Developing and Testing a Geomorphic Mapping Protocol in Mount Rainier National Park, Washington

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Abstract

The grand landscapes and river systems of Mount Rainier National Park (MORA) are influenced by its glaciovolcanic geology and the temperate climate of the Pacific Northwest. Mapping geomorphic changes is a crucial step to understanding, interacting with, and preserving the pristine environments of the Park. Geologic hazards and large-scale hydrologic events are common within park boundaries, putting infrastructure and cultural and historical sites at risk of permanent damage. In this study, I present a protocol for mapping geomorphic features remotely and in the field, and I test the protocol along an at-risk road segment along the Nisqually River. With ArcGIS Pro, I defined site boundaries with a watershed delineation, designated key geomorphic features custom to the unique environment of the Park, and assigned key attribute domains to further describe each mapped feature. Then, I mapped landform features using LiDAR and aerial imagery in Pro and used ArcGIS Online and Field Maps for in-field mapping with a mobile tablet and a backpack-mounted GNSS receiver. After extensive testing, the protocol is in its preliminary phase and ready to be applied to other park field sites for further testing and repeat mapping projects. The resulting inventory suggests that the protocol is suitable for the remote and rugged characteristics of the Park when paired with recent LiDAR data and favorable GNSS conditions. The standardized methods and taxonomy proposed in the protocol allow for recording landform changes and initial site characterization that can be used to identify locations for hazard mitigation. The protocol is repeatable, providing a standardized format useful for comparison between different locations and timescales. While the protocol is designed for the features found near Mount Rainier, it can be readily modified for other fluvial and hillslope environments. In its final form, this geomorphic mapping protocol will equip MORA geologists and resource managers with a standard approach to documenting MORA's most geologically dynamic and at-risk infrastructure and resources.

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Introduction

Every year, geologic hazards occur within the boundaries of Mount Rainier National Park that disrupt accessibility and everyday operations. The most common hazards, such as debris flows, floods, and landslides, are typically hydrologically driven and occur within or adjacent to drainages surrounding the glaciated mountain. Since 1926, there have been more than 60 recorded debris flows within the Park (Beason et al., 2021). Mitigating the impacts of hazards like these on infrastructure and wilderness habitats requires extensive assessment efforts to identify landforms that can contribute to such events.

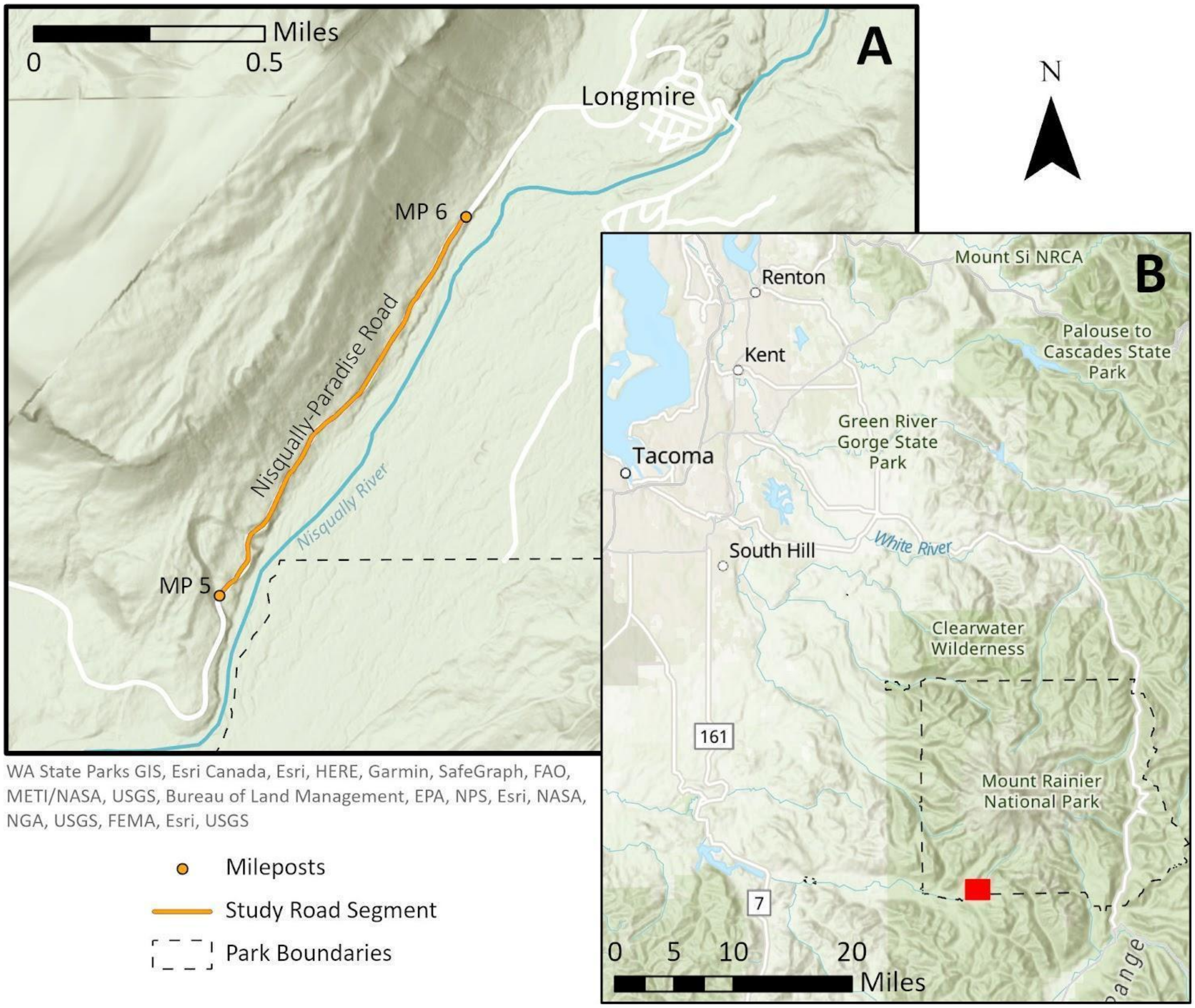
The headwaters of the Nisqually River initiate on the southern flank of Mount Rainier, less than a mile west of Paradise, Washington. From there, the river floodplain runs closely adjacent to Nisqually-Paradise Road for miles. Due to the river's proximity and recent increases in frequency and magnitude of hazardous events (Lancaster et al., 2012), the road is continually at risk of being damaged, degraded, and even destroyed. The road is the only route that provides year-round access to Paradise, the most popular destination in the Park and launching point for the busiest hikes, climbs, and other activities. To keep Paradise accessible, the Imminent Threats Division within the MORA Geology Group considers protecting this road to be a major priority. The group often takes the lead on developing geohazard mitigation strategies, projects that require extensive field mapping and site investigation. While they are well equipped to accomplish such tasks, they have not yet organized a full assessment protocol to standardize their methodology.

To assist in the efforts of the MORA Geology Group, I designed a functional protocol for mapping geomorphic landforms that influence threats to park infrastructure and assets. With this protocol, hereafter called the Geomorphic Mapping Protocol, geoscientists of varying skill levels will be able to produce repeatable geomorphic landform inventories at locations of interest within the Park. These standardized methods are designed so that final map products are consistent regardless of who conducts the mapping. The Geomorphic Mapping Protocol will allow the Geology Group to provide stakeholders such as resource managers, maintenance crews, and the general public with valuable information regarding the ongoing evolution of the landscapes they oversee. I tested the new protocol along a portion of Nisqually-Paradise Road, compiling an inventory along the road segment that the Geology Group considers to be most at risk. Hazards from both hillslope and fluvial processes threaten the road between Milepost 5 and Milepost 6. This study, within the process boundaries of proximal geomorphic features of that road segment, is intended to provide insight for developing mitigation strategies.

Background

Problem Description

Situated between the Nisqually River and prominent forested hillslopes, the Nisqually-Paradise Road is at risk of damage by geologic hazards from both sides. The road segment between mileposts 5 and 6 may be the most vulnerable (Figure 1). Eastbound, the mile-long segment begins five miles from the Nisqually Entrance of MORA and ends half a mile from Longmire, Washington. It gets as close as 25 feet to the right bank of the river and stays within 150 feet for the entire segment. On both sides of the road, the hillslopes are as steep as 40° in many places, including just between the road and riverbank near milepost 5. At the closest points, the road lies less than 35 feet above the river, which has been widening and aggrading over time (Bullock et al., 2007).



WA State Parks GIS, Esri Canada, Esri, HERE, Garmin, SafeGraph, FAO, METI/NASA, USGS, Bureau of Land Management, EPA, NPS, Esri, NASA, NGA, USGS, FEMA, Esri, USGS

Figure 1: (A) Location map of the Nisqually River valley at Longmire, WA showing proximity of the river to Nisqually-Paradise Road from mileposts 5 to 6. (B) Index map of study area relative to Tacoma, WA and other major geographic locations.

Throughout the Park, routes near the major drainages of Mount Rainier, like the Nisqually-Paradise Road, face destruction from glacially sourced mass movements such as debris flows and outburst floods. In 1926, the first recorded debris flow in the Park occurred in the Nisqually River watershed (Beason et al., 2021). These large-scale debris flows and flooding events are typically triggered by high-intensity rainfall at high elevations, especially in steep, proglacial gullies (Lancaster et al., 2012). In November 2006, at least six known debris flows initiated during a particularly wet storm event known as an “atmospheric river” (Neiman et al., 2008), resulting in permanent alterations to the landscape and destruction of park infrastructure. Over the course of 36 hours, the area experienced 18 inches of precipitation that ultimately caused each watershed to overflow (Bullock et al., 2007). Along the Nisqually River, the resulting floods washed away 200 yards of the Nisqually-Paradise Road at Sunshine Point and caused significant undercutting at mileposts 5, 6, and 9 of the road. Following this storm, many studies examined debris flow susceptibility, frequency, forecasting, and detection in the Park (Beason et al., 2021; Lancaster, et al., 2012; Lindsey, 2015), greatly contributing to our understanding of how and when these events occur. Here, I describe practices that may help mitigate these hazards through site characterization to better prepare for the next event and protect park assets like Nisqually-Paradise Road. In this report, I present a new assessment protocol to identify geologic hazards that threaten important park infrastructure. I then apply this new protocol to assess the risk of landslide, flood, and related hazards to MP 5-to-6 of the Nisqually-Paradise Road.

Regional Setting

Mount Rainier, also known as Tahoma, is an active stratovolcano in the Cascade Range of the western United States in the state of Washington, about 60 miles southeast of Seattle and 40 miles southeast of Tacoma (Figure 1). Active volcanism in the Cascades is driven by the subduction of the Juan de Fuca oceanic plate under the North American continental plate. Mount Rainier is the largest volcano in the Cascade volcanic arc. At 14,410 feet above sea-level, Mount Rainier has 29 named glaciers (Beason et al., 2021) and is the most glaciated mountain in the contiguous United States. The current edifice of Mount Rainier began erupting half a million years ago, building upwards with continuous layers of lava flows (Sisson, 1995). Historically, the primary historic lava flow deposition has consisted of basaltic andesite, but deposition of mudflows, breccia, and ash has also been common (Fiske et al., 1963). In addition to volcanic deposits, other rocks exposed in the Park include tuff-breccias, graywacke, and volcanic siltstones. The oldest formation within park boundaries is the Ohanapecosh unit from the late Eocene epoch, measuring over 10,000 feet in thickness (Fiske et al., 1963).

Site Geology

Schasse's (1987) 1:100,000 scale map of the Mount Rainier quadrangle identifies ten different geologic units within proximity to the study area (Figure 2), six of which can directly impact the study road segment. The Nisqually-Paradise Road mainly overlies Holocene-aged lahar deposits with fragmental volcanic rock (Qvl), a unit that extends into the river-valley floor. Quaternary-aged alluvium (Qa) also sits on the valley floor near the right bank, adjacent to the southern half of the study road segment. The river's left bank consists of Pleistocene-aged Evans Creek alpine glacial drift (Qad(e)). The northeastern quarter of the road segment lies on a contact between the Holocene-aged lahar unit and a blended unit of Tertiary-aged fragmental volcanic rocks and lahar deposits belonging to the Ohanapecosh Formation (Ovc(oh)). That unit continues adjacent to the road until it meets a Tertiary-aged andesite also of the Ohanapecosh Formation (Ova(oh)). Lastly, a Quaternary-aged andesite unit (Qva(mr)) lies upslope from the Ohanapecosh units and the road.

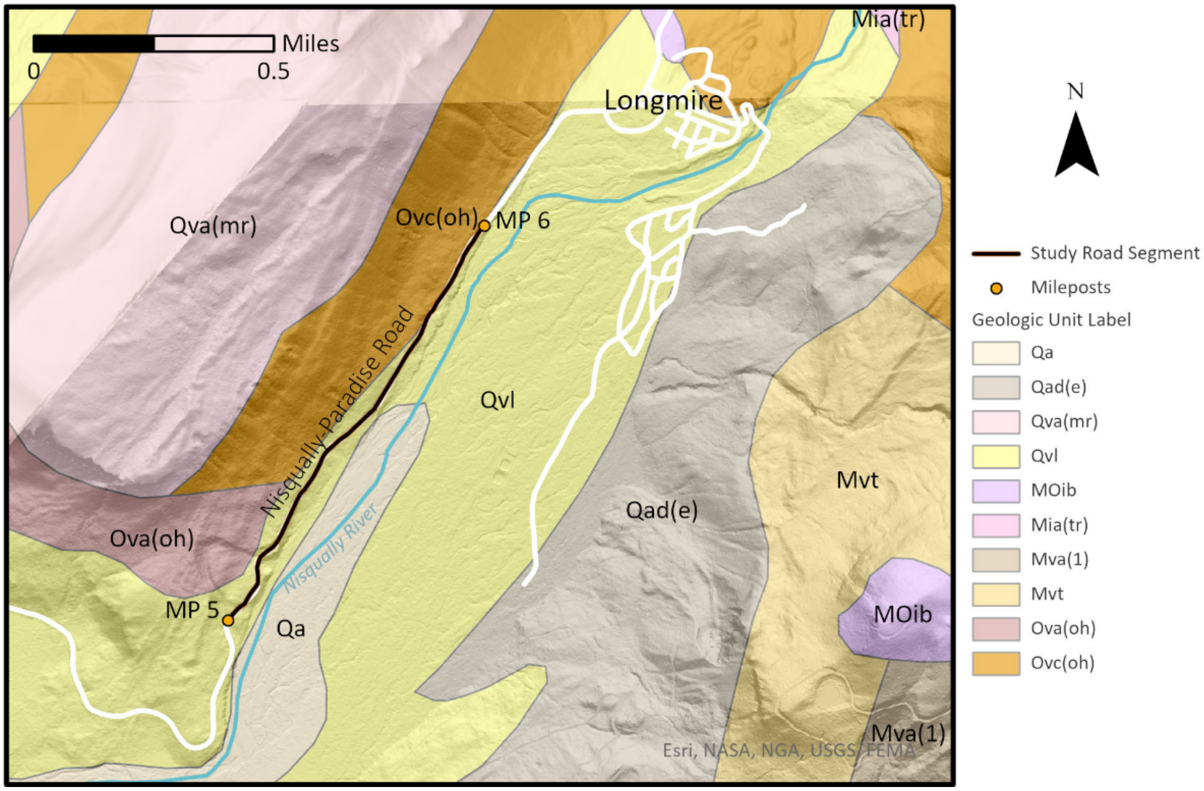


Figure 2: Geologic map of the study area (Schasse, 1987). The geologic units are defined as: (Qa) Holocene-aged alluvium, Qad(e) Pleistocene-aged alpine glacial drift, Qva(mr) Pleistocene-aged andesite, Qvl Holocene-aged lahar deposits, MOib Miocene-Oligocene-aged intrusive rocks, Mia(tr) Miocene-aged acidic intrusive rocks, Mva(1) Miocene-aged andesite, Mvt Miocene-aged tuffs and tuff breccias, Ova(oh) Oligocene-aged andesite, and Ovc(oh) Oligocene-aged volcaniclastic deposits or rocks.

Previous Studies on Landform Identification

Prior to this study, the MORA Geology Group conducted a methods review on geomorphic landform identification and mapping, selecting a study from Wheaton et al. (2015) to use to conduct geomorphic site investigations within MORA. The first project they oversaw with the Wheaton et al. (2015) methods was a 2019 risk assessment along the Nisqually River. This study and the Geomorphic Mapping Protocol are a follow-up on that initial methods review and risk assessment.

In 2015, Wheaton et al. defined fluvial geomorphic mapping taxonomy to clarify and standardize geomorphic naming conventions for users representing every relevant discipline, including land managers, engineers, biologists, ecologists, and geomorphologists. They created a tiered framework for identifying landforms in riverscape settings based on several key features split into categories like geomorphic units, margins, and structural elements. The study lists numerous options within these categories, displaying geomorphic units as floodplains, terraces, or channels that are separated by margins of either anthropogenic or natural origins such as banks, levees, and roads. The study identifies structural elements, such as woody debris, boulders, and culverts, that could hydraulically influence channel flow and river morphology. The locations of these features can be used by park staff to track and forecast channel behaviors at different flow and flood stages and better understand ongoing geomorphic evolution at a given site.

In 2017, the Washington Geological Survey (WGS) produced a comprehensive tool for hillslope landform mapping in coordination with the Oregon Department of Geology and Mineral Industries (DOGAMI) (Slaughter et al. 2017). This protocol provides methodology for digitally mapping significant slope failure features, such as landslide deposits, rockfall deposits, and alluvial fans, with LiDAR data, aerial imagery, and GIS software. It also outlines standardized methods of field verifying these features. The WGS developed this mapping protocol with the intention of compiling a comprehensive statewide landslide inventory. From there, they can identify areas of potential landslide hazard and raise awareness of the dangers and economic impact of landslides across the state of Washington. This protocol can be directly applied to geomorphic mapping methods within the Park to better assess hillslope hazards that pose a risk to infrastructure and resources.

Previous Site Study

In 2019, Geoscientists-in-the-Parks Interns at MORA conducted a risk assessment along the Nisqually River (Cutter et al., 2019). Their assessment began with a three-tiered mapping effort based on the Wheaton et al. (2015) study. Then, they compared aerial imagery to measure bank erosion and channel widening. Finally, they used cross-sectional profiles along two stretches of river valley to calculate average cross-valley slopes. With the information from their mapping and river valley surveys, they identified seven areas with moderate to high levels of risk to park infrastructure and visitors along the Nisqually River, including a stretch of the river from the Longmire Bridge to Milepost 5 of the Nisqually-Paradise Road. They recommended a continuous monitoring plan for this area, describing a high possibility of damage to the road and unpredictable erosion rates near infrastructure within the next decade. Their assessment serves as a primer for future mitigation efforts and a proof-of-concept for applying Wheaton et al. (2015). to MORA. I use this work to produce an updated protocol customized to Mount Rainier's intricate landscape.

MORA Geology Group & The Imminent Threats Division

The Imminent Threats Division is a developing program within MORA's Geology group dedicated to monitoring the ongoing interactions between park operations and natural processes. In 2016, park geomorphologist Mr. Paul Kennard started a precursory group mainly focused on flood response efforts staffed by student volunteers and interns. This group served as a connection between the Natural Resources and Maintenance divisions of the Park, becoming the first to provide scientific studies for natural hazard response efforts. In 2018, Mr. Kennard retired, and the group moved under the supervision of park geologist Mr. Scott Beason. With this move, the scope of projects expanded to cover all geologic and hydrologic hazard events that occur in the Park. Not only does the group provide hazard response services, but they are also responsible for projects and studies that contribute to the protection of people and park infrastructure from these events. At present, the Imminent Threats Division is staffed by two geologists, Mr. Taylor Kenyon and Mr. Robby Jost, with seasonal appointments, assisted by interns and student volunteers.

Methods

The main task accomplished during this study was compiling fluvial and hillslope features each assigned with their own set of descriptive attribute options into one overarching GIS template. I developed a protocol with several facets, selected a test site to apply the protocol, collected geomorphic data, compiled it, then analyzed the results.

Compiling and Defining Features for the Geomorphic Mapping Protocol

At its core, the Geomorphic Mapping Protocol is mostly sourced from Wheaton et al. (2015) and the WGS Landslide Inventory Protocol (Slaughter et al., 2017). Working alongside the MORA Geology Group, we selected specific geomorphic features from Wheaton et al. (2015) that were most relevant to the lowland, glacially sourced watersheds of MORA. In this Geomorphic Mapping Protocol, 'Fluvial' features were defined under two categories, margins or structural elements (Table 1), depending on where they were located in Wheaton's tiered framework. Within the Geomorphic Mapping Protocol, I define a margin as a boundary that signals the transition of a geomorphic unit in context to the river valley. The feature layer *Banks* is used to identify and differentiate between the margins that are encountered in the Park, whereas *Geomorphic_Unit* signals the transition between hillslopes, terraces, active floodplains, and in-channel areas (Figure 3). The *Geomorphic_Unit* feature is categorized as a 'Fluvial' feature, but has a subcategory to map portions outside of the river valley as a 'Hillslope'. This feature serves to generalize the entire ground surface of the study area into geomorphic zones based on flood stage heights and geomorphic processes.

In Wheaton et al. (2015), structural elements were defined "as discrete objects that directly influence hydraulics." For the structural elements in the Geomorphic Mapping Protocol, *Individual_LWD_pieces* are defined as any woody debris piece estimated to be a minimum of 30 feet long and 1 foot in diameter, *Large_Boulders* are estimated to be at least 3 feet on the shortest axis, and *Log_Jams* are accumulations of woody debris capable of blocking or strongly influencing channel flowpath and morphology (Figure 3). These features are classified further using the Wheaton et al. (2015) framework with defined key attributes. In the Geomorphic Mapping Protocol, a feature layer is sourced from the "Type" section of the Wheaton et al. (2015) framework, the fields of the feature layer are sourced from the "Key Attributes" section, and the descriptive categories of "Key Attributes" make up the domains of the protocol. Not all of these features and attributes are exactly the same as the Wheaton framework, but the features have been distilled to better match the needs of the stakeholders within MORA.

Since the Wheaton et al. (2015) study only covers fluvial geomorphic features, the Geology Group requested that 'Hillslope' feature layers be added to continue mapping outside of the river floodplain. We included the WGS Landslide Inventory Protocol (Slaughter et al., 2017) to provide comprehensive coverage of hillslope features. We also added a number of additional features that impact the roadway but are not part of the fluvial or hillslope protocols we adopted. These features include *Anthropogenic_Surfaces*, defined as any permanent surfaces of anthropogenic origin, *Seeps*, indicating the presence of surfacing groundwater, *Drainage_Pathways_Streams*, used for indicating streambeds and other minor water drainages present on a hillslope, and *Culverts*/*Culvert_Points*, identifying infrastructure used to redirect water under roadways. As I tested the whole protocol in the field, I modified many of the features and their fields and domains to acknowledge newfound nuances, although I kept the WGS protocol intact.

Once the Geology Group and I identified and defined the features for our framework, I manually organized them into ArcGIS Pro and drafted all dependent values to each. To begin, I created fluvial and hillslope feature datasets to add to the Geomorphic Mapping Protocol geodatabase. I drafted the selected features within their corresponding datasets as either point, line, or polygon features depending on the landforms represented. In total, there are five 'Fluvial' and fourteen 'Hillslope' features in the Geomorphic Mapping Protocol (Table 1). Next, I drafted data fields within each feature attribute table, and assigned domains to each field. These domains serve as descriptive codes that apply key attributes to the mapped features and appear as a drop-down menu of options for the mapper to choose from. To better track data collection and editing, I added the *Receiver_Type* attribute field and editor tracking.

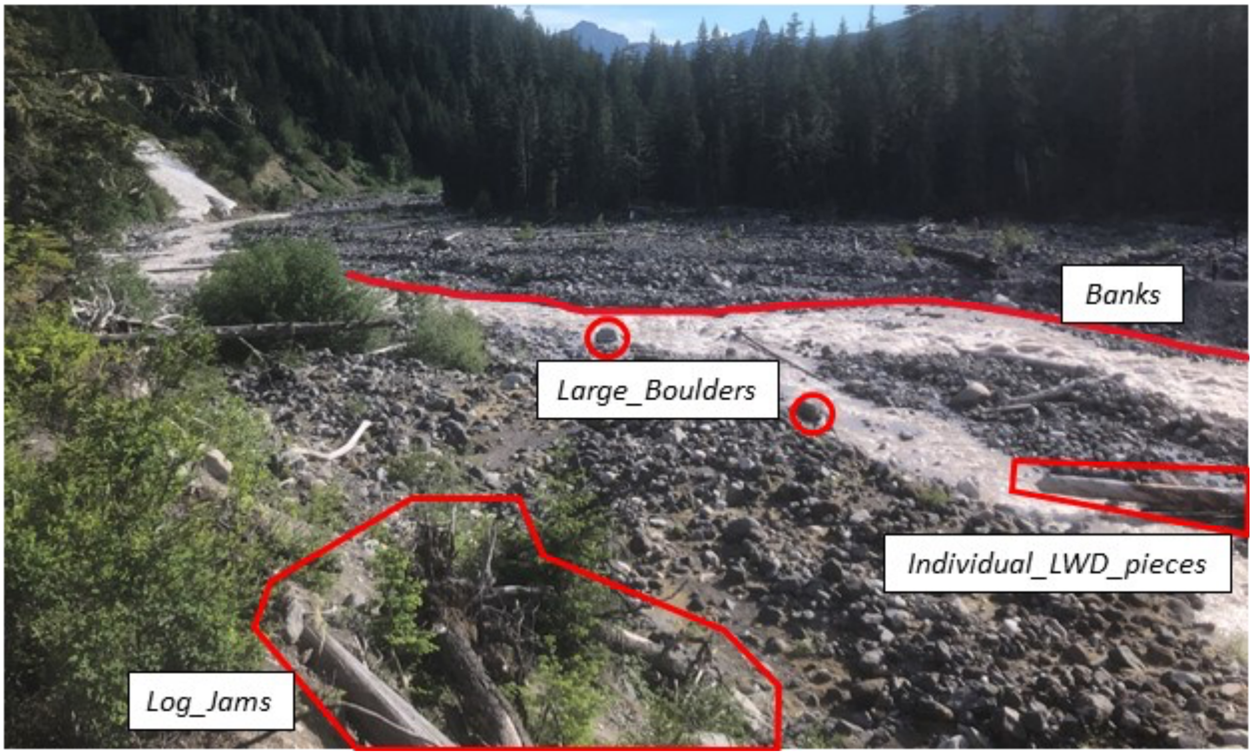


Figure 3: Annotated site photo of in-field examples of some 'Fluvial' dataset features including *Banks*, *Individual_LWD_pieces*, *Large_Boulders*, and *Log_Jams*. This photo is a southeast facing view of the Nisqually River from the Wonderland Trail near Cougar Rock Campground on June 24th, 2021.

Site Selection and Watershed Delineation

The MORA Geology Group identified Mileposts 5-to-6 on the Nisqually-Paradise Road as an area of interest to test the new protocol. I performed a watershed delineation in ArcGIS Pro to specify the process boundaries in which the relevant landforms could be influenced by both geologic and hydrological processes. To locate the boundaries of the site and its watershed, I used the Hydrology tools in the Spatial Analyst toolbox of ArcGIS Pro. Using the Lewis County

2009 Digital Surface Model (DSM) sourced from the Washington State DNR LiDAR portal (Mann et al., 2010), I used the Fill, Flow Direction, and Flow Accumulation tools to create rasters from each previous output. Next, I reclassified the flow accumulation raster four different times to filter the output raster at varying levels of detail, differentiating large rivers from small streams. I used this flow accumulation raster to identify the main stem of the catchment that flows through the road segment of interest, then added a "pour point" to the outlet of this stem to single out all branches of the watershed upstream of the point. Finally, I used the pour point layer and the flow direction raster in the Watershed tool to create a final raster of the watershed to define the extent of the study area. This delineation resulted in the creation of a watershed boundary that encompasses the road segment of interest along with adjacent hillslopes and river floodplains (Figure 4).

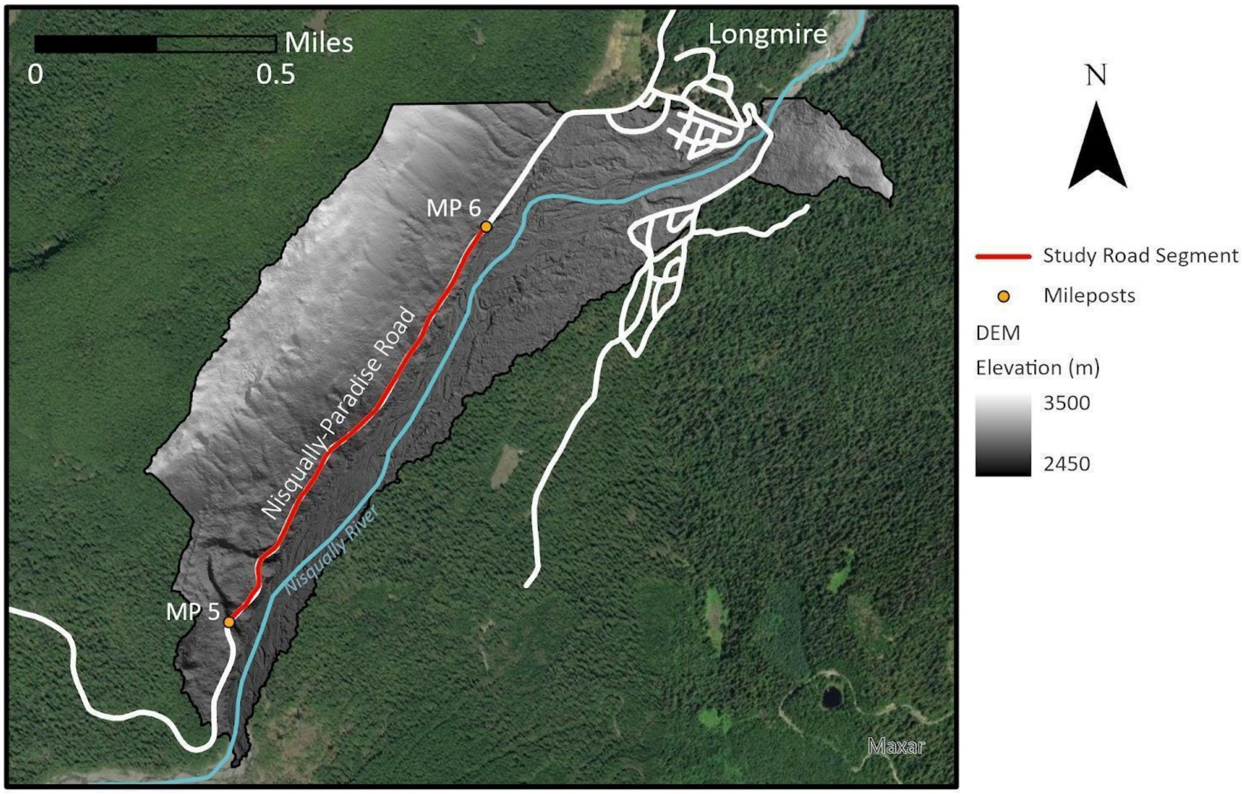


Figure 4: Map of watershed identifying the geomorphic process boundaries of the study area (shown by DEM). Park roads are shown in white.

Data Collection

Data collection consisted of two primary modes: remote (computer based) and field based. I used the coordinate reference system NAD 1983 UTM Zone 10N for all GIS work in this study. Once I had a working draft of the protocol and the study area delineated, I began data collection to build out the geomorphic landform inventory of the study site using the "create feature" tool in ArcGIS Pro's editor menu. I mapped fluvial and hillslope features at a maximum scale of 1:500 and a minimum scale of 1:24,000. When mapping features following the WGS protocol, I mapped at a finer scale than the intended final map scale as suggested (Slaughter et al., 2017). The basemaps and imagery I used while remote mapping include a slope raster created with 1-meter resolution LiDAR data using the ‘Slope’ Spatial Analyst geoprocessing tool, 0.5 meter Maxar orthoimagery, a roads with mile markers layer, and a contour lines layer, when available. The slope layer should be symbolized using ‘Stretch’, a black-to-white continuous color scheme, and selecting the invert box. Collecting this inventory allowed me to test the protocol’s functionality and make real time edits as I went along. I began mapping in ArcGIS Pro using the features observable in DEM-created slope and hillshade layers. Many of the features observable in the LiDAR included fluvial margins, anthropogenic surfaces, and landslide deposits.

In order to collect data in the field, I published the feature layers in ArcGIS Pro to ArcGIS online, configuring their settings for offline use in ESRI’s mobile device application, ArcGIS Field Maps. In ArcGIS Online, I set each feature layer to full sharing, editing, and exporting abilities, and added them to a project webmap. In the webmap settings, I defined a map area that would be available in Field Maps. Once in Field Maps on a designated tablet provided by MORA’s Geology group, I downloaded the map area on the tablet, configuring it for field data collection. In the initial field mapping phase, I used the standard onboard consumer-grade GNSS receiver to collect data at a maximum scale of 1:1000. To collect the feature location, I would hold the tablet as close to the feature as safely possible to collect its location. Over time, it became clear that the tablet's GNSS system could not readily provide accuracy below about 12 feet, and I had to switch to using a higher accuracy receiver. Here, the Geology group provided me with an Emlid RS2 Receiver that I could mount to a backpack (noting the device height), and collect points, lines, and polygons with sub-meter precision for each feature. We connected the receiver to Field Maps through the Emlid ReachView 3 tablet application. Due to the trial-and-error nature of this study, these mid-project changes in my methods and protocol introduced some inconsistencies to the resulting inventory.

For future data collection with the Geomorphic Mapping Protocol, I recommend using a computer with the processing power necessary to run ArcGIS Pro, a GNSS receiver with survey-grade accuracy and precision, and a mobile WiFi enabled tablet or smartphone with an operating system that supports both ESRI ArcGIS applications and connectibility with the chosen GNSS Receiver.

Analysis Methods

The data collected for the inventory in this study was compiled in a straight-forward tabular format, therefore, I did not need to do any post-processing. However, for each change made to the protocol, I had to update the previously collected data to match the new format. For example, if new fields were added to a feature layer that already had data collected, I needed to update that data to account for the new field. Also, as mentioned in Wheaton et al. (2015), some attributes weren’t applicable to any given instance of these features in the field site, so I added a “Not Applicable” option to differentiate blank empty fields from “Null” data. I determined that the inventory would be available for analysis by park stakeholders only when the data fields for each feature are all properly filled and verified.

The inventory collected from the Geomorphic Mapping Protocol testing phase is a compilation of spatial features with specific attributes assigned to them. I assigned specific symbology to each feature to present the inventory in a map format. There are many different attributes that describe the features. To compare features based on these attributes, I reclassified the feature to display different symbology based on their attributes. For example, I compared features visually by classifying features within the *Receiver_Type* field in order to observe where each feature was mapped with remote techniques, with an Emlid GNSS receiver, or with a consumer-grade tablet GNSS receiver. With this information, I could identify inconsistencies in the data collected and double-check them spatially with the varying collection methods.

The WGS landslide inventory is largely GIS based, therefore I found some geospatial analysis to be necessary to map a landslide deposit within the study area. This involved creating a slope gradient layer from the LiDAR to help map landslide scarps and flanks as well as adjacent hillslopes. Furthermore, I used the DEM to collect the adjacent slope angle, scarp height, failure depth, movement direction, and deposit volume to provide a detailed description of the landslide deposit as part of my inventory. See Slaughter et al. (2017) for detailed information regarding the landslide inventory protocol methods.

Results

The Geomorphic Mapping Protocol

The final rendition of the Geomorphic Mapping Protocol is an amalgamation of features identified in the Wheaton et al. (2015) study, the WGS landslide mapping protocol, and throughout the field testing phase. Figure 5 shows a decision tree identifying instances when the Geomorphic Mapping Protocol refers to the WGS protocol and Wheaton et al. (2015) study for mapping these select features. My protocol template geodatabase (Appendix A) can be opened in any GIS program to view the organizational framework of the protocol features, fields, and domains. Tables 1, 2, and 3 display a simplified hierarchy of this framework. Table 1 shows the map attributes that are visible in the final map product. The feature classes are broken into two feature datasets, ‘Fluvial’ and ‘Hillslope’.

There are five feature classes under the ‘Fluvial’ feature dataset, four of which are simplified fluvial margins and structural elements sourced from Wheaton et al. (2015). The *Banks* and *Geomorphic_Unit* feature classes are used for defining margins and landform boundaries within the study area. The *Individual_LWD_pieces*, *Large_Boulders*, and *Log_Jams* feature classes are used as identifiers of major fluvial structural elements commonly found in the waterways of MORA.

The ‘Hillslope’ feature dataset consists of fourteen feature classes, including one modified from Wheaton et al., 2015, four assigned by the MORA Geology Group, and the rest are directly taken from the WGS landslide mapping protocol. The WGS protocol covers a major portion of hillslope mapping relevant to hazard susceptibility, which left me to only develop standards that fall outside of their scope of focus. I left the WGS features unmodified as recommended by the protocol documentation. From Wheaton et al. (2015), *Culvert_Points* and *Culverts* are considered structural element feature classes where the polylines feature is used for cases where both the inlet and outlet for a culvert can be located and the points feature is used if only one of the two can be located. The remaining non-WGS sourced feature classes do not call for further attribute collection.

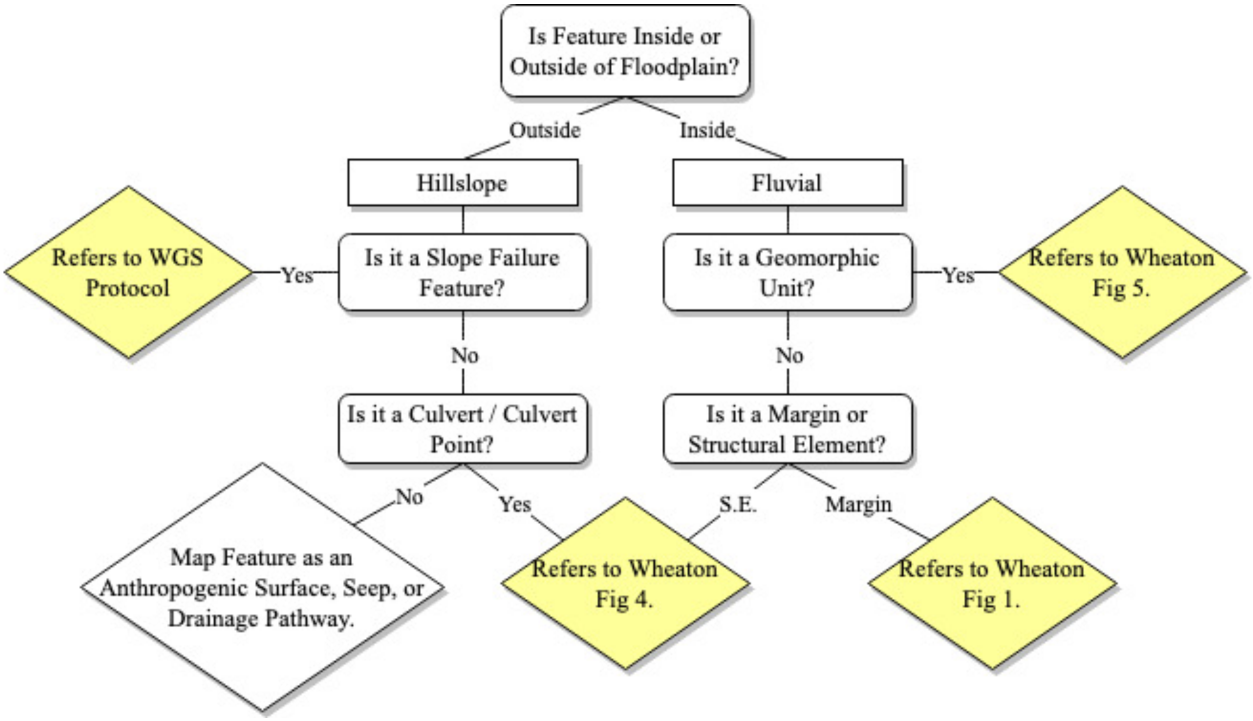


Figure 5: Mapping flow chart and decision tree outlining cases in the Geomorphic Mapping Protocol that call to the WGS Landslide protocol (Slaughter et al., 2017) and Wheaton et al. (2015) study. Referenced Wheaton et al. (2015) figures are reproduced in Appendix B.

Table 2 provides a look at the next step deeper into the protocol I have assembled. Here, I present the field names of each feature class to show the types of attributes collected for each mapped feature. The descriptions for each field name are in Table 3. Each feature class has standard attributes related to its spatial reference, geometry type, and collection data, such as 'OBJECTID', 'Shape', 'Shape_Length', 'Shape_Area', 'created_date', and 'last_edited_date'. Many of the field names used in this protocol are sourced directly from Figures 1 and 4 of the Wheaton et al. (2015) study to follow their proposed taxonomy framework for identifying fluvial margins and structural elements. These fields can be found in the *Banks*, *Individual_LWD_pieces*, *Large_Boulders*, *Log_Jams*, *Culvert_Points*, and *Culverts* feature classes. Many field names were initially prescribed by the MORA Geology Group, and as I tested the protocol, some field names were added over time as needed. These field names include the 'Erosion' and 'Moisture' fields in the *Banks* feature class, the 'Imbedded' field in structural elements feature classes, and the 'Inlet_or_Outlet' and 'Impairment' fields in the *Culvert_Points* and *Culverts* feature classes respectively. Overall, a total of 23 different attribute fields can be found in the protocol to define the geomorphic feature classes of focus.

To collect metadata for each feature, I enabled 'editor tracking' in ArcGIS Pro to note who mapped the feature, when they mapped it, who last edited it, and when they last edited it. Additionally, I added the *Receiver_Type* field to the Geomorphic Mapping Protocol for all features to designate what tool was used to collect the spatial data for that particular feature. In the case of this project, I collected feature locations in ArcGIS Pro with imagery, using a consumer grade GNSS system onboard a tablet or smartphone, or using an Emlid Reach RS2 GNSS receiver tethered to the tablet. Each tool has a different resolution, and thus the location of features mapped with different tools has different uncertainty. The information placed in the *Receiver_Type* field can be used to track the varying levels of uncertainty associated with the mapped data and the associated inventory can be graded depending on this information in its entirety.

Each individual field in a feature class attribute table can be populated with a variety of descriptive values depending on the data being collected. Many of these are numerical values measured during collection or text fields with predetermined options defined in the domains of the feature classes, grouped under each individual field name. These domains are described in Table 3, and they are limited to specific features depending on the fields that are defined to those features.

The Inventory

Almost every feature class from this protocol was identified within the process boundaries of the field site, and therefore represented in the Nisqually-Paradise Milepost 5-to-6 inventory. The only features not identified within this study were *fans*, *rockfall deposits*, and *shallow landslides*, which are all described in the WGS protocol. An ESRI geodatabase of my inventory is in Appendix C, providing access to the complete dataset of features mapped within the study site of interest. A visual representation of the mapped features can be viewed in Figures 6, 7, and 8. Figure 6 shows the various geomorphic units, boundaries, and margins that define the river valley and represent the general channel behaviors observable at the site of interest. The legend in Figure 6 shows the *Banks* feature split into four different margins. ‘Channel Margin’, ‘Levee’, and ‘Valley Bottom Margin’ are sourced from the feature field ‘Margin Type’, whereas ‘Confining Margin’ is sourced from the feature field ‘Confinement’. The *Banks* feature has both ‘Margin Type’ and ‘Confinement’ assigned to it, therefore a bank can be labeled as both a ‘Channel Margin’ and a ‘Confining Margin’, for example.

Figure 7 shows the spread of structural elements and other miscellaneous features mapped within the site. Over the course of the mapping process, a total of 28 culverts, 44 individual large wood pieces, 24 large boulders, 28 log jams, and 1 seep were individually mapped. Additionally, six different anthropogenic surfaces and 24 drainage pathway stream segments were also mapped, found in both the floodplain as well as adjacent hillslopes.

The final part of this inventory tests the WGS protocol on the study site (Figure 8). Of the four landslide types covered in the WGS protocol, ‘landslide deposits’ was the only one identified in the area. Figure 8 presents the location of a relatively old landslide deposit located on the southwest end of the study road segment, including its general boundaries, scarps, and flanks mapped following the WGS protocol. Also, there is one *Field_Check_Location* located within the *Landslide_Deposits* polygon. This is an indication that I field verified the digitally-mapped landslide, noting characteristics and key attributes that can be viewed in the full inventory (Appendix C).

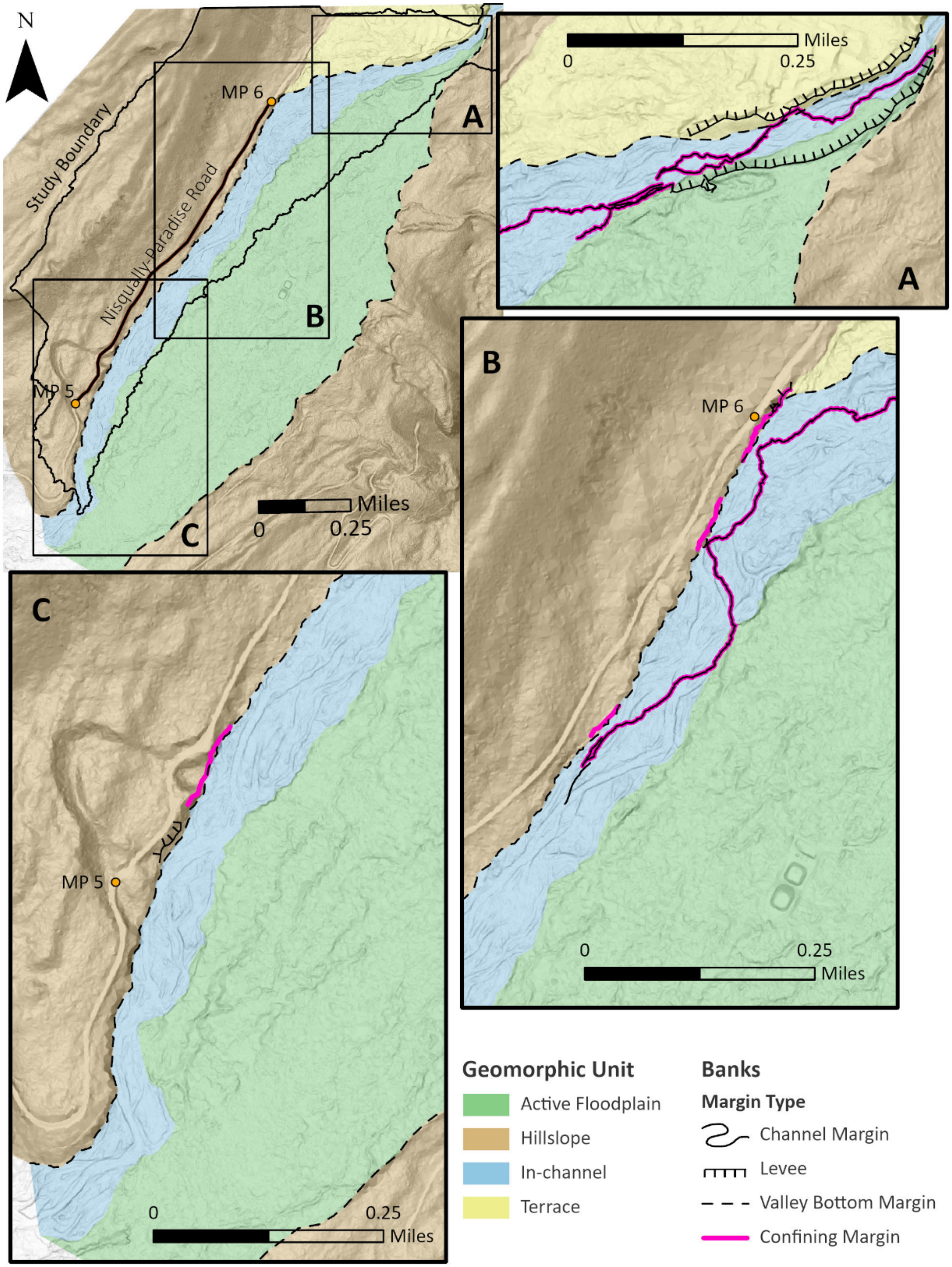


Figure 6: Inventory map of *Geomorphic_Unit* and *Banks* features classified by stage heights and types. The reference map is scaled at 1:25,000. Sections (A), (B), and (C) are scaled at 1:10,000.

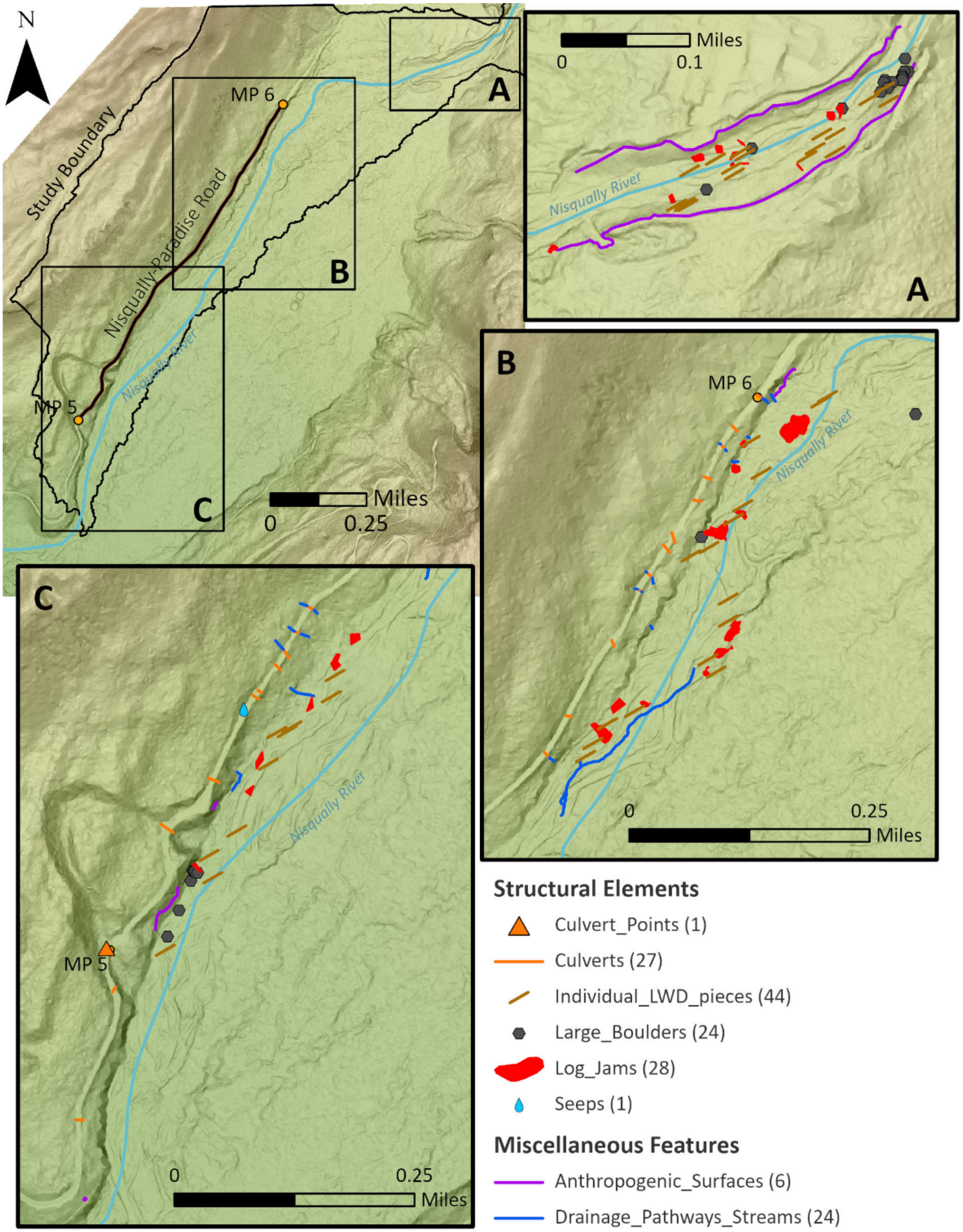


Figure 7: Inventory map of structural elements and miscellaneous feature classes identified within the process boundaries of the study site with total feature counts in the parentheticals. The reference map is scaled at 1:25,000. (A) The northeast corner of the study site is scaled at 1:7,500. (B) and (C) Centralized and northeast segment view of the site scaled at 1:10,000.

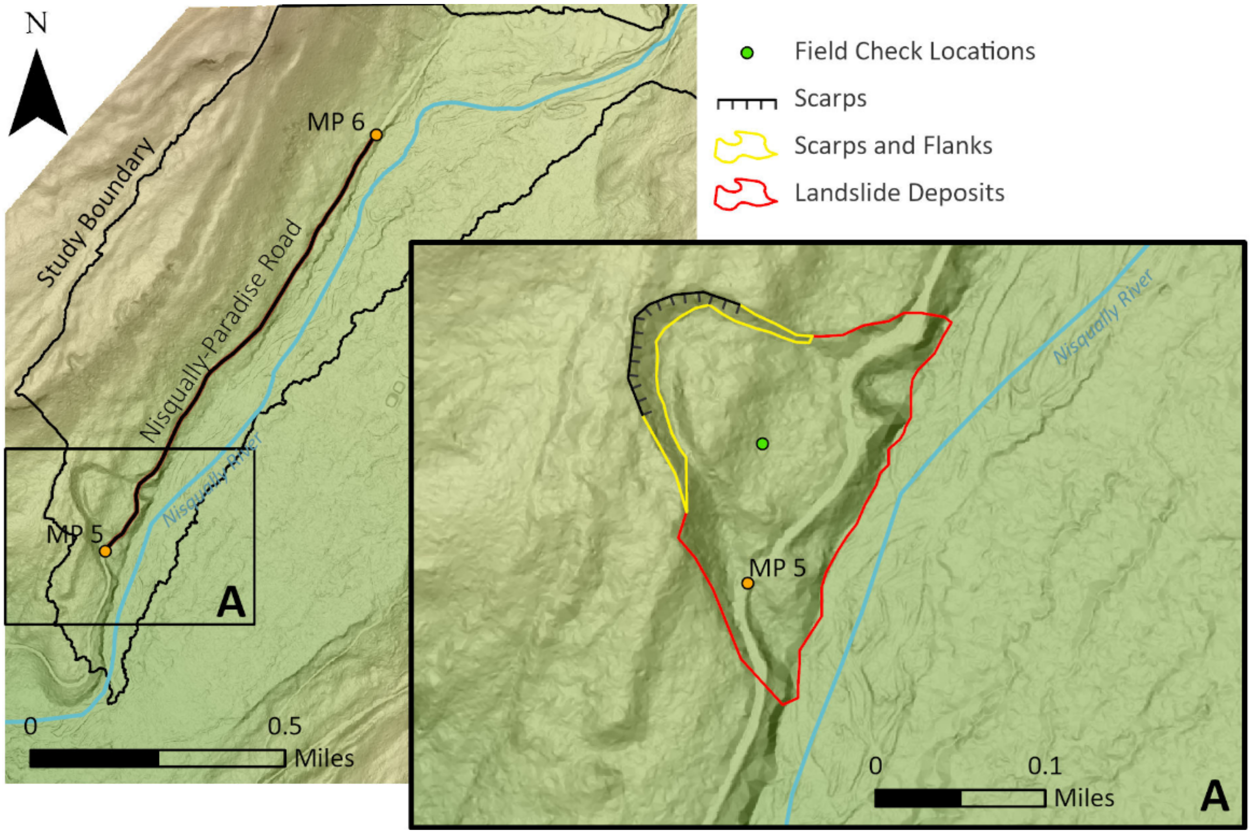


Figure 8: Inventory map showing the *Landslide_Deposits* feature layers mapped within the study site using the WGS protocol.

Discussion

Interpretation of Observations and Analyses

A benefit of developing this protocol in collaboration with the professional geoscientists in the MORA Geology Group is vetting with continuous consultation from the very people who will be using it in the place it is designed for. Overall, the protocol is a melding of the Wheaton et al. (2015) study on fluvial landform taxonomy and the WGS protocol for mapping landslides with LiDAR (Slaughter et al., 2017). It combines concepts and methodology from these two peer-reviewed geomorphic mapping publications to provide a comprehensive remote and field mapping framework. Applying these concepts, we added and modified relevant features and key attributes, such as *Seeps*, *Anthropogenic_Surfaces*, *Culvert_Points*, *Culverts*, and *Drainage_Pathways_Streams* to further refine resulting inventories. As the Geology Group applies this protocol to different sites in the Park, they may find in the future that more aspects should be added from the foundational references and beyond, or some proposed features are less useful than originally thought. As it stands, the protocol is in its 'Beta' phase, yet it is complete enough to produce inventories useful to the MORA geologists.

The inventory I compiled during the protocol testing efforts is essentially a snapshot of the study site during the 2021 summer season with varying levels of accuracy and completion. Any inventory data mapped using LiDAR-produced hillshades and slope layers is by its nature, potentially outdated and may not represent landscape changes that occured between LiDAR data collection and time the mapping occurred. The Lewis County 2009 LiDAR data (Mann et al., 2010) was used because it was the most recent dataset available that covered the study area, but it does not cover the whole park. In order to apply this protocol everywhere in the Park, the Geology Group will use a parkwide dataset from 2008 for its operational version of the protocol until a newer dataset is available. For the most part, the 2009 LiDAR data worked for the inventory collection here, but the site selection watershed delineation was truncated on the north end due to the lack of coverage. In an ideal scenario, a more recent and representative LiDAR dataset would be used while mapping using this protocol.

The *Receiver_Type* attribute field in the inventory designates what tool was used to map the data, differentiating between digital imagery/LiDAR mapping or in-field mapping with various GNSS methodology. The variation in these methods of collection creates uncertainty in the inventory as a whole, but the different designations can be used for a variety of future analyses and decision-making. For example, varying levels of the banks and channel margins were mapped using both LiDAR and the Emlid Reach RS2 receiver. The resulting data can be used to compare bank positions between 2009 and 2021, providing a coarse estimate of erosion rates within the study site. This inventory does not provide survey-grade accuracy and precision, but the attributed data may identify areas within the study site that can be targeted for finer resolution surveys in the future.

Collecting the data with varying grades of GNSS receivers was a useful exercise allowing for visual comparison in the resulting data (Figure 9). Here I compare the output of mapping polyline features with the consumer grade GNSS receiver within mobile phones/tablets versus the Emlid Reach RS2 receiver. Inset A in this figure shows the results of continuous polyline mapping with low accuracy receivers. These resulting lines are jagged and overlapping, providing a poor representation of channel banks and other linear geomorphic features found in natural environments. Inset B shows the jagged lines mapped with the tablet alongside smoother lines mapped using the higher-grade Emlid receiver. The red and blue lines in Inset B represent two different bank features, but show a side by side comparison of the outputs the different receivers provided. Another example of conflicting data is visible in inset A of Figure 6. This map shows a confining channel margin mapped with the tablet crossing over a valley bottom margin into the terrace geomorphic unit polygon mapped using the LiDAR. Using the measure tool in ArcGIS Pro, I found that these features overlapped roughly 5 to 8 meters. This overlap is likely attributed to both the inaccuracy of the tablet and the age of the LiDAR data. The LiDAR is over 12 years old, and the terrace unit has incised since then. Once I made these observations during the field season, it was clear that consumer grade GNSS receivers would not provide sufficient results in remote study locations within the Park. In locations where the GNSS conditions are not ideal, the mapper should plan to collect field data when the site should have optimal satellite visibility and geometry, and could set up a GNSS base station to conduct a Real-Time Kinematic (RTK) survey for higher accuracy mapping results.

When testing this protocol, my primary focus was developing the field methodology and user experience. Consequently, the strongest aspects of the protocol are attributed to mapping the smaller polygon and point features such as structural elements. The field site provided many opportunities to map these non-continuous and largely accessible features where I could focus on finer details and physical observations with ample time. Inversely, I had less opportunity to develop exclusively digital features. For example, the *Geomorphic_Unit* feature could be mapped to a higher scale in the future, using curvature tools and profile lines to interpret different landform features. With that in mind, these features are site dependent, and higher resolution might be more appropriate for smaller study sites with greater topographic variation.

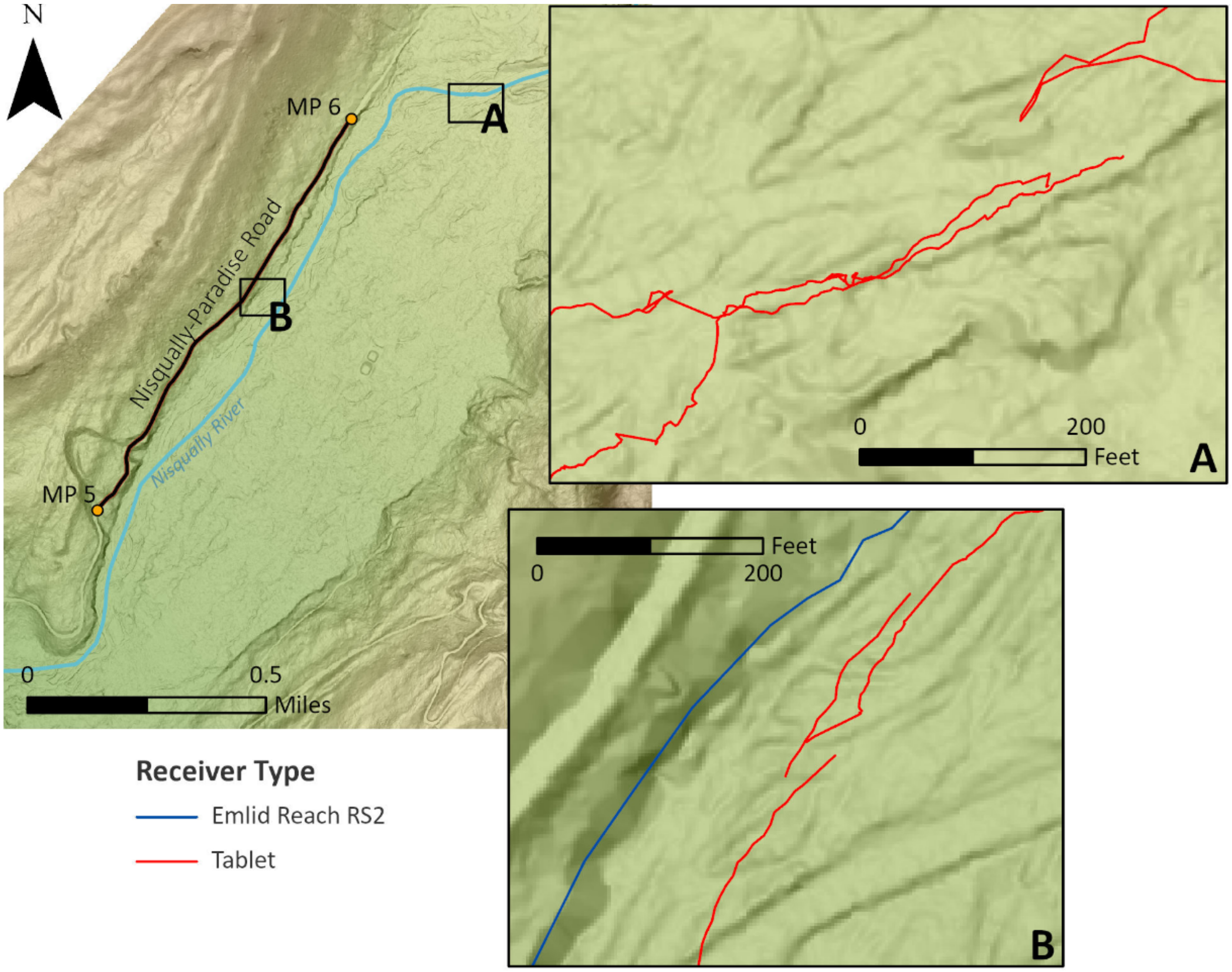


Figure 9: Map showing the smoother linear features mapped with the Emlid Reach RS2 (blue) compared to the erratic output produced with a tablet (red). (A) 1:2000 scale snapshot of overlapping and jagged linear features mapped with a tablet. (B) 1:2000 scale snapshot of the jagged tablet-mapped bank features (red) compared to different bank features mapped using the Emlid (blue) with smoother and higher accuracy results.

One final note about the inventory is that I added editor tracking fields after I completed mapping, so these fields do not exist in the inventory and are only in the protocol template. Filling out these fields serves more of an operational purpose and also allows the viewer to follow a chronology of mapping and additional metadata that can be used for future analysis.

Benefits of the Geomorphic Mapping Protocol

As it stands, this protocol can be used as a standardized format to create digital geomorphic landform inventories with a high degree of flexibility. The inventory can also be used as an initial layout to monitor the overall evolution of the site as major events occur. The nature of the field-enabled mapping with mobile devices provides an efficient data management process through cloud-based ArcGIS Online. Depending on the online settings, the inventory can be accessed, added to, and edited by anyone within the Park, agency, or public. With the correct configurations, the inventories can be readily transferred, and anyone with a general geoscientific background can readily make contributions. Additionally, the protocol covers mapping at a wide range of scales, making it applicable to a broad variety of sites with little variation to methodology. All of this can be accomplished by one mapper with minimal and relatively inexpensive equipment.

Complementary to the ease of accessibility and usability, this protocol has the potential to improve natural and historical resources management within the Park and beyond. With consistent and rapid repeat mapping of sites prone to geohazards and hydrological events, stakeholders can observe and monitor geomorphic conditions and landform evolution on a range of timescales. This data enables management to proactively make informed and actionable decisions that can assist in the preservation of public-land resources. These improvements extend beyond Mount Rainier National Park and can benefit research efforts on interdisciplinary and interagency levels. The protocol is customized for MORA, but can be modified to apply to any landscape.

Limitations of Results

This protocol was designed for mapping and describing information about the geomorphology of a field site of interest within the Park. While it can be used elsewhere, the protocol would need to be modified and tested to include characteristics specific to the new site's geologic setting. The protocol is logical and repeatable but should be tested in different locations within the Park from start to finish to fully verify its viability. This concept of testing the protocol at representative locations is key for producing inventories that provide a complete picture of the sites (and hazards) of interest.

The main goal of mapping an inventory at this study site was to test the protocol in real-time and was not meant to be a complete representation of the site. Due to changes in methodology, the inventory is not only incomplete, but also presents inconsistent and inaccurate data. The low precision of the GNSS receivers within the tablets and mobile phones produced locations of features a minimum of 12 feet. This precision was worse in portions of the field site with limited satellite visibility and multipath reflected signals due to trees and other reflective surfaces. Another relic of the method changes in the mapping is the varying mapping scales used. Initially, I could not use defined scales systematically until the methods were tested, adding even more inconsistencies to the inventory data.

When high quality LiDAR and aerial imagery is available, a majority of the mapping described in this protocol can be conducted remotely. However, this reference data is not produced frequently enough to rely on these methods alone. Also, more accessible and low cost alternatives, such as UAV surveys, are not permissible within national park boundaries. As a result, the protocol methods rely on relatively inefficient and time consuming field surveys. This study's field site featured rugged and uneven terrain with impassable river channels and densely vegetated hillslopes. The amount of mapping that I could accomplish in one day was quite limited and required multiple outings.

Due to the highly dynamic nature of the Nisqually River valley, the site underwent many changes between mapping outings. The site would present different features depending on the time of day and recent weather. The daily high flow of the river occurs during the warmest part of the day as meltwater is provided from the glacial source at a higher rate. The river is also prone to significant behavior changes due to seasonal characteristics. In late October and early November of this year, a large flood occurred on the Nisqually River. This flood reworked the previously mapped features and deposited a layer of new sediment onto the floodplain. Monitoring such an ever-changing environment requires frequent repeat mapping efforts, which may not always be achievable in many of the Park's remote and rugged locations.

Recommendations for Future Work

The major themes for further developing this proposed protocol involve repetition. With this complete protocol, a mapping effort should be conducted within the same boundaries early in the summer of 2022. This should allow for a comparative visualization of features mapped with only one winter of changes. Additionally, it would be useful to test this protocol at other sites in the Park, addressing any new issues encountered. Retesting the protocol in different locations and incorporating required changes will make it more representative of the entire park and help verify the proposed methods here. As these sites are identified and tested, the individual inventories will begin to contribute to a comprehensive parkwide inventory.

As the parkwide inventory grows, data management will become more complicated. The ArcGIS Online platform houses data in the 'cloud', viewable in a web map format and accessible in ArcGIS Pro through the 'Portal' feature. In discussions with the Geology Group, we determined it would be useful to automate two-way data migration from ArcGIS Online to a server hosted database. Each version of the inventory should be saved separately for analysis and eventual archiving.

As the protocol is further tested, it may be appropriate to revisit the initial foundational literature to consider other parameters originally left out and further blend the two methods together. The features selected from the Wheaton et al. (2015) study were chosen to fit the specific needs of the MORA Geology Group, but different features may be required in other settings. On the other hand, there are features to the WGS protocol, such as relationship classes, that can likely make this protocol more efficient as well. Using relationship classes can reduce redundancies and streamline the protocol in a more logical manner.

There are many tools in ArcGIS Pro that can automate analyses associated with these feature classes. The Geology Group and I envision a more mature and developed protocol having the ability to rapidly calculate morphometric parameters beyond the standard calculated geometry of the current protocol, such as lengths, areas, or volumes of each feature. These parameters could include calculating confinement, longitudinal and cross valley gradients from polyline feature classes, and further relevant geostatistical patterns that can be used for hazard forecasting.

Conclusion

The Geomorphic Mapping Protocol proposed in this study provides the MORA Geology Group and park management with a step-by-step workflow for monitoring geomorphic conditions and landform evolution within the Park. Stakeholders can apply this methodology to a site of interest and identify landform and feature quantities, prevalence, geometry, and proximity. Armed with this information, they can perform geostatistical and geospatial analyses to better prepare for and mitigate damages from geohazards and major hydrological events. I designed the protocol based on peer-reviewed publications that identify and utilize process-based naming conventions to standardize interpretations. Furthermore, I designed it in collaboration with the MORA Geology Group to ensure viability and compatibility with the Park's greatest needs.

With this documentation, the protocol is presented as a functional model with a template geodatabase supplied in Appendix A. Currently, the protocol is already implemented within the MORA Geology Group where it will continue to develop. Testing this model within the Nisqually River study area revealed a number of challenges and inconsistencies to modify and adjust. Through the many mapping efforts over the field season, the Geology Group and I identified minimum standards for mapping scales, GNSS collection accuracy, and aerial imagery quality. The final inventory product is incomplete but contains comparative data useful for justifying the decision-making that went into building this protocol. Moving forward, this protocol is ready for continuous testing at the original site adjacent to the Nisqually-Paradise Road as well as numerous other locations in the Park with similar hazards. While this testing continues, the MORA Geology Group will be able to build a parkwide inventory of geomorphic features and landforms to actively monitor and manage the restless landscapes of Mount Rainier National Park.

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Tables

Table 1: Protocol feature classes, and their corresponding geometry types split by feature datasets ‘Fluvial’ and ‘Hillslope’.

Fluvial

Feature	**Geometry Type**
Banks	polyline
Geomorphic_Unit	polygon
Individual_LWD_pieces	point
Large_Boulders	point
Log_Jams	polygon

Hillslope *WGS protocol feature

Feature	**Geometry Type**
Anthropogenic Surfaces	polyline
Culvert_Points	point
Culverts	polyline
Drainage_Pathways_Streams	polyline
*fan**	polygon
*field_check_simple**	point
*landslide_deposit**	polygon
*recent_landslide_point**	point
*rock_fall_deposit**	polygon
*rock_fall_scarp**	polyline
*scarp**	polyline
*scarp_and_flank**	polyline
Seeps	point
*SLIP_landslide**	polygon

Table 2: Protocol feature classes and their corresponding fields.

*Data collection fields associated with every feature class.

Fluvial

Banks	*Geomorphic_Unit*	*Individual_LWD_Pieces*	*Large_Boulders*	*Log_Jams*
OBJECTID	OBJECTID	OBJECTID	OBJECTID	OBJECTID
Shape	Shape	Shape	Shape	Shape
Shape_Length	Shape_Length	Origin	Origin	Shape_Length
Erosion	Shape_Area	Type	Type	Shape_Area
Moisture	Stage_Height	Orientation	Orientation	Origin
Origin	GU_Form	Position	Position	Type
Margin_Type		Obstruction_Type	Obstruction_Type	Orientation
Confinement		Stages_Influenced	Stages_Influenced	Position
		Shear_Zone_Type	Shear_Zone_Type	Obstruction_Type
		Imbedded	Imbedded	Stages_Influenced
				Shear_Zone_Type
				Imbedded

Hillslope

Anthropogenic_Surfaces	*Culvert_Points*	*Culverts*	*Drainage_Pathways_Streams*	*Seeps*
OBJECTID	OBJECTID	OBJECTID	OBJECTID	OBJECTID
Shape	Shape	Shape	Shape	Shape
Shape_Length	Origin	Shape_Length	Shape_Length	
	Type	Origin		
	Orientation	Type		
	Position	Orientation		
	Obstruction_Type	Position		
	Stages_Influenced	Obstruction_Type		
	Shear_Zone_Type	Stages_Influenced		
	Imbedded	Shear_Zone_Type		
	Inlet_or_Outlet	Impairment		

*Receiver_Type
created_user
created_date
last_edited_user
last_edited_date

Table 3: Feature class field names and their corresponding data types, domains, and domain options.

Field	Description	Data Type	Domain	Domain Options
OBJECTID	Feature reference ID.	Object ID	-	-
Confinement	Notes if the margin is actively confining the channel.	Text	Confinement	Yes No Not Applicable
created_date	Date each feature was initially mapped.	Date	-	-
created_user	User who initially mapped each feature.	Text	-	-
Erosion	Notes if the margin is eroded or non-eroded.	Text	Bank Erosion	Eroded Non-Eroded Not Applicable
GU_Form	Notes if the geomorphic unit form is concave, convex, or planar.	Text	GU Form	Concave Convex Planar
Imbedded	Notes if the feature is resting on the ground and completely observable or imbedded in the ground and only partially observable?	Text	Imbedded	Imbedded Resting
Impairment	Notes the extent in which the culvert is impaired, if at all.	Text	Impairment	Clear Partially Impaired Fully Impaired
Inlet_or_Outlet	Notes if the located culvert endpoint is an inlet or an outlet.	Text	Inlet or Outlet	Inlet Outlet
last_edited_date	Date of the last edit made to the feature.	Date	-	-
last_edited_user	User who last used edited the feature.	Text	-	-
Margin_Type	Notes if the margin is a channel margin, bedrock valley margin, valley bottom margin, or levee.	Text	Margin Type	Channel Margin Bedrock Valley Margin Valley Bottom Margin Levee Not Applicable
Moisture	Notes if the channel margin is actively wet or dry from recent flow activity.	Text	Bank Moisture	Wet Dry Not Applicable

Obstruction_Type	Notes how the structural element obstructs the channel.	Text	Obstruction Type	Complete Barrier Porous Barrier Deformable Barrier Sieve Funnel Roughness Not Applicable
Orientation	Notes what orientation the structural element is positioned.	Text	Orientation	Transverse Streamwise Diagonal Standing Not Applicable
Origin	Notes if the feature is of natural or anthropogenic origin.	Text	Origin	Natural Anthropogenic Not Applicable
Position	Notes where the structural element is located in relation to the channel?	Text	Position	Bank-Attached Channel Spanning Mid-Channel Side-Channel Floodplain Not Applicable
Receiver_Type	Device used to locate features.	Text	-	-
Shape	Feature geometry.	Geometry	-	-
Shape_Area	Feature area.	Double	-	-
Shape_Length	Feature length.	Double	-	-
Shear_Zone_Type	Notes how the structural element influences the channel flow.	Text	Shear Zone Type	Wake Eddy Hydraulic Jump Not Applicable
Stage_Height	Notes what flood stage the geomorphic unit lies within.	Text	Stage Height	Hillslope Terrace Active Floodplain In-channel
Stages_Influenced	Notes what flood stage the structural element lies within.	Text	Stages Influenced	Baseflow Bankfull Flow Typical Flood Rare Flood Not Applicable
Type	Notes if the feature is natural organic, natural inorganic, or anthropogenic.	Text	Type	Natural Organic Natural Inorganic Anthropogenic Not Applicable

Appendices

Appendix A: Geomorphic Mapping Protocol Template

Digital Appendix: GeomorphMappingProtocolTemplate.gdb

Appendix B: Wheaton et al. (2015) Figures referred to in Figure 5

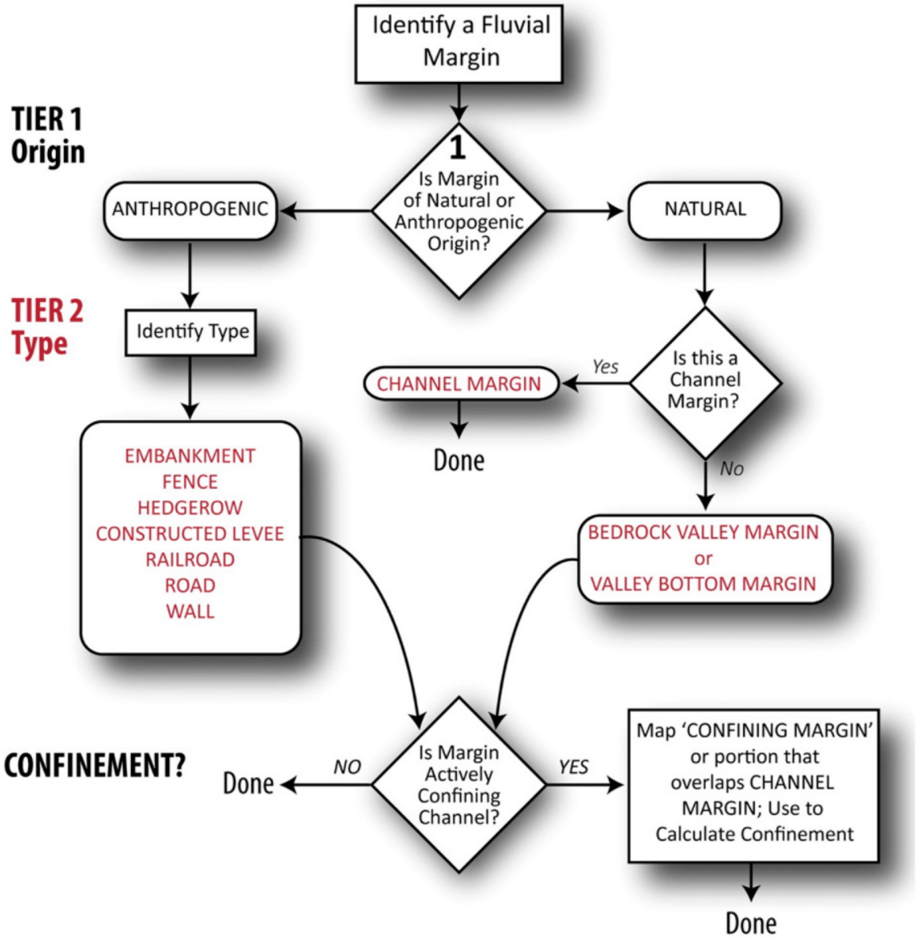

Fig. 1. Tiered fluvial margins classification framework.

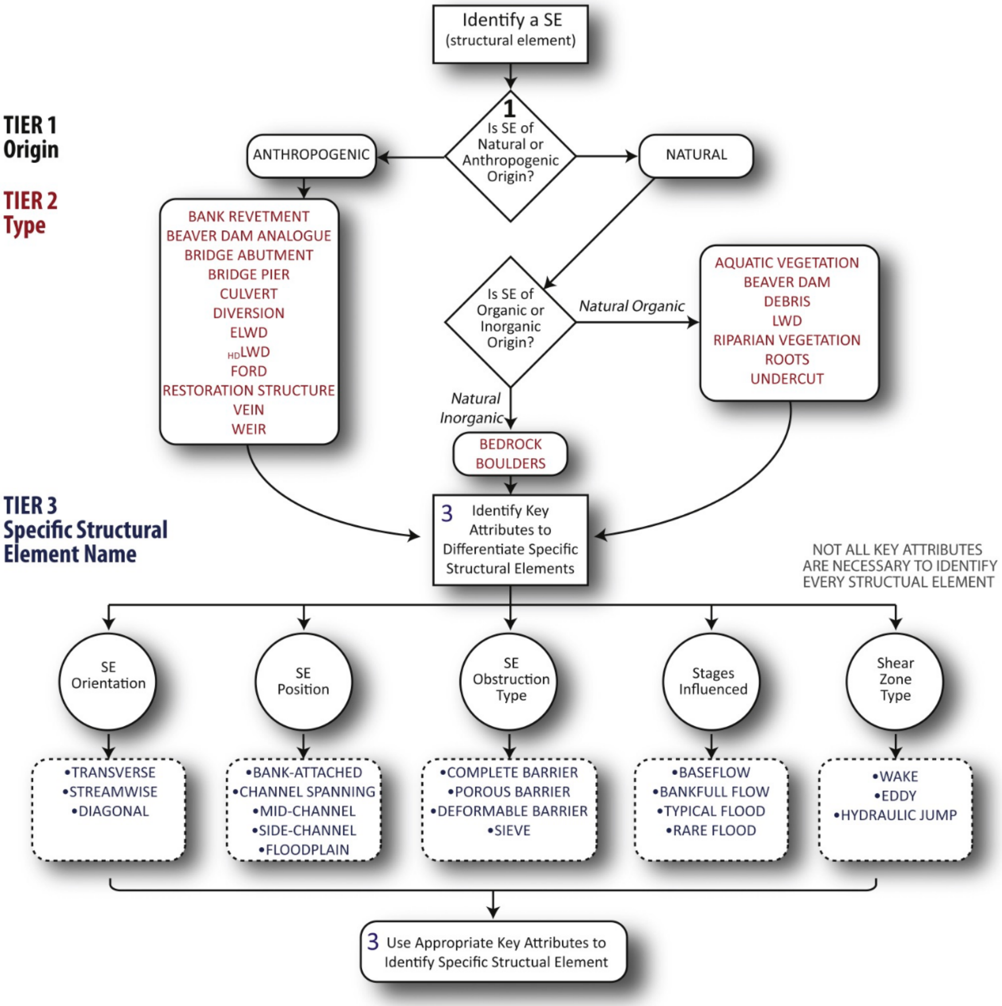

Fig. 4. Tiered fluvial structural element classification framework.

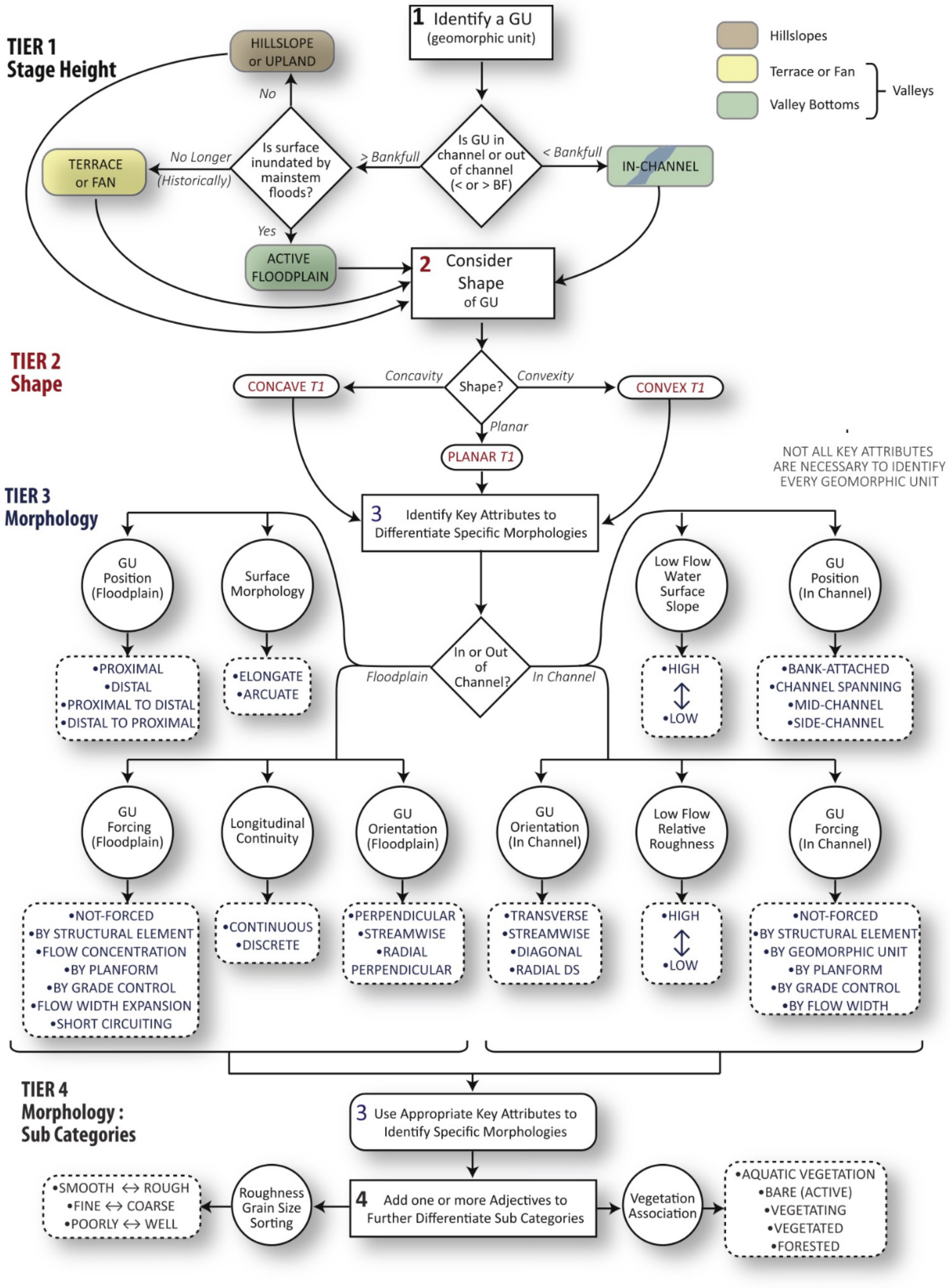

Fig. 5. Tiered fluvial geomorphic unit classification framework.

Appendix C: Milepost 5-to-6 Geomorphic Inventory

Digital Appendix: MORA_Geomorphic_Inventory_MP5to6.gdb