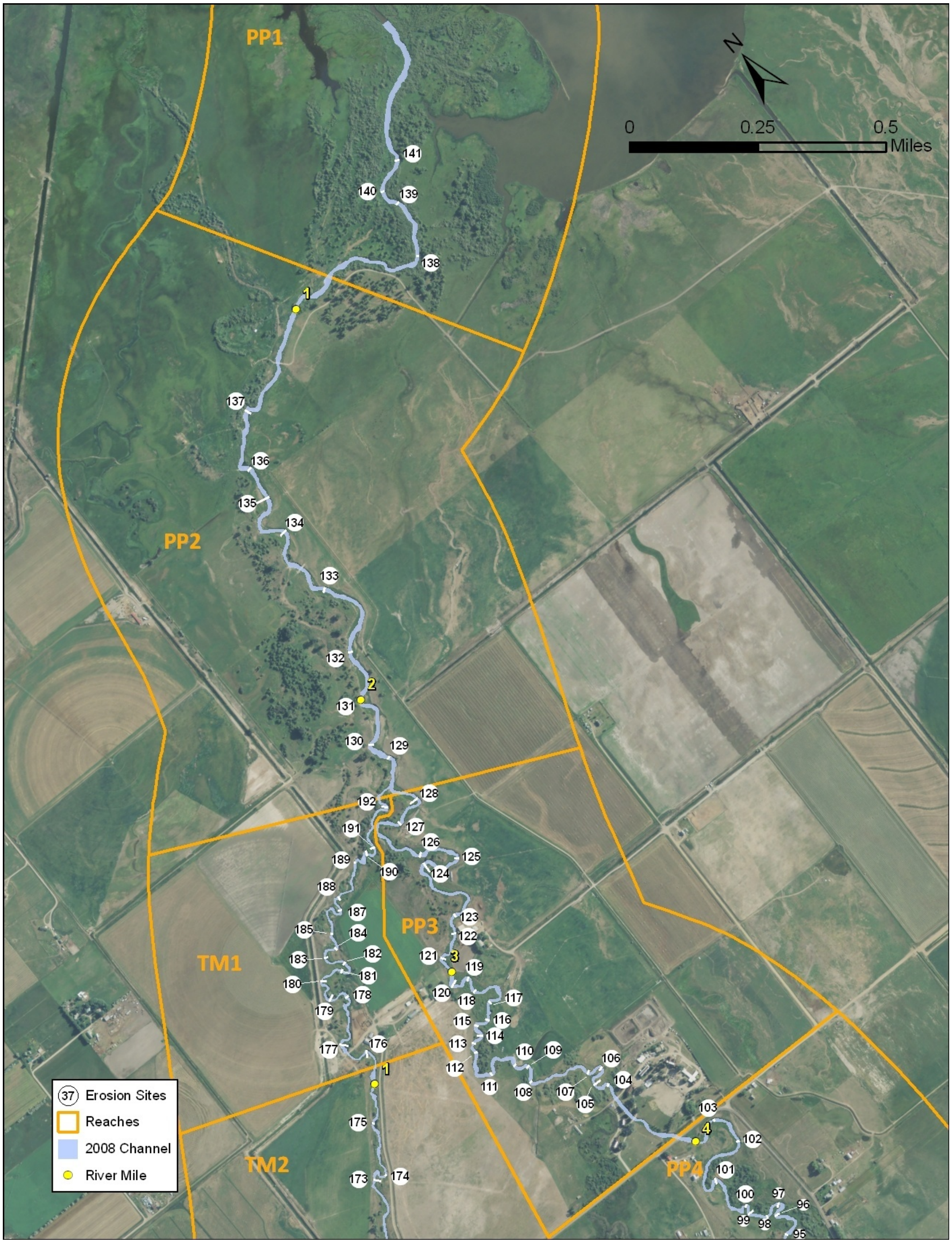

Figure 39. Reaches PP1-PP3. Note: site numbers are not sequential and relate to statistics in Appendix B.

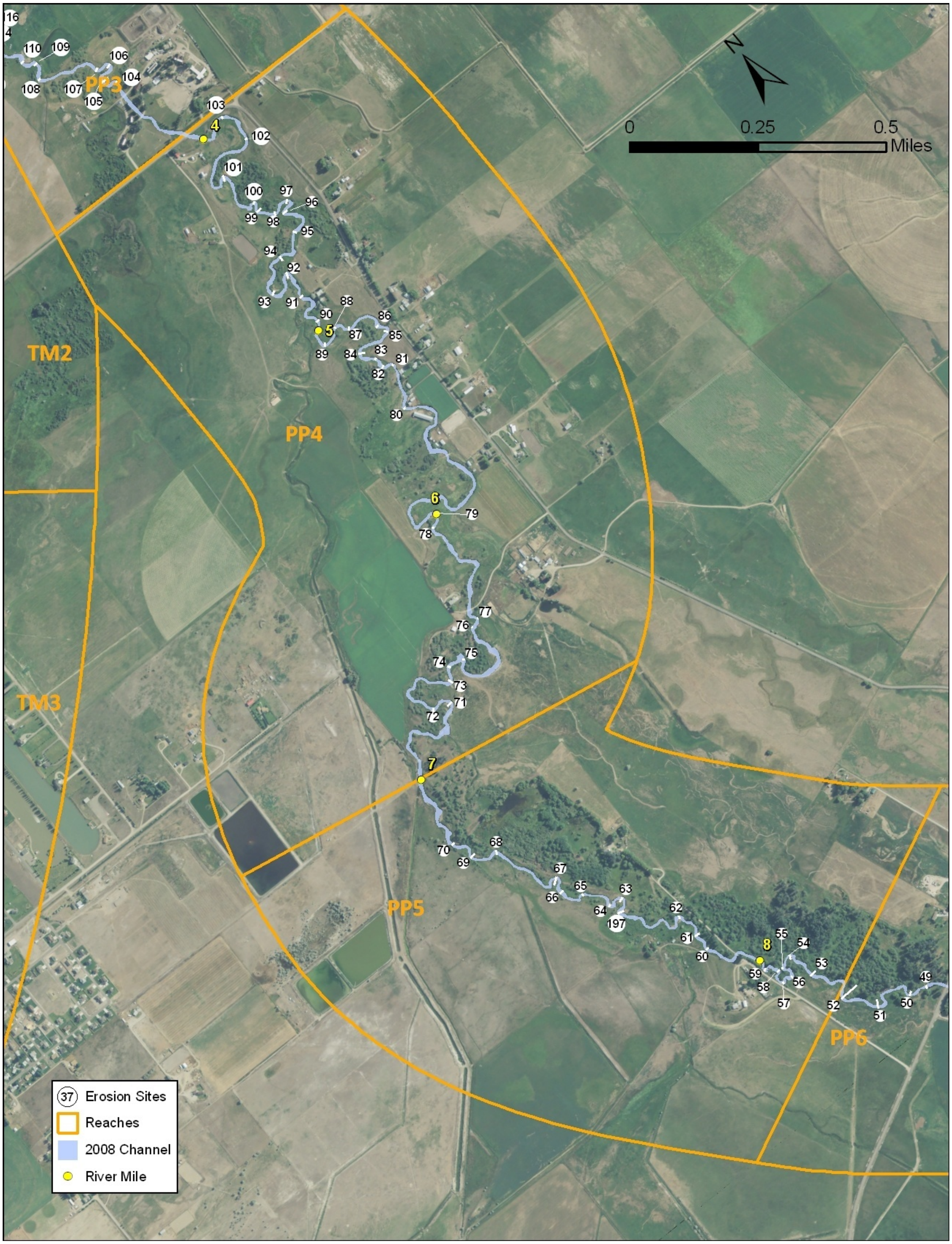

Figure 40. Reaches PP4-PP5. Note: site numbers are not sequential and relate to statistics in Appendix B.

Figure 41. Reaches PP6-PP8. Note: site numbers are not sequential and relate to statistics in Appendix B.

Figure 42. Reaches PP8-PP10. Note: site numbers are not sequential and relate to statistics in Appendix B.

Figure 43. Reaches PP9-PP10. Note: site numbers are not sequential and relate to statistics in Appendix B.

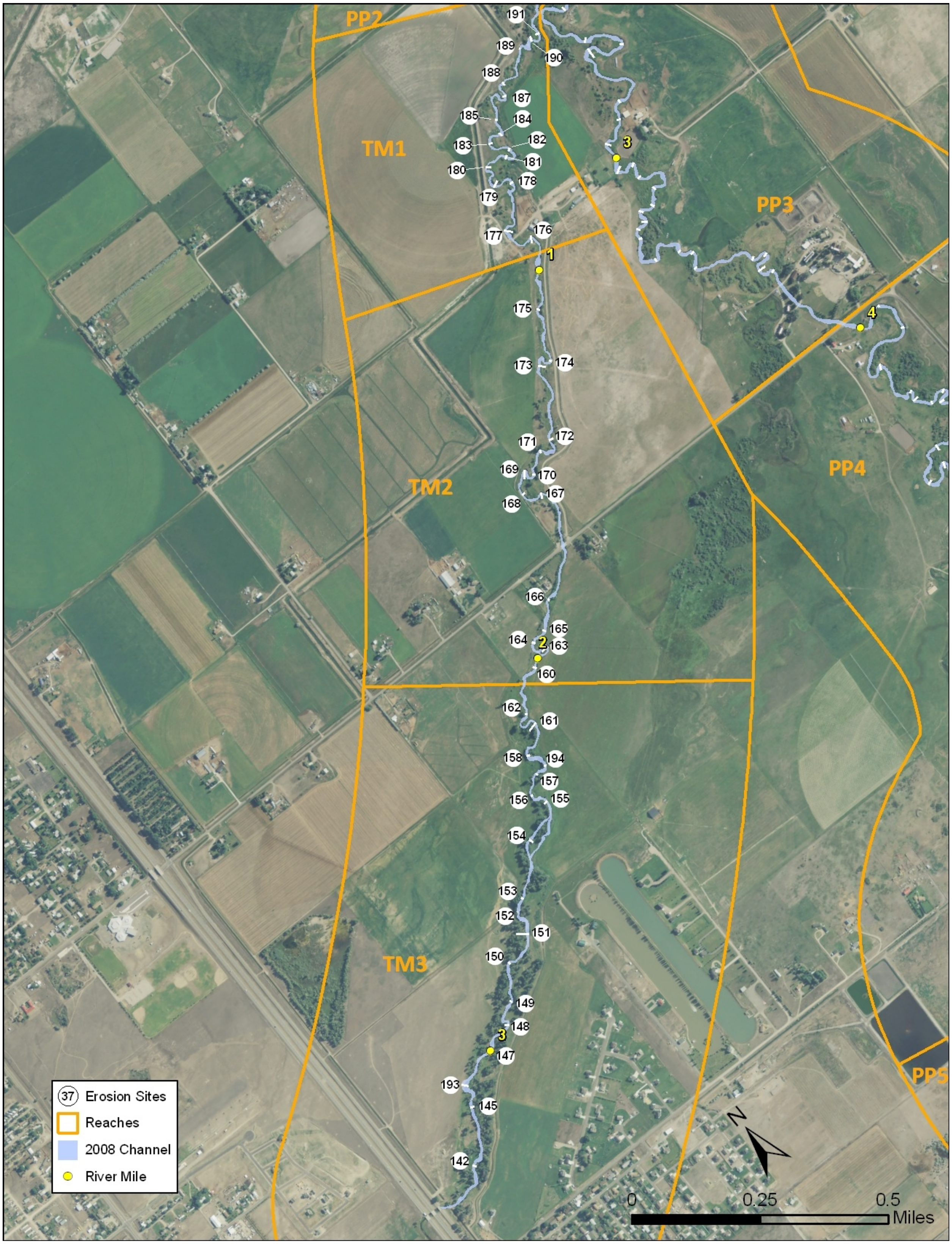

Figure 44. Reaches TM1-TM3. Note: site numbers are not sequential and relate to statistics in Appendix B.

8 Appendix B: Migration Rate Measurements

Stream	Site Id	Site River Mile	Maximum Vector Length (ft)	Mean Vector Length (ft)
Prickly Pear Creek	1	14.71	123.33	104.96
	2	14.64	99.73	73.47
	3	14.45	94.19	79.95
	4	14.51	43.79	35.13
	5	13.81	52.21	46.31
	6	13.76	92.39	66.96
	7	13.70	96.57	88.50
	8	13.58	33.44	30.94
	9	13.55	30.61	28.68
	10	12.84	38.96	37.00
	11	12.75	44.14	42.30
	12	12.56	37.90	33.82
	13	9.88	49.52	42.29
	14	12.33	58.54	53.97
	15	12.19	28.66	24.20
	16	12.02	79.11	68.27
	17	11.92	46.17	41.76
	18	11.83	48.87	43.15
	19	11.79	44.67	35.10
	20	11.67	34.78	33.59
	196	11.60	97.70	120.46
	21	11.55	17.35	16.30
	22	11.49	35.08	30.72
	23	11.30	50.78	47.41
	24	11.02	40.04	38.68
	25	10.57	43.18	38.19
	26	10.50	66.60	60.67
	27	10.44	73.05	64.94
	28	10.37	39.97	32.50
	29	10.27	27.08	24.18
	30	10.03	130.99	110.45
	31	9.95	48.63	44.37
	32	9.89	109.38	79.33
	33	9.85	50.11	44.22
	34	9.81	39.08	35.61
	35	9.74	82.90	70.62
	36	9.66	52.83	51.06
	37	9.70	31.88	26.71
	195	9.58	93.01	106.68
	38	9.41	68.57	58.44
	39	9.31	106.28	80.61
	40	9.26	81.30	67.84
	41	9.22	36.58	29.65
	42	9.18	57.92	52.75
	43	9.12	94.99	88.83
	44	8.88	148.12	127.83

Stream	Site Id	Site River Mile	Maximum Vector Length (ft)	Mean Vector Length (ft)
Prickly Pear Creek	45	8.80	75.65	64.73
	46	8.74	61.12	58.29
	47	8.72	50.85	42.07
	48	8.67	46.57	41.48
	49	8.54	40.75	37.27
	50	8.51	54.91	48.20
	51	8.40	103.83	88.69
	52	8.33	217.23	169.81
	53	8.23	78.67	69.12
	54	8.16	58.65	48.67
	55	8.14	23.95	22.36
	56	8.11	33.29	27.21
	57	8.08	29.25	26.06
	58	8.05	34.38	26.98
	59	8.02	38.89	33.64
	60	7.88	35.37	31.47
	61	7.85	65.11	57.55
	62	7.79	38.14	32.60
	197	7.62	54.79	78.55
	63	7.60	65.15	51.85
	64	7.57	31.36	26.96
	65	7.50	27.54	26.58
	66	7.45	49.27	44.09
	67	7.41	91.11	77.48
	68	7.26	55.71	41.43
	69	7.20	67.80	54.94
	70	7.15	45.57	42.94
	71	6.76	67.86	50.30
	72	6.72	31.52	28.20
	73	6.55	58.82	46.74
	74	6.52	41.14	34.03
	75	6.49	26.62	25.56
	76	6.30	16.80	13.02
	77	6.27	16.84	14.82
	78	6.03	33.23	27.95
	79	6.00	36.10	31.47
	80	5.47	32.04	27.72
	81	5.38	28.53	26.15
	82	5.35	35.16	32.90
	83	5.33	31.99	25.91
	84	5.29	76.91	59.33
	85	5.22	50.63	43.64
	86	5.19	36.41	29.40
	87	5.11	46.49	41.21
	88	5.08	30.51	26.29
	89	5.04	45.01	36.47
	90	4.98	41.41	34.86
	91	4.89	44.30	40.10

Stream	Site Id	Site River Mile	Maximum Vector Length (ft)	Mean Vector Length (ft)
Prickly Pear Creek	92	4.84	72.57	55.56
	93	4.77	60.19	59.24
	94	4.68	66.79	61.31
	95	4.61	41.79	37.46
	96	4.54	62.29	47.22
	97	4.50	53.11	49.69
	98	4.46	41.88	32.59
	99	4.43	71.14	55.38
	100	4.41	35.57	31.56
	101	4.31	68.36	52.96
	102	4.14	36.93	32.90
	103	4.07	39.95	33.64
	104	3.78	41.93	38.26
	105	3.75	86.55	79.05
	106	3.71	56.00	50.78
	107	3.68	51.39	44.91
	108	3.55	38.03	31.73
	109	3.52	47.88	44.16
	110	3.49	38.77	31.20
	111	3.40	41.35	35.65
	112	3.33	41.68	36.26
	113	3.31	44.13	34.14
	114	3.29	67.97	59.48
	115	3.26	51.85	38.63
	116	3.23	49.01	45.13
	117	3.20	49.47	39.72
	118	3.10	48.25	41.36
	119	3.07	50.30	42.66
	120	3.03	95.66	70.23
	121	2.97	67.91	56.10
	122	2.91	47.48	45.27
	123	2.87	47.02	42.53
	124	2.68	115.34	106.61
	125	2.60	45.41	37.09
	126	2.52	59.34	54.66
	127	2.36	53.11	45.81
	128	2.29	108.30	101.16
	129	2.16	66.34	51.60
	130	2.12	61.40	47.15
	131	2.00	32.38	32.12
	132	1.89	51.67	49.21
	133	1.72	61.08	51.43
	134	1.56	89.92	72.93
	135	1.43	150.70	122.41
	136	1.37	60.33	49.77
	137	1.24	76.53	68.85
	138	0.69	47.74	39.25
	139	0.58	47.12	40.83

Stream	***Site Id***	***Site River Mile***	***Maximum Vector Length (ft)***	***Mean Vector Length (ft)***
Prickly Pear Creek	140	0.53	41.49	36.24
	141	0.46	45.38	40.31
Tenmile Creek	142	3.27	46.88	41.98
	143	3.24	38.67	29.80
	144	3.22	39.16	29.65
	145	3.14	46.27	43.22
	147	3.00	46.59	33.76
	148	2.93	50.18	43.61
	149	2.87	35.97	33.62
	150	2.79	35.66	29.03
	151	2.72	133.25	120.50
	152	2.67	50.44	43.00
	153	2.63	33.29	32.69
	154	2.51	56.49	53.37
	155	2.42	50.00	46.10
	156	2.39	31.68	28.67
	157	2.34	38.25	31.12
	158	2.27	47.11	39.00
	160	2.02	46.27	40.19
	161	2.19	108.91	93.53
	162	2.13	32.14	30.77
	163	1.98	139.75	109.59
	164	1.96	40.02	37.22
	165	1.93	41.77	39.36
	166	1.86	26.56	24.03
	167	1.63	67.70	49.45
	168	1.58	38.64	36.69
	169	1.53	98.64	71.40
	170	1.50	32.58	25.50
	171	1.45	38.77	30.52
	172	1.39	48.73	44.49
	173	1.24	83.27	79.11
	174	1.19	25.57	21.43
	175	1.08	35.16	31.39
	176	0.92	84.12	58.10
	177	0.86	102.15	80.69
	178	0.74	44.07	41.97
	179	0.70	83.78	67.88
	180	0.64	60.29	53.77
	181	0.60	45.31	40.70
	182	0.56	46.17	43.86
	183	0.51	46.22	41.72
	184	0.48	44.87	37.85
	185	0.45	30.69	30.69
	186	0.45	30.69	27.30
	187	0.36	59.05	48.64
	188	0.33	53.24	45.67

Stream	Site Id	Site River Mile	Maximum Vector Length (ft)	Mean Vector Length (ft)
Tenmile Creek	189	0.24	24.32	23.19
	190	0.20	61.63	43.41
	191	0.17	52.97	49.47
	192	0.06	73.14	59.83
	193	3.09	62.11	47.27
	194	2.31	32.09	25.89

Note: Sites 195, 196, and 197 were not used in the statistical analysis of migration because movement appears to have been in part avulsion.

9 Appendix C: Geodatabase Directory

Layer Name	***Description***
Avulsion_Pathways	Topographic features identified as potential avulsion pathways.
banklines_1955	1955 banklines
banklines_1995	1995/97 banklines
banklines_2008	2008 banklines
FEMA_flood_draft	Draft FEMA floodplain designations.
CL_2008_M	2008 channel centerline with internal linear measures.
RM_tenths	Centerline divided into tenths of miles.
HMZ	Historic Migration Zone
Migration_Vectors	Lines representing measured migration from 1955 to 2008.
reach_breaks	Project reaches.
image_use_1955	Index to the images used to digitize the 1955 banklines.
CMZ_boundary_line	Outermost boundary of the Channel Migration Zone (CMZ) as a line layer, for display purposes.
CMZ_boundary_poly	Outermost boundary of the Channel Migration Zone (CMZ) as a polygon.
CMZ	Complete CMZ layer, including the HMZ, buffer and high Avulsion Hazard Zones (AHZ).

10 Appendix D: Accuracy Assessment

Note: the following text was initially presented as a Memo dated November 2, 2010.

This memo presents an accuracy assessment of the CMZ data creation process for Prickly Pear and Tenmile Creek.

The CMZ development process involves several steps of data preparation and interpretation. Each step involves a certain level of accuracy associated with the conversion of analog information to digital format for use in a GIS environment. To determine the overall digital accuracy of the CMZ process, the accuracy of each step must be quantified and the resulting measurements added together. The basic workflow is as follows:

1. Georeferencing of aerial photography
2. Digitizing of channel banklines
3. Digitizing of migration vectors

A discussion of the accuracy issues associated with each of these steps is outlined below.

1. Georeferencing of Aerial Photography

Error can be introduced into the positional accuracy of aerial photographs by aerotriangulation technique, ground control reliability, photogrammetric characteristics, scribing precision, resolution and processing algorithms[1.] Individual errors from any one of these sources is usually quite small and typically cannot be quantified. However, the National Standard for Spatial Data Accuracy (NSSDA) has been developed to help overcome this obstacle. The NSSDA provides a suite of methods for quantifying the positional accuracy of aerial photographs and other spatial data.

Three sets of aerial photographs were used for CMZ development: 1955, 1995/97 and 2008. The latter two photo series were checked for accuracy by the USGS according to the NSSDA. The reported accuracy appears in Table 1 as a Root-Mean-Square Error (RMSE) statistic. The 1955 images were obtained as raw digital scans and were subsequently georeferenced in ArcMap by the Helena GIS office. DTM performed an accuracy assessment using NSSDA methods for horizontal accuracy.

The basic steps involved in the NSSDA process are as follows:

1. Select a set of test points from the data set being evaluated (here, the 1955 images);
2. Select an independent data set of higher accuracy that corresponds to the data set being evaluated (here, the 2009 NAIP imagery);
3. Collect measurements from identical points from each of those two sources;
4. Calculate a positional accuracy statistic using a worksheet of equations.[1]

The results from the NSSDA assessment for the 1955 imagery appear in Table 1 as an RMSE statistic.

Table 5. Horizontal accuracy of photography series used for Prickly Pear/Tenmile CMZ development.

Image Series	*Source*	*NSSDA Horizontal Accuracy (RMSE)*
1955	USDA APFO	2.3m
1995/97	USGS	< 2.5m
2008	USGS	< 3m

2. Digitizing of Channel Banklines

Banklines approximating a bankfull water level were digitized at one of two different scales, depending on the photo resolution. On the two older image sets, a scale of 1:2,000 was used. For the high-resolution 2008 series, a scale of 1:1,500 was more appropriate. These scales represent a balance between a scale at which channel migration can be reasonably detected and the appropriate scale at which the images should be used. In other words, 'zooming in' beyond these scales was not supported by the accuracy and resolution of the imagery, and 'zooming out' resulted in an inability to resolve banklines well. These scales were essentially discovered through experimentation in ArcMap. After digitizing, a randomized check on the banklines was performed in which the scale was decreased (by 'zooming in') and the linework evaluated. In all cases, the line fell within 3 meters of the actual bankline seen on the image. Since this distance is within the reported error of the imagery, this level of accuracy was deemed acceptable. The error associated with digitizing banklines could also theoretically be quantified for the 2008 photo series via a GPS exercise. A series of test points along interpreted banklines from the imagery would be visited in the field via GPS to determine whether or not the point was in fact located along a bank. However, this approach presents obvious resource constraints, and would also leave the 1955 and 1995/97 banklines with no analogous method. Also, most resource-grade GPS units acknowledge a possible positional error of up to 2 meters, depending on field and satellite conditions.

3. Digitizing of Migration Vectors

The digitizing of migration vectors is subject to the same type of error as the banklines, since both depend on interpretation of the imagery. The vectors were drawn at the same scale as the banklines for each respective image series. Consequently, the amount of expected error does not exceed 3 meters. This value was verified with a randomized check on the vectors. While the banklines were all digitized by the project GIS technician, the vectors were drawn by the geomorphologist. This 'second look' at the banklines provided a level of quality assurance, and if any obvious bankline errors were discovered they were fixed prior to vector digitizing. Once digitizing was finished, all of the vector lengths at each migration site were averaged, a step that helps mitigate the errors resulting from photo interpretation.

4. Cumulative Accuracy Assessment

Each of these steps in CMZ data creation imparts a small amount of error to the final product. Adding the maximum possible errors of all steps yields a potential horizontal error of 8.3 to 9 meters (27.2 to 29.5 feet) in the final product. This is a theoretical maximum amount of error, however. The actual cumulative error is likely much lower. For this maximum to be reached at a given point, all of the errors from each step must occur in the same direction at their maximum magnitude. It is more likely that, at any given location, errors from one or more steps partially or completely mitigate those from the others.

In summary, it is impossible to know the exact error at any one location in the study area, especially since historical ground conditions can no longer be measured in the field. The practical horizontal error should not reach the maximum theoretical error value of 9 meters, for the reasons outlined above.

[1]Geospatial Positioning Accuracy Standards, Part 3: National Standard for Spatial Data Accuracy. Federal Geographic Data Committee, publication FGDC-STD-007.3-1998. Available: http://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part3/chapter3.