Flathead River Watershed Assessment (NetMap)

Analysis of Road Surface Erosion and Other Watershed Attributes in the Montana, USA and British Columbia, Canada Portions of the Basin in Support of the International MOU

For the U. S. Fish and Wildlife Service (Denver, CO)

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NetMap Analysis: Flathead River Watershed

Executive Summary:

The NetMap watershed assessment of the Flathead River basin (covering both US and Canadian portions) includes analyses of: 1) forest road erosion and sediment delivery to streams, 2) other road risk factors, 3) other erosion processes, 4) floodplains and channel migration zones, 5) fish habitats, 6) wildfire risk and post fire erosion, and 7) climate change. The main conclusions of the analysis are listed below. Although this report contains an overview of the watershed assessment, NetMap's Digital Landscape and Analysis Tools (requires ArcGIS) will provide more comprehensive and geographically extensive analysis capabilities conducted by involved stakeholders.

(1) The potential for forest road (unpaved) sediment production and delivery to streams is substantial and varies from high to low across the watershed. The highest predicted road surface erosion and sediment delivery to streams is within the Canadian portion of the watershed due to higher road densities (km/km^2) and larger road widths.
(2) A comparison between predicted road surface erosion and estimated background sediment yields at the scale of individual hillsides and channel segments (locally and cumulative downstream) reveals that in many locations, predicted road erosion can exceed background sediment yields by tens to hundreds of percent. Higher values are restricted to local hillsides and stream reaches and to upper tributaries. Characterization of road hydrologic connectivity and predicted surface erosion could be improved by incorporation of geo-referenced road drainage structures in both the US and Canada.
(3) There are numerous locations in the watershed where road related gully erosion may be cause for concern.
(4) Floodplain and terrace surfaces occur as an elevation mosaic along the Flathead River mainstem and its tributaries, providing a provisional analysis of channel migration zones. Road segments at potential risk within that zone can be identified.
(5) Distributions of Bull Trout and Westslope Cutthroat Trout and a prediction of Westslope Cutthroat Trout habitat quality are used to map and evaluate environmental stressor (road erosion, wildfire, climate change) – habitat intersections. Mapping of Bull Trout and Westslope Cutthroat Trout habitat extent could be improved (in the US portion) and extended into Canada using available field information on fish distribution/quality; data can be transferred to NetMap's synthetic stream layer.
(6) Using forecasts available from the Western Environmental Threat Assessment Center (WWETAC), predictions of fire probability and fire severity (flame length) were mapped across the US portion of the watershed. NetMap's habitat-stressor analysis reveals where the highest fire probability overlaps the highest fire severity and where that pair intersects sensitive fish habitats. Other analyses reveal where the highest fire probability and highest fire severity overlaps with the highest potential for post fire erosion.
(7) Climate Change forecasts for temperature, precipitation, snow accumulation and runoff were mapped across the Flathead River watershed (University of Washington, Climate Impacts Group). Stressor – habitat intersection analysis reveals where the highest projected reductions in summer flow overlap with the highest predicted fire severity. The analysis can be used to help inform pre wildfire planning (fuels reduction, prescribed fire etc.). Significant reductions in snow

accumulation are forecasted and highly dependent on elevation patterns in the watershed. This prediction, along with forecasted changes in temperature and precipitation, leads to forecasted reductions in summer flow and increases in winter flows and floods.

Analyses conducted in the Flathead River basin, using a range of tools in NetMap, can be applied to natural resource planning activities involving forestry, fisheries, wildfire and climate change or for planning restoration projects. NetMap tools combined with readily available data were used to create a multi-scale analysis to provide insights into road, channel, and watershed scale attributes pertinent to aquatic systems. Field visits/measurements are recommended to be used in conjunction with the NetMap analyses. No field work was conducted during this study.

Introduction

The US Fish and Wildlife Service, in support of the International Memorandum of Understanding concerning the Trans Boundary Flathead River (2010), commissioned a watershed assessment focusing on analysis of road surface erosion sources in the Flathead River watershed, including in the Canadian portion of the basin. Study objectives involve identifying the spatially variable sources of road sediment production and delivery to streams across the Flathead River basin using computer modeling. Additional analyses include mapping: (1) other sediment sources in the Flathead River specifically those pertaining to gullying and shallow failure, (2) fish habitats (distribution of Westslope Cutthroat Trout and Bull Trout and modeling the potential quality of cutthroat trout), (3) floodplains/channel migration areas, (4) wildfire risk and post fire erosion threat, and (5) climate change. The analysis system NetMap (Benda et al. 2007, Benda et al. 2009, www.terrainworks.com), comprised of digital landscapes and analysis tools, is used in all components of the analysis. The Flathead River watershed has an area of 4,055 km^2 with the upper 1,125 km^2 located in Canada (**Figure 1**).

This report provides a brief overview of the NetMap analysis in the Flathead River. Spatial snapshots of the various results are provided in the Figures. For more detailed analysis capabilities and for results that span the entire Flathead watershed, refer to NetMap tools and the Flathead Digital Landscape (contact the US Fish and Wildlife Service or www.terrainworks.com for additional details).

A key objective of this USF&W supported assessment is to provide a numerical framework (e.g., Digital Landscape plus NetMap tools) for other involved stake holders to conduct their own analyses and to support ongoing and future field studies in the Flathead River watershed.

Methods

A digital landscape of the Flathead River basin was developed using a composite (merged) digital elevation model (DEM) using a 10 m DEM (US National Elevation Dataset [NED]) and a Canadian 15 m DEM (0.75 arc-second) (http://www.geobase.ca/geobase/en/data/cded/description.html). The digital landscape includes a synthetically derived stream layer produced from a set of flow routing algorithms within NetMap. The US National Hydrography Dataset (NHD) was used as a channel mask in both the US and Canada portions of the basin to guide synthetic channel delineation in low relief and low gradient areas (e.g., all areas less than 4%). Regressions for channel bankfull width and depth are from Vogel et al. (1999) and Rafn (2007) respectively (analysts using NetMap tools can change the regressions).

Gully erosion and shallow landsliding located on steep and convergent hillslopes deliver a range of particles sizes to channels ranging from boulders to silt/clay. Bedload (cobble, gravel, sand) is the primary sediment caliber stored in channels. Hillslope surface erosion and road surface erosion contribute mostly fine sediment to streams and rivers (sand and smaller) and is considered suspended load. Although suspended load can increase turbidity and impact water quality and aquatic life, it is not a significant contributor to in-channel sediment storage.

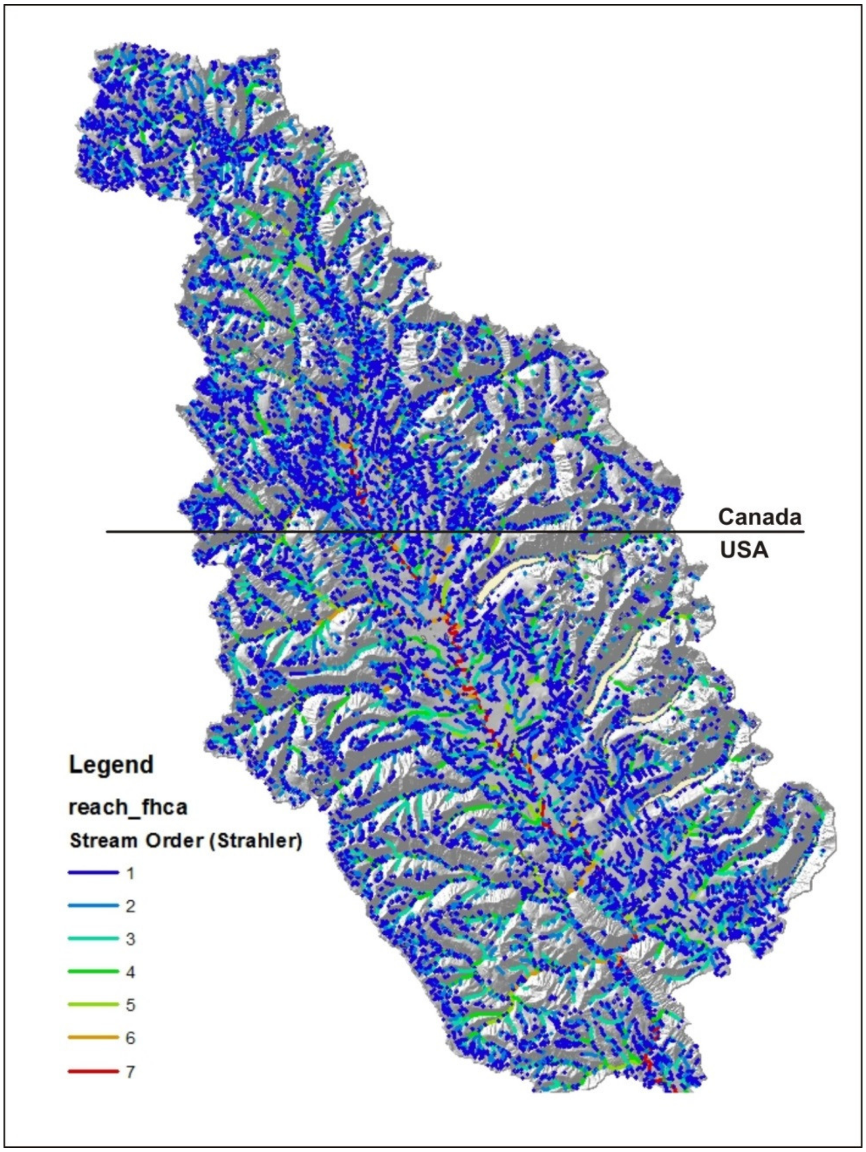

Figure 1. The Flathead River watershed study area showing stream orders.

Road Density: Subbasin and Hillslope-Channel Segment Scales

An analysis of road density (length per unit area in km/km^2 or mi/mi^2) is often used as a proxy for potential impacts from road networks (USFS 2012). In NetMap, road density is calculated at: (1) the subbasin scale (US HUC 6th level, 12 digit) and (2) at the scale of individual channel segments and drainage wings (drainage wings refer to local contributing areas located on either side of individual stream segments, typically on the order of tenths of a square kilometer in area) (**Figure 2**). Road density calculated at the scale of drainage wings and individual channel segment reveal a greater level of variability in road density, and in other watershed attributes.

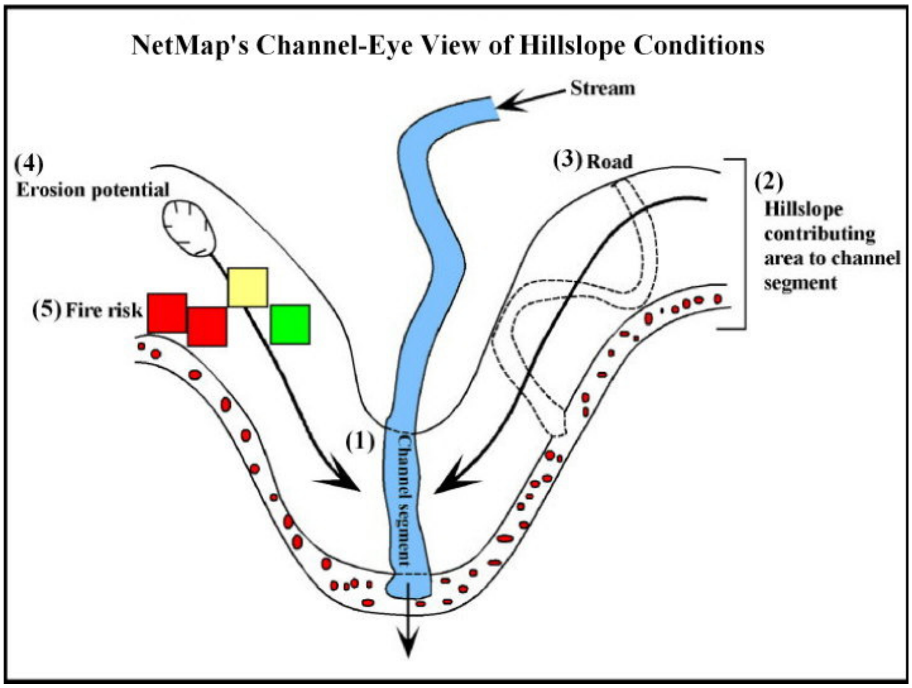

Figure 2. NetMap drainage wings are located on either side of individual channel segments (#1 segment length ranges from approximately 50 to 200 m). Watershed attributes located in the wings (#2) such as roads and pipelines (#3 as line data) and erosion potential, fire risk and climate change forecasts (#4, #5 as grids or rasters) are summarized at that scale (approximately a few tenths of a square kilometer) and reported to stream segments, providing a fish eye view of terrestrial conditions.

Road Surface Erosion and Sediment Delivery to Streams

Surface erosion on unpaved roads is governed by road gradient, length of road that is hydrologically connected (e.g., length of overland flow on a road surface), road width, road surfacing (native, gravel), traffic level (high to low), time since grading, and the routing of road surface runoff to streams (Luce and Black 1999, Sugden and Woods 2007). Two road surface erosion models were used in NetMap's analysis in the Flathead River: (1) WEPP and (2) GRAIP-Lite.

The WEPP [road surface erosion model in NetMap](#) (Flanagan and Livingston 1995) employs road width, drainage length, road gradient, surface material, soil type, and traffic level. Since WEPP predicts sediment delivery to streams (t/yr), the intervening hillslope distance and gradient between individual road segments and the nearest stream (referred to as the "buffer") influence the amount of sediment delivered to channels. If the road drains directly to a stream channel, no buffer is considered. For additional technical background on the WEPP road surface erosion model, see: http://forest.moscowfsl.wsu.edu/fswepp/docs/wepproaddoc.html.

The Geomorphic Road Analysis and Inventory Package model (GRAIP-Lite) is an empirically based approach developed by Luce et al. (2012) in the US Forest Service, Rocky Mountain Research Station (Boise, Idaho). Road sediment production is predicted by:

$$E = B*R*S*V \qquad \text{(Eq. 1)}$$

where E is road sediment production (kg/yr), B is the base road surface erosion rate, R is the elevation difference between the road segment end points, S is the road surface factor and V is the vegetation factor. V and therefore E are calculated separately for each combination of road surface type and road maintenance level. $V = 1 - 0.86x$ where x is the fraction of the road where flow path vegetation is greater than 25%.

Field measured base erosion rates (kg/yr) exist for Oregon Coast Range, sandstones (79 kg/yr); Idaho Batholith, granitics (33 kg/yr); Montana, Belt Series meta sedimentary (7 kg/yr); and Eastern Oregon, Umatilla River, basalt (1.5 kg/yr). The vegetation factor calibration data sets exist for Seeley, Montana; Siuslaw River, Oregon Coast Range; Umatilla River, Eastern Oregon; Idaho, Middle Fork Salmon; Idaho, Middle Fork Payette; and Idaho, South Fork Salmon. A "master" vegetation calibration dataset that is the average of all of them is included in NetMap's GRAIP-lite interface and is used in this analysis.

NetMap's implementation of GRAIP-Lite can be found here.

To calculate road surface erosion potential using either the WEPP or GRAIP model requires that the imported GIS road layers (that contain individual road segments that are kilometers long) be subdivided into hydrologically connected segments (**Figure 3**). This includes road segments that drain directly into stream channels as delineated in NetMap's synthetic stream network and those segments that are bounded by topographic high and low points (with the predicted drain point located at the topographic low point). NetMap's road drainage tool breaks the road at pixel cell borders and then re-aggregates them as necessary for various types of road analyses (**Figure 4**). Hydrologic road segments may vary from tens to thousands of meters in length and most commonly in the range of tens to hundreds of meters. In addition, users can import a set of geo-referenced drain points representing culverts and secondary drainage structures (rolling dips, waterbars) which are used to inform drain point location in the models; due to lack of data this enhancement was not done in the Flathead Watershed Assessment (but could be done later by stakeholders using NetMap tools).

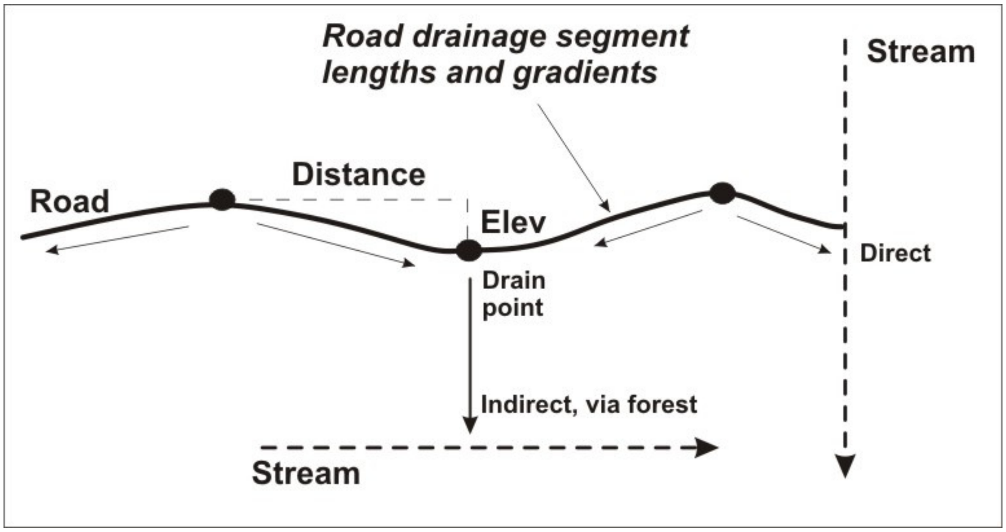

Figure 3. Road segments in NetMap are defined by their hydrological connectivity, either directly to streams or indirectly via predicted drain points and the routing of flow from those points to stream channels. Users can import their own GIS drain points to facilitate the analysis.

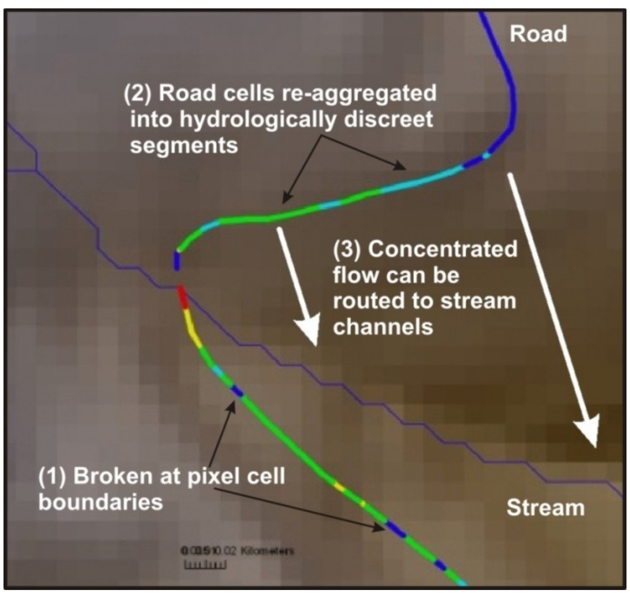

Figure 4. (1) GIS road layers in NetMap are first broken at pixel cell borders. (2) Road segments are then re-aggregated into hydrologically connected segments draining either directly to stream segments or indirectly (road drain points) via land surfaces to stream channels (3). (3) Delivery of sediment from roads to streams requires road segment be geo-referenced to stream segments.

Each road segment is geo-referenced to the stream segment that it drains into, either directly at road-stream crossings or indirectly via the land surface (via gravity flow paths) (**Figures 3 and 4**). Individual stream segments (ranging in length approximately 50 to 200 m in length) may have more than one road segment draining into it. In the WEPP model, road drainage that flows overland through the land surface to stream channels can either cause a reduction in predicted sediment delivery to streams (deposition on the forest floor) or an increase driven by erosion of the forest floor. In the GRAIP-Lite model, sediment delivery declines with increasing distance of the road to the stream channel.

We obtained road shapefiles from the US Forest Service and from Canadian Forest companies (Matt Heller, US Fish and Wildlife Service, personal communication); there are numerous areas of high road density in the Canadian and US portions of the watershed (**Figure 5**).

Figure 5. There are extensive logging road networks in the US and Canadian portions of the Flathead River basin.

The following parameter values are used in the WEPP and GRAIP-Lite road surface erosion models:

WEPP:

- Climate: Cligen = KALISPELL WB AP MT;
- Road Design: insloped, veg/rock ditch,
- Road width = US 4 m/Canadian 6-10m wide (Google Earth)
- Road fill = 5m at 50%;
- Traffic level = low (e.g., lack of traffic data);
- Soil: sandy loam, 20% rock fragments;
- Road surface = gravel

GRAIP-Lite:

- Base erosion rate = 7 kg/yr (Montana empirical data)
- Canadian road surface “Loose” = Aggregate (in GRAIP Lite), 10 m wide roads
- Canadian road surface “Rough” = Native (in GRAIP Lite), 6 m wide roads
- Vegetation Factor (used Master, all data)

Gully and Shallow Landsliding Potential

The potential for gully erosion and shallow landsliding are considered together since the topography associated with each is similar (steep and convergent landforms, **Figure 6**). Both processes are driven by hillslope (or swale) gradient, degree of topographic convergence, and contributing drainage area (Montgomery and Dietrich 1994, Miller and Burnett 2007, Parker et al. 2010). To analyze these processes we use a parameter in NetMap called ‘Generic Erosion Potential’ (GEP). GEP provides a relative measure of potential erosion based on slope steepness and convergence, recognized topographic indicators of shallow landsliding and gully erosion. GEP is based on topographic attributes of slope gradient, local contributing area, and topographic convergence derived from the DEM:

$$GEP = S*aL/b \qquad \text{(Eq. 2)}$$

where S is slope gradient (m/m), aL is a measure of local contributing area to a DEM pixel equal to the number of adjacent pixels that drain into it (varies between 0 and 8), and b is a measure of topographic convergence equal to the projection of flow direction out of a pixel onto the pixel edges. Values of b are 1 on planar slopes, less than 1 on convergent topography, and greater than 1 on divergent topography. Higher values of GEP are calculated in areas of steeper, more convergent topography. Higher values of GEP correspond to higher landslide densities and to higher gully-initiation-point densities (Miller and Burnett 2007).

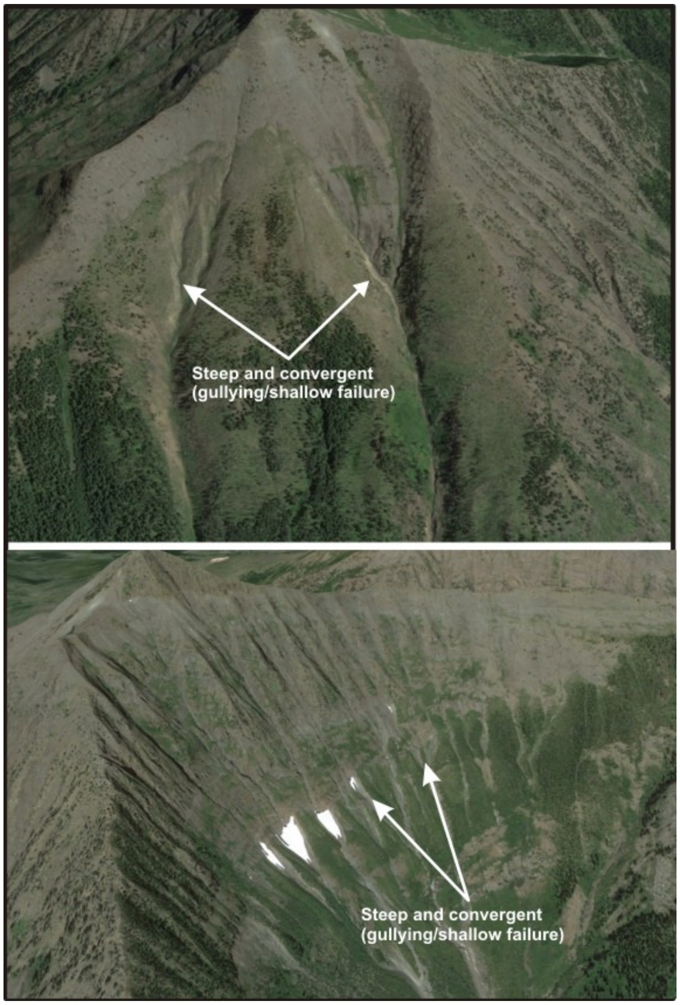

Figure 6. Examples of steep and convergent landforms prone to gullying and shallow landsliding in the Flathead River watershed.

GEP can stand alone providing a relative index of erosion potential. However, to create a more intuitive index and to estimate a “background” sediment yield (to compare with predicted road erosion), GEP indices are converted to spatially distributed sediment supply (t/km^2/yr). This requires an estimate of average basin sediment yield. During this analysis, however, independent estimates of sediment yield for the Flathead River basin could not be located. As an approximation, we apply erosion rates estimated by different methods in wider geographic areas that include the Flathead River basin. A rate of 35 t/km^2/yr is based on regional denudation (a region encompassing western Montana) determined from suspended sediment records (Judson and Ritter 1964). A second rate is estimated using a surface erosion model (WEPP) for post fire conditions in forested areas of western Montana; rates in the general vicinity of the Flathead River range between 500 and 1000 t/km^2/yr (Miller et al. 2011). Studies of post-fire erosion have shown increases of up to two to three orders of magnitude following wildfire (Morris and Moses 1987, DeBano 2000, Benavides-Solorio and MacDonald 2005). Considering that post fire erosion rates in semi-arid areas are much higher than during non-fire periods, a conservative basin average erosion rate for the Flathead River basin using these data is 5 to 30 t/km^2/yr. Based on these approximations, we apply a single value of 20 t/km^2/yr to illustrate the average rate of erosion associated with gullying and shallow landsliding (and to estimate a background rate to compare predicted road erosion).

Floodplains and Channel Migration Zones

Mapping floodplains and channel migration zones is often done in the context of a watershed assessment for the purpose of identifying ecologically important areas and to identify potentially hazardous locations for roads and pipelines. Identifying floodplains and migration zones is also important in the context of forestry activities that involve maintenance of in-stream wood recruitment and stream bank integrity afforded by vegetative rooting strength. Typically the most accurate approach for delineating floodplains and migration areas is to map them using field data and aerial photography. However, this watershed assessment is limited to computer based modeling of these landforms.

To characterize valley-floor surfaces in NetMap, DEM cells are classified according to elevation above the channel (**Figure 7**). Each cell within a specified search radius of a channel (a multiplier of bankfull widths) is associated to the closest channel cell, with distance to the channel weighted by intervening relief. Valley-floor DEM cells are associated with specific channel segments that are closest in Euclidean distance and have the fewest and smallest intervening high points. The elevation difference between each valley floor cell and the associated channel location is normalized by bankfull depth or by the absolute elevation above the channel. This procedure is repeated for every channel segment. For additional information on the use of NetMap's floodplain mapping tool see technical support and see how the tool has been used in watershed scale restoration planning, see http://www.hydrol-earth-syst-sci.net/15/2995/2011/ .

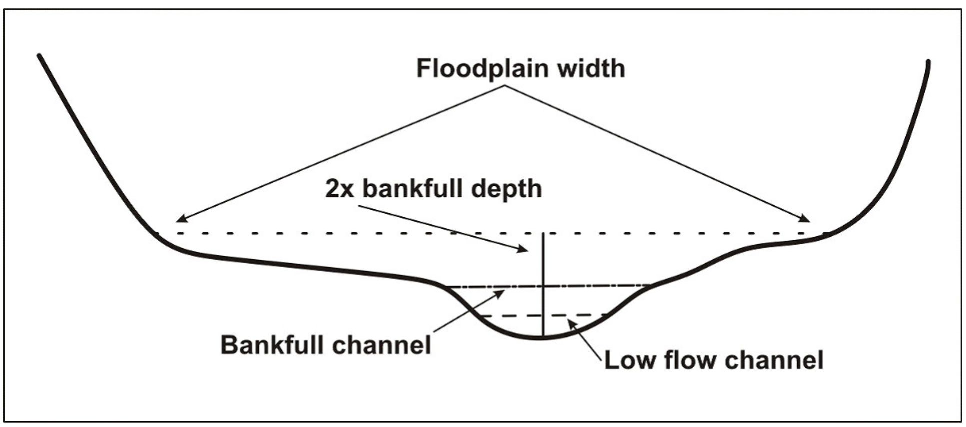

Figure 7. A sketch showing the location of the active floodplain within a valley that contains a small stream at summer low flow. In NetMap, a user selects an elevation above the channel from which to map floodplain width in units of bankfull depths or using an absolute elevation above the channel (e.g., same for all segments regardless of channel size).

Fish Habitats

The spatial extent of Bull Trout and Westslope Cutthroat Trout in the Flathead River is mapped based on existing data sources for these species (http://www.nwfsc.noaa.gov/trt/mapsanddata.cfm). In addition, to characterize the spatially varying fish habitat quality for Westslope Cutthroat Trout in the Flathead River basin, an intrinsic potential model is used (Peterson et al. 2008). The model, in NetMap, takes two forms, the full Bayesian Belief Network (BBN) and the intrinsic potential version that is restricted to three watershed attributes: channel gradient, channel width and stream temperature. An optimum stream temperature (10 – 15^{o}C) is assumed in the model application. The analysis of the distribution, abundance and relative quality of cutthroat trout habitat can be used in risk assessment. For example, an analyst can identify where the roads with the highest surface erosion potential and sediment delivery intersect the highest fish habitat quality (e.g., habitat-stressor intersections).

NetMap also includes a habitat model for Bull Trout but the geographic restrictions of the model make it unsuitable for the Flathead River watershed.

Wildfire and Post Fire Erosion (Pre and Post Fire Planning)

Wildfires can represent a significant stressor in the Flathead River watershed. High fire severity (large flame length) can lead to extensive areas of mineral soil, accelerated erosion (surface, gully, landsliding), increases in channel sedimentation and large impacts on water quality and fish habitats. This is referred to as the "Wildfire Cascade" in NetMap (**Figure 8**). However, under certain conditions, wildfires and associated accelerated delivery of sediment and organic material to streams can provide long term net ecological benefits (Benda et al. 2003)

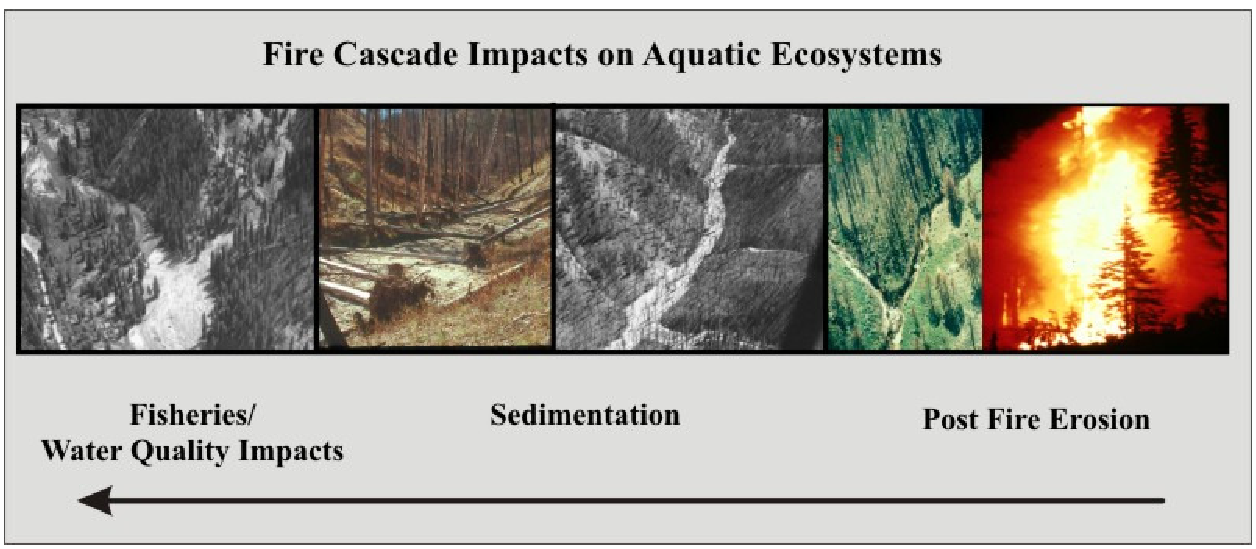

Figure 8. A "fire cascade" is the cascading sequence of impacts that begins with high severity fire, accelerated erosion, increased channel sedimentation and large impacts on fisheries and water quality.

NetMap's Fire Cascade tool is applied as part of the Flathead River watershed assessment. Federal wildfire predictions for probability and severity (flame length) (WWETAC) are contained within the fire cascade tool. Post fire erosion prediction (surface erosion using the WEPP model) is based on results from Miller et al. (2011). For more site specific analysis of pre and post wildfire conditions and the erosion associated with it, users can apply NetMap's site specific fire-erosion tool.

The wildfire probability and severity forecasts in NetMap (developed by WWETAC) cover only the US portion of the Flathead River watershed. However, predictions of fire probability and severity that might be available in British Columbia could be incorporated into NetMap. Using the channel segment scale drainage wings in NetMap (Figure 2), predicted fire severity is reported to stream segments, offering a channel- or fish-eye view of fire severity. In addition, the channel segment values are aggregated (summed and area weighted) downstream, providing a means to examine predicted fire severity at any spatial scale defined by the channel network. NetMap's Fire Cascade tool is used to quickly identify locations in the Flathead River watershed where the highest fire probability intersects with the highest fire severity, and where that pair intersects valuable habitat.

Climate Change Vulnerability

An assessment of climate change vulnerability is included in the Flathead River watershed assessment. NetMap's climate change vulnerability tool provides an efficient means to quickly locate the greatest forecasted changes in climate (percent change from historical) in temperature, precipitation, snowmelt and related in-stream flow measures. The scenarios represent a composite average of ten global climate models (GCM) for the western US using four bracketing scenarios based on four GCMs (ECHAM5, MIROC_3.2, HADGEM1, and PCM1). Predictions are for one greenhouse gas scenario (A1B, a middle of the road scenario for future emissions). Results are in percent change from historical (1916-2006) to forecasts in 2040. Forecasts were obtained from University of Washington Climate Impacts Group.

The tool can also be used to quickly search for landscape vulnerability to climate change by examining intersections among climate change, wildfire risk, and in-stream habitat and channel sensitivity indicators (using any percentile of the distribution). Some of the analyses are included in this report; however, interested stakeholders should access the NetMap tools and the Flathead River Digital Landscape and conduct their own analyses.

Basin-scale Channel Analysis and Subbasin Classification

Modeling results for road surface erosion, sediment yield from gullies/ shallow failures, road surface erosion (delivered to streams), and fish habitats are evaluated at the scale of the river network (using the entire Flathead River network) in the analyses that follow. Results for a select set of attributes are also summarized at the scale of subbasins (hydrologic unit code 6 level [12 digit]) in NetMap. This supports analyses and visualization of network wide patterns of the various watershed attributes and habitat-stressor intersections.

Results

Road Analysis: Road Density

Road density (km/km^2) at the scale of HUC 6th subbasins ranges from zero to 2.5 km/km^2 (**Figure 9**). The highest road densities correspond to subbasins in the Canadian portion of the watershed.

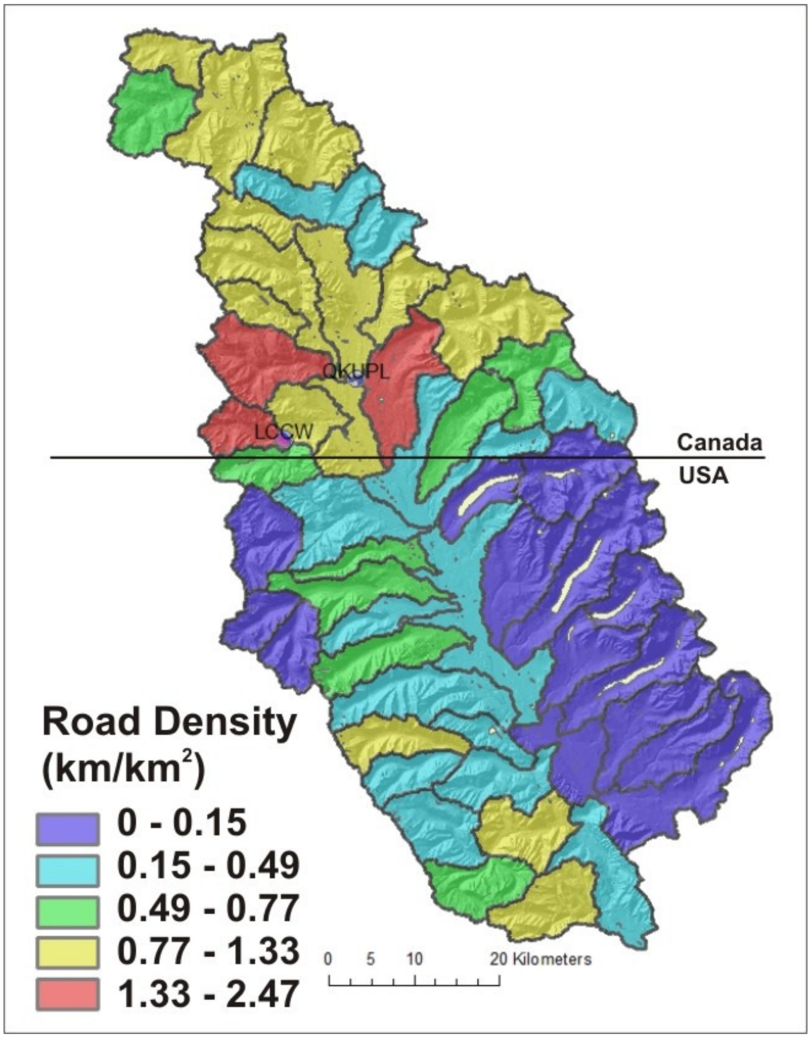

Figure 9. Road density in the Flathead River watershed classified at the scale of Hydrologic Unit Code (12 digit) ranged from zero to 2.47 km per square kilometer. The highest values are located in the Canadian portion of the basin.

Road density was also calculated at the scale of individual hillsides located on either side of individual channel segments (referred to as "drainage wings", Figure 2). Channel segments ranging in length in the NetMap Flathead dataset of 50 to 200 m correspond to drainage wing areas of several tenths of a square kilometer. Hillside-channel segment scale road density in the Flathead River watershed ranged from zero to 101 km/km^2 (**Figure 10**). An analysis of the highest road densities (arbitrarily set at the top 10% and top 2%) reveals that the majority of the locations are in the Canadian portion of the Flathead River watershed (**Figure 11**).

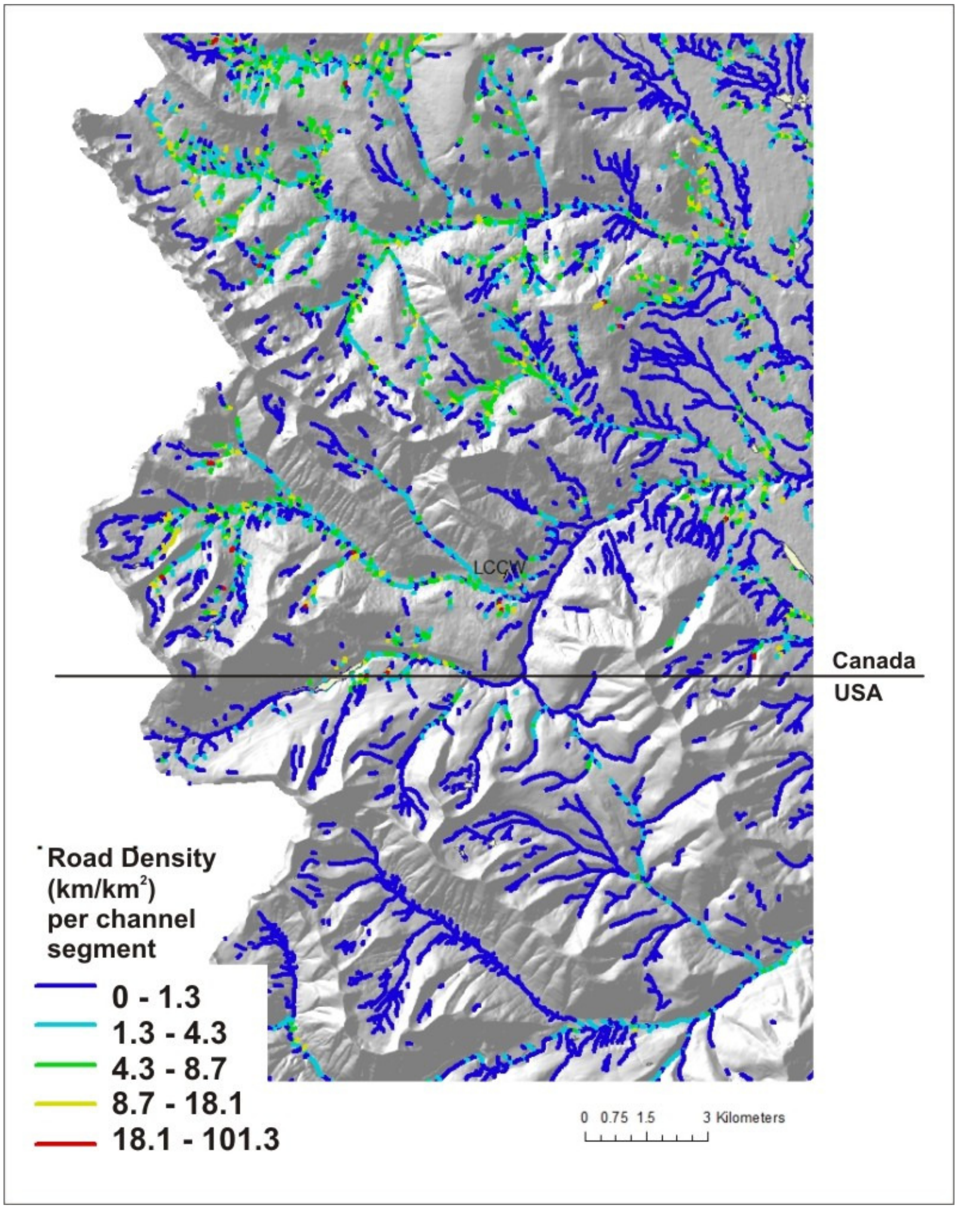

Figure 10. Road density in the Flathead River watershed classified at the scale individual channel segments and associated individual hillsides (Figure 2) range from zero to 101 km per square kilometer. Compare reach scale road density with subbasin scale road density (Figure 9). To see the full basin results, use NetMap tools with the Flathead River Digital Landscape.

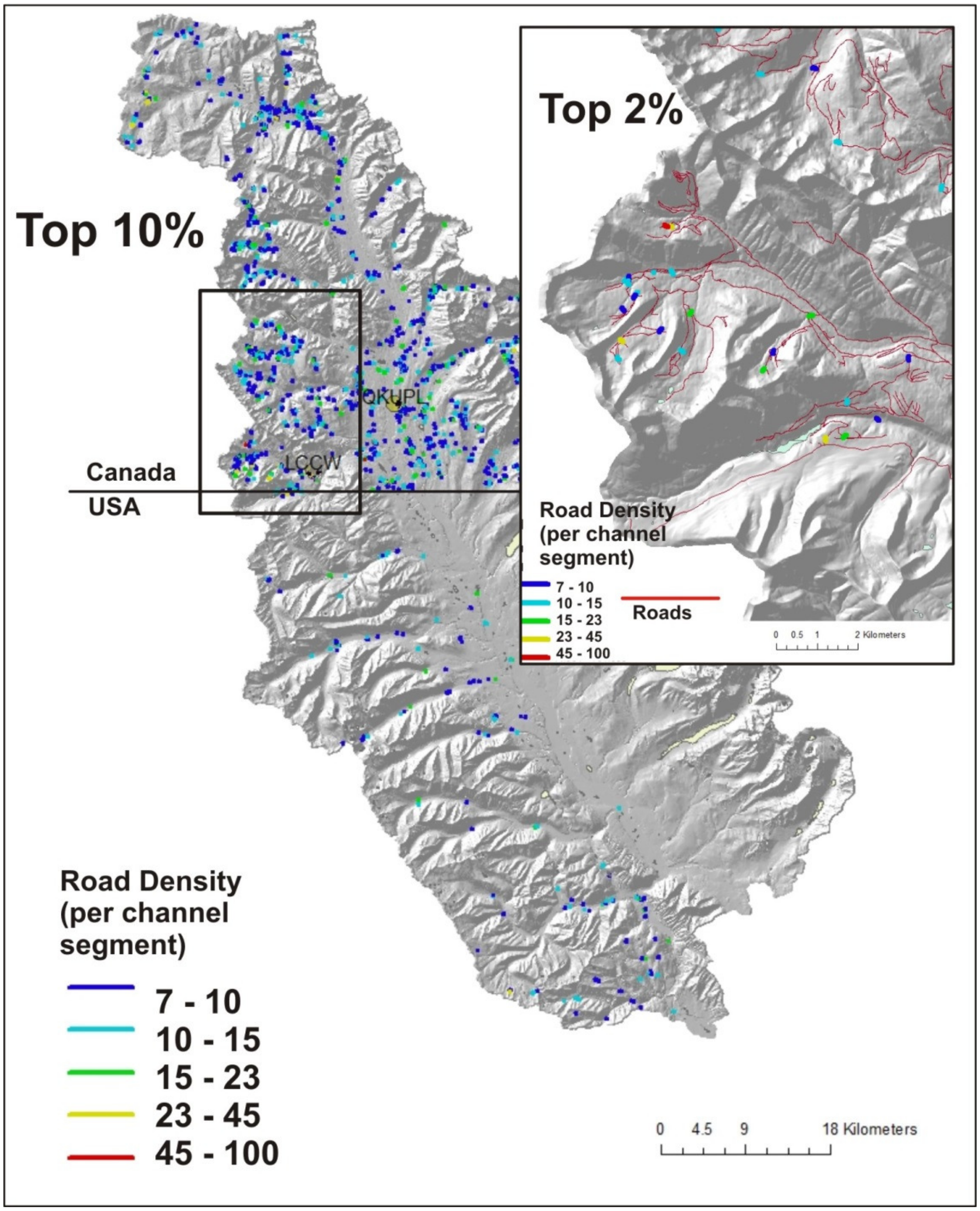

Figure 11. NetMap's overlap tool allows identifies any percentile of the full distribution of road densities (or any watershed parameter). Shown are examples for the top 10% and the top 2%. The highest road densities are located in the Canadian portion of the basin. To see the full basin results, use NetMap tools with the Flathead River Digital Landscape. The thin red lines in the inset figure are the known mapped road segments.

Road Analysis: Road Hydrologic Connectivity

To predict road surface erosion requires knowledge of the hydrologic connectivity of roads or the potential length of overland flow on roads. Analysis of road hydrologic connectivity (e.g., Figure 3) was accomplished using the composite DEM, the synthetic stream network and the US and Canadian road layers. However, the Flathead Watershed Assessment includes the full digital landscape and NetMap analysis tools so additional road drainage (and road surface) analyses can be done following the initial analysis/report. Using road-stream intersections and topographic high and low points along roads (e.g., Figure 3), predicted hydrologic connectivity (lengths) ranges from less than a few meters to over 700 m (**Figure 12**). Characterization of road hydrologic connectivity and predicted surface erosion could be improved by incorporation of geo-referenced road drainage structures in both the US and Canada.

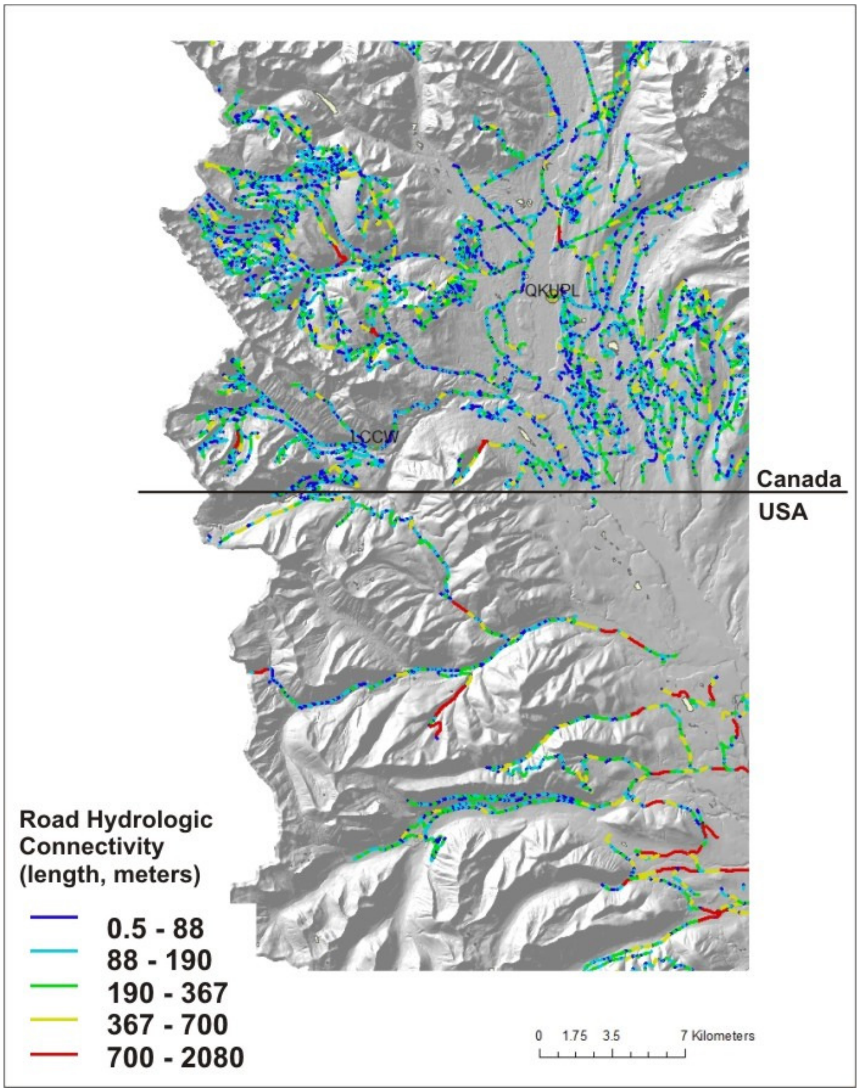

Figure 12. Using NetMap's road hydrologic connectivity tool the predicted lengths (using road-stream intersections and DEM topography, e.g., Figure 2) range from less than a meter to greater than 700 m. GPS locations for road drainage structures could be used in subsequent analyses to improve the accuracy of predictions in NetMap. To see the full basin results, use NetMap tools with the Flathead River Digital Landscape.

Road Analysis: Road Surface Erosion, Production and Delivery to Streams

Two road erosion models were applied in the Flathead River watershed (GRAIP-Lite and WEPP). For efficiency the report limits the presented results to the GRAIP-Lite model; WEPP results and a comparison between the GRAIP-Lite and WEPP predictions are found in Appendix 1. For full GRAIP-Lite and WEPP results, refer to the NetMap Digital Landscape with Analysis Tools.

The volume of erosion generated on roads is typically more than the amount of sediment that is delivered to stream channels. Unless road erosion is delivered directly to stream channels at stream crossings, surface erosion contained in running water that is routed through forested land (below roads and above streams) typically becomes trapped in roughness elements (vegetation, downed logs) or road drainage infiltrates into the ground, leaving the sediment behind. An illustration of sediment production and sediment delivery to streams (using GRAIP-Lite results) are shown in **Figure 13.**

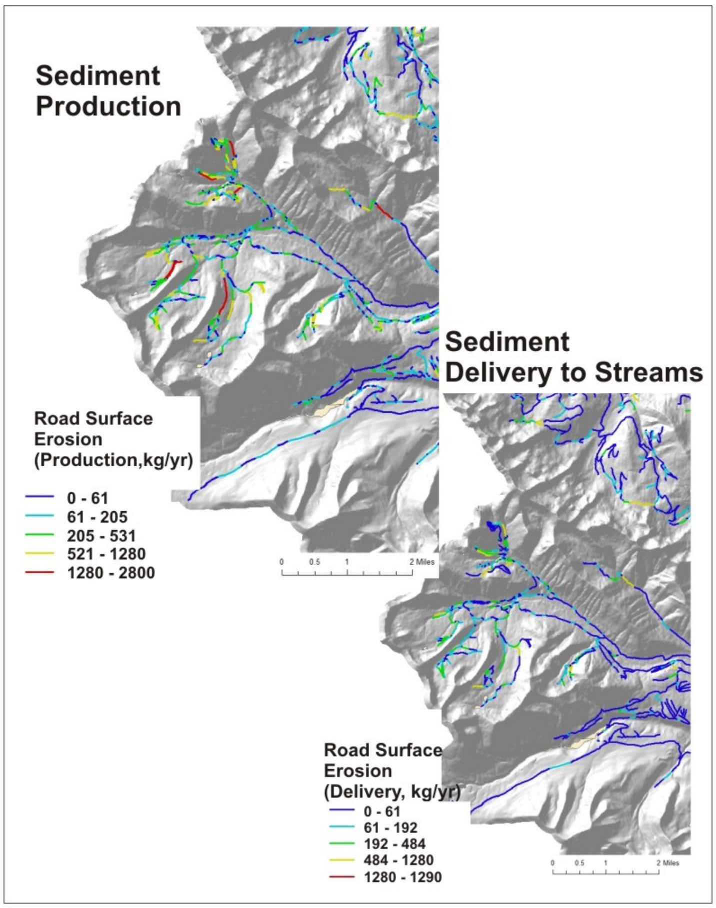

Figure 13. A comparison between road surface erosion - production and road surface erosion - delivery to streams in the GRAIP-Lite model illustrates how distance from the road segments to streams greatly diminishes the delivery of sediment to streams. To see the full basin results, use NetMap tools with the Flathead River Digital Landscape.

Road Analysis: Sediment Delivery to Streams

In Figure 13, road surface erosion results are shown as road lines. In NetMap, each road segment is geo-referenced to specific channel segments (based on topographic flow directions) and thus predicted road surface erosion is reported to channel segments, offering a fish-eye view of road surface erosion (that portion delivered to streams). This is illustrated for a portion of the Flathead River in **Figure 14**.

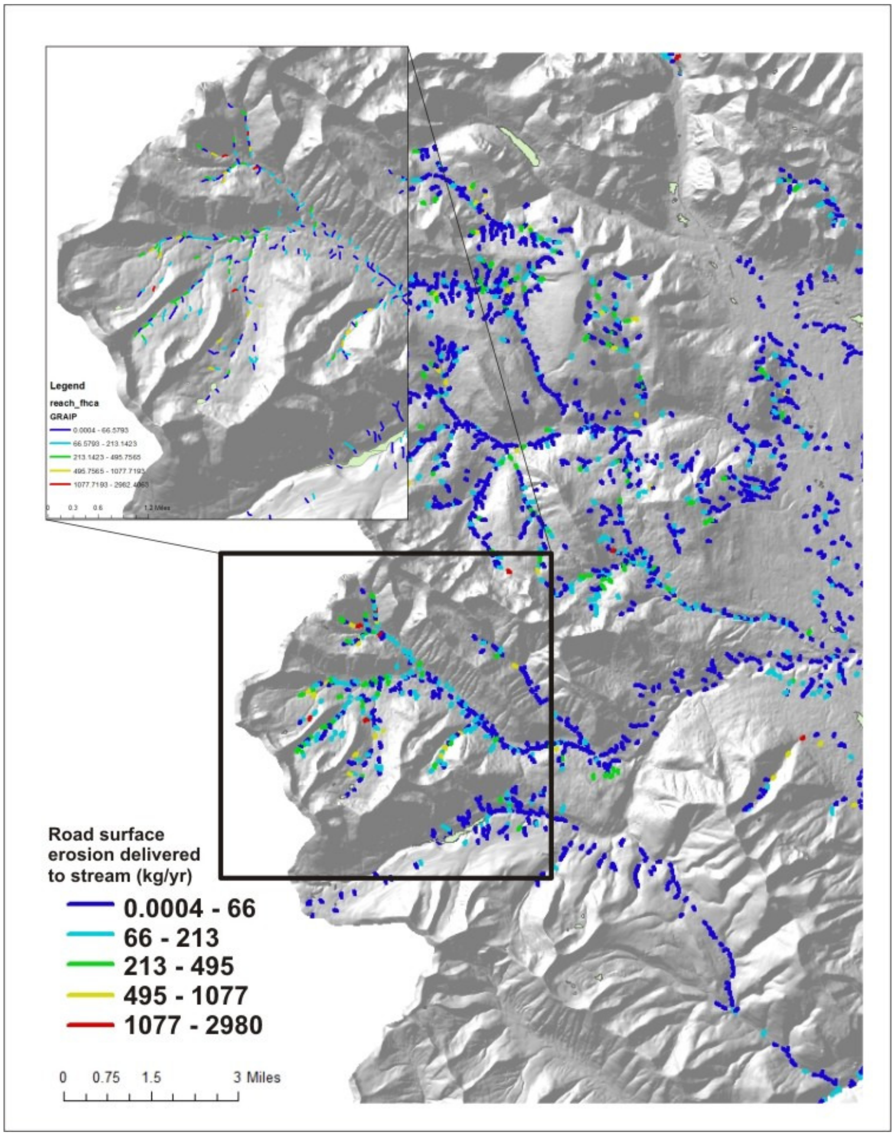

Figure 14. Predicted road surface erosion (portion delivered to streams) is reported to individual channel segments (GRAIP-Lite). To see the full basin results, use NetMap tools with the Flathead River Digital Landscape.

In addition to channel segment predictions of road surface erosion (Figure 14), predicted road erosion in NetMap is also accumulated downstream (summed and area weighted), revealing tributary scale patterns of road surface erosion (**Figure 15**). GRAIP-Lite predictions of road surface erosion at the watershed scale are on the order of 2 to 4 kg/ha/yr, comparable to other GRAIP-Lite modeling studies, particularly in areas of similar road densities (Luce et al. 2001).

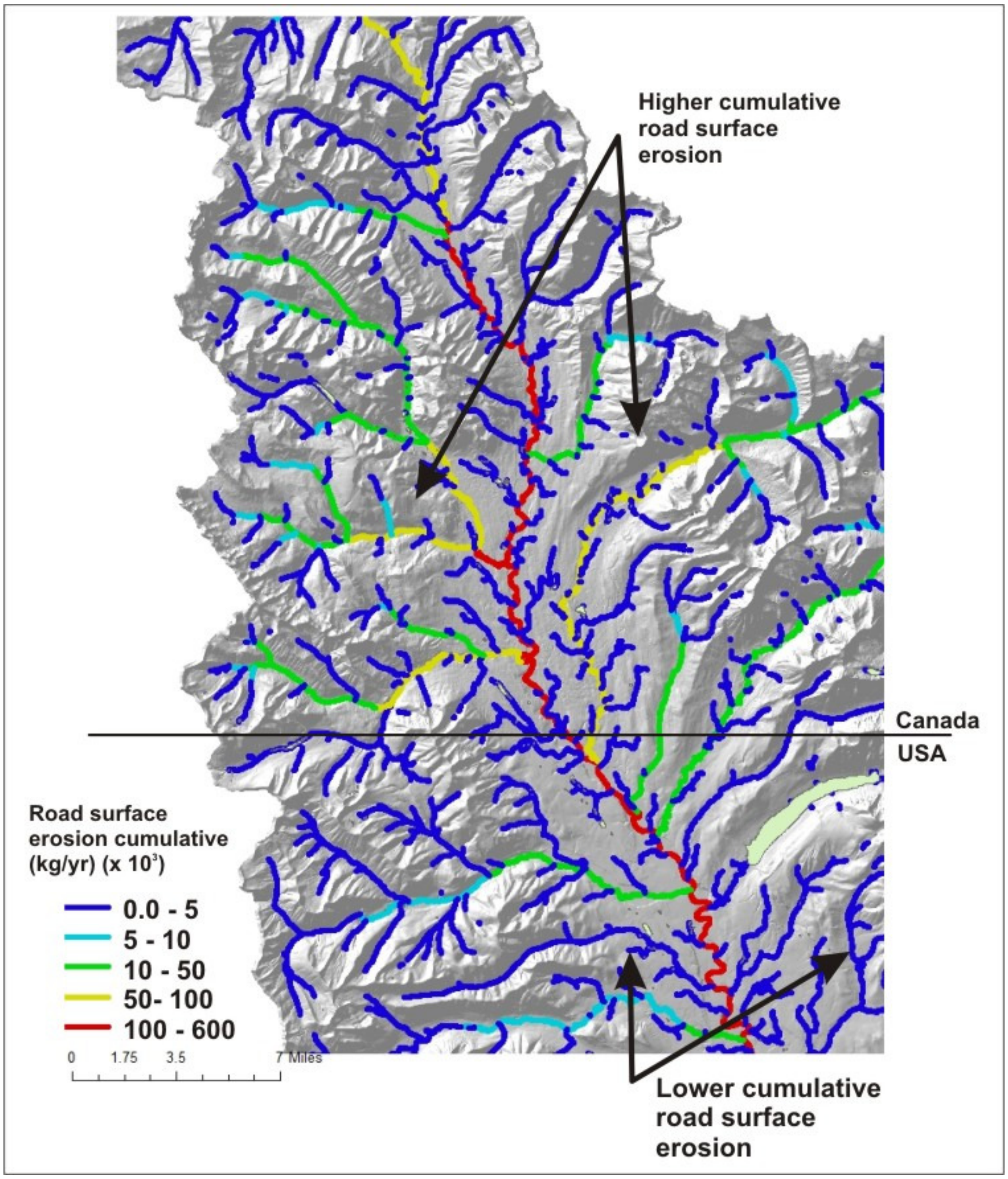

Figure 15. Predicted road surface erosion (portion delivered to streams, GRAIP-Lite) is accumulated (and area weighted) downstream, revealing which tributaries have the highest potential for road surface erosion. To see the full basin results, use NetMap tools with the Flathead River Digital Landscape.

Other road surface erosion predictions are available in NetMap, such as predicted GRAIP (and WEPP) results aggregated back to the original road segments. **Figure 16** shows the total summed predicted road surface erosion (delivered to channels) mapped onto the original (longer, multi-kilometer) GIS road segments, identifying those roads that could potentially produce the greatest amount of sediment.

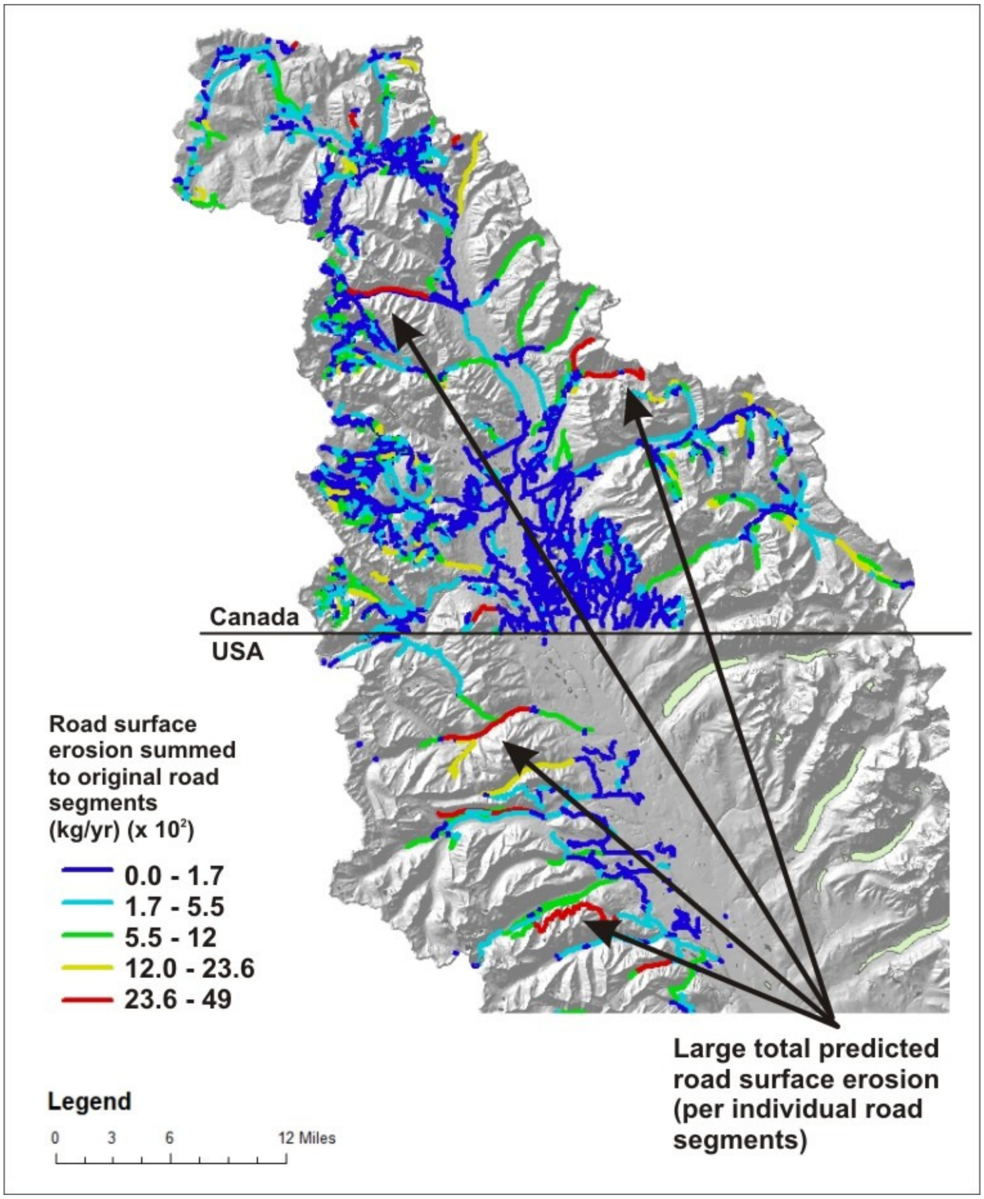

Figure 16. Predicted road surface erosion (portion delivered to streams, GRAIP-Lite) summarized back onto the original corporate road layers (USFS, Canadian Forest Company). To see the full basin results, use NetMap tools with the Flathead River Digital Landscape.

Another approach is to aggregate the predicted road surface erosion back to the original road segments, but distributed per unit road distance (total predicted sediment/total road length). The analysis reveals hotspots in the road network where potential road surface erosion (delivery to streams) may be the highest (**Figure 17**).

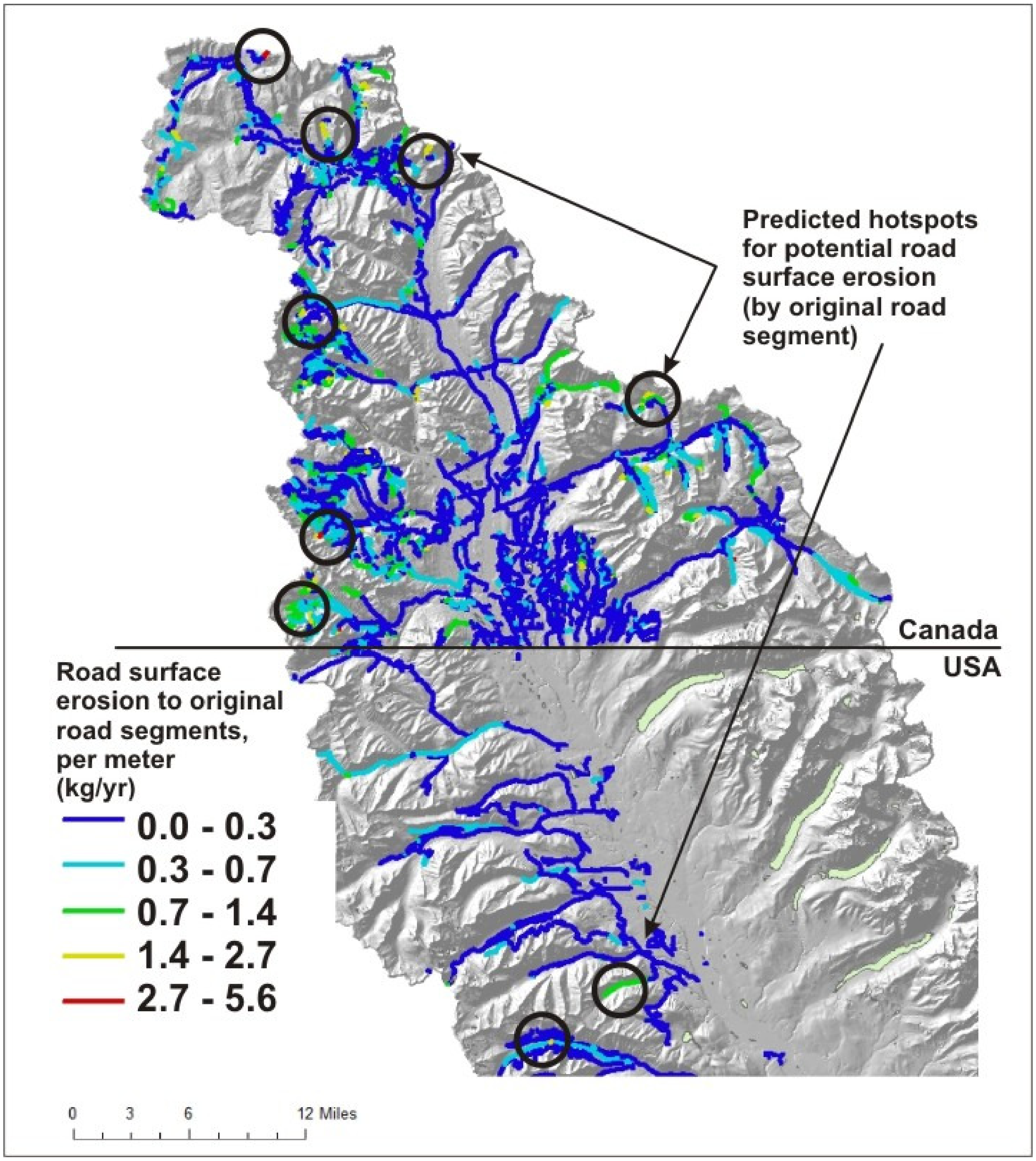

Figure 17. Predicted road surface erosion (portion delivered to streams, GRAIP-Lite) summarized onto the original corporate road layer segments, by per meter. To see the full basin results, use NetMap tools with the Flathead River Digital Landscape.

To evaluate model accuracy, field measured estimates of road surface erosion – production and road surface erosion – delivery to streams are compared to model results. Field measured rates of road erosion production (not including delivery) were made in western Montana by Sugden and Woods (2007). Climate in their study basins (average 60 – 100 cm/yr) is similar to the higher elevation areas of the Flathead River. Restricting their field measurements to 0.05 ha plots (n=20) on native surface roads during the three year study (2002-2004), results ranged from 0 to 97 t/ha/yr (**Table 1**). Annual mean sediment production ranged from 2.1 t/ha/yr to 9.9 t/ha/yr with an overall mean of 5.4 t/ha/yr (Table 1). NetMap's GRAIP Lite and WEPP sediment production values were converted to hectare of road production for native surface roads only for comparison. Using predictions from 13,393 individual road segments (native surface only), GRAIP Lite results ranged from 0 to 17 t/ha/yr (mean = 1.8 t/ha/yr) and WEPP results ranged from 0 to 22.5 t/ha/yr (mean = 0.21 t/ha/yr) (Table 1). For the WEPP predictions, a low traffic level was used. However, on steeper roads in the Flathead River watershed, increasing traffic levels in the WEPP model from low to high can increase predicted sediment production by a factor of three to five. The traffic levels on commercial forest land reported in Sugden and Woods (2007) indicated a relatively high traffic level (of up to 5045 vehicle passes including logging trucks). Thus, WEPP results for many road segments could be increased to a mean of up to approximately 1 t/ha/yr (Table 1).

Table 1. Comparison among GRAIP-Lite and WEPP predictions of surface erosion and field measurements (Sugden and Woods 2007).

Source	**Range**	**Average**
GRAIP (NetMap)[3]	0 – 17 t/ha/yr	1.8 t/ha/yr
WEPP (NetMap)	0 – 22.5 t/ha/yr[1] 0 - ~100 t/ha/yr[2]	0.2 t/ha/yr[1] ~1.0 t/ha/yr[2]
Sugden and Woods (2007)[4]	0 – 96.9 t/ha/yr	5.4 t/ha/yr

[1] Native surface roads, low traffic levels.
[2] Native surface roads, high traffic levels (projected).
[3] GRAIP Lite does not use traffic levels.
[4] Field measurements on native surface roads, relatively high traffic levels.

NetMap GRAIP-Lite results (average = 1.8 t/ha/yr) are similar to the Sugden and Woods (2007) average field measurements of 5.4 t/ha/yr; this may result from GRAIP-Lite utilizing actual field measured road erosion production rates in western Montana. The WEPP predicted annual average road erosion (production) of 0.2 to ~1 t/ha/yr is also similar to the Sugden and Woods (2007) values. Direct comparisons are not possible since GRAIP does not include a climate component and WEPP predictions are based on 50 years of simulated climate compared to the field measured values that reflect actual climate from years 2002 through 2004. Characterization of road hydrologic connectivity and predicted surface erosion could be improved by incorporation of geo-referenced road drainage structures in both the US and Canada.

Broader scale comparisons between WEPP and GRAIP-Lite predictions can be made. NetMap contains a tool for classifying any watershed attribute at the scale of subbasins; this is accomplished by calculating the full frequency distribution of values (of any parameter, such as predicted road surface erosion) and choosing some attribute of the distribution (mean, median) or a specific percentile (top 10%, lower 20%, etc.). US HUC 6th level (12 digit) subbasins are classified by the predicted road surface erosion and sediment delivery using both GRAIP-Lite and WEPP model results. The analysis identifies the subbasins with the greatest potential for road surface erosion and sediment delivery to streams in the Flathead River watershed (**Figures 18 and 19**).

The classification of road surface erosion – delivery to streams by HUC 6th field subbasins using both GRAIP-Lite and WEPP results shows the same overall pattern of high to low values in the subbasins. Overall, the majority of the highest sediment producing subbasins occurs in Canada , in part due to a much higher road density there (Figure 9).

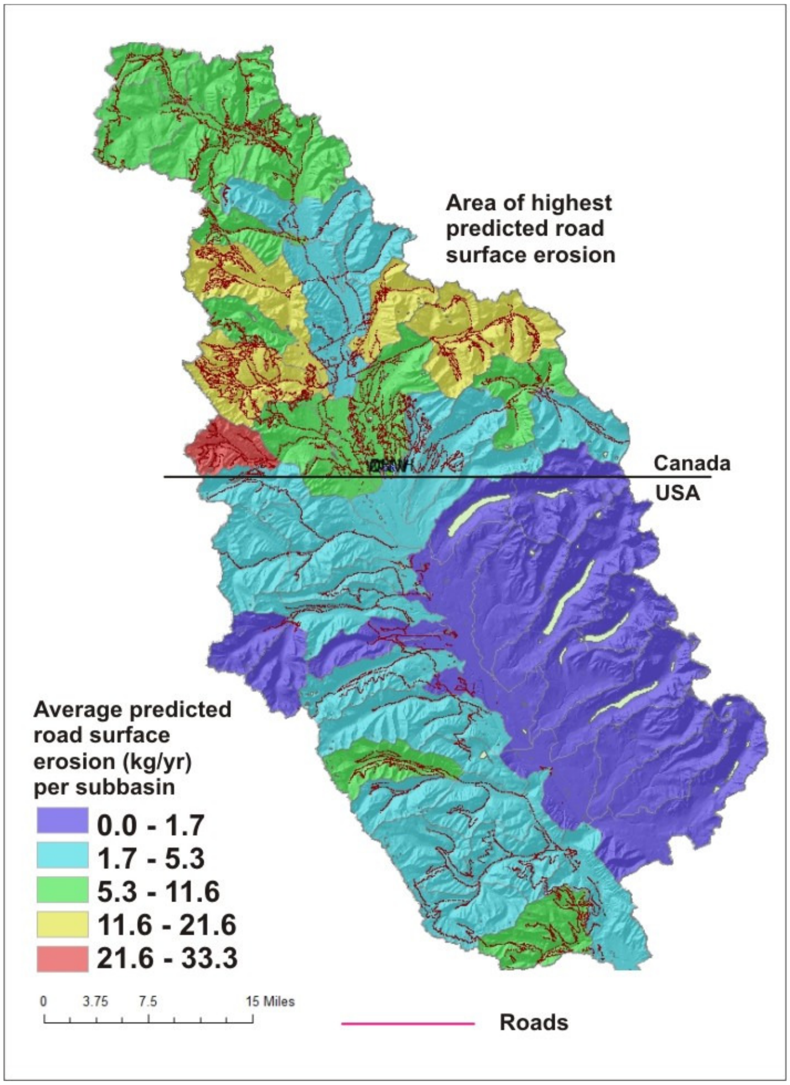

Figure 18. Using the Sort & Rank tool in NetMap, the potential for road surface erosion (portion delivered to streams, GRAIP-Lite) is mapped at the scale of US HUC 6th level subbasins, revealing where the greatest potential occurs in the Flathead River watershed. To see the full basin results, use NetMap tools with the Flathead River Digital Landscape.

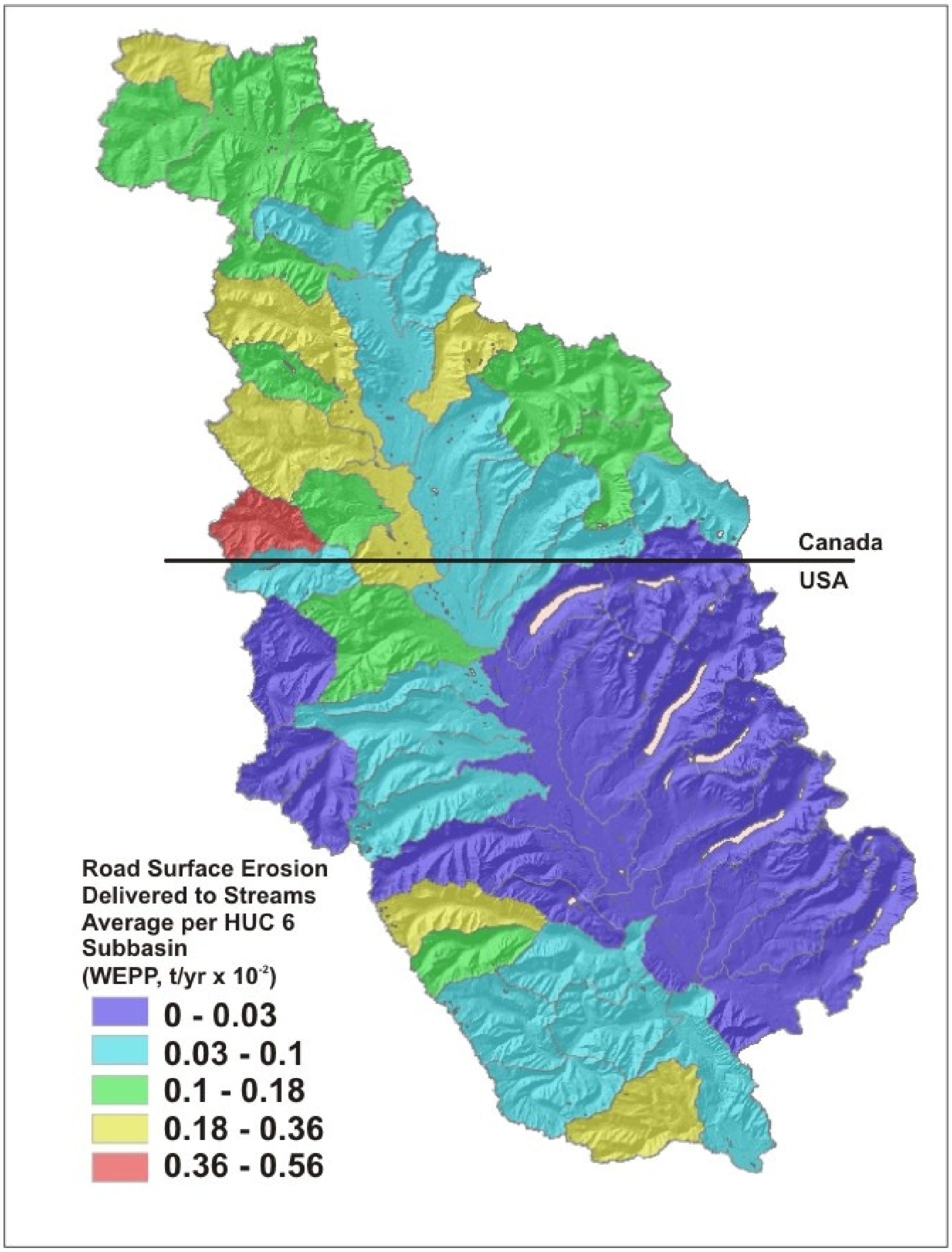

Figure 19. Using the Sort & Rank tool , the potential for road surface erosion (portion delivered to streams, WEPP) is mapped at the scale of US HUC 6th level subbasins, revealing where the greatest potential occurs in the Flathead River watershed. To see the full basin results, use NetMap tools with the Flathead River Digital Landscape.

It is informative to compare the predicted road surface erosion to background erosion in the Flathead River basin as a relative measure of road surface erosion significance and its potential impacts on water quality and fisheries. This requires a spatially explicit mapping of variable sediment yield across the watershed. An estimate of background sediment yield is required to conduct this analysis (next section).

Analysis of Landslide/Gullying and Conversion to Sediment Yield

NetMap's generic erosion index (GEP) is used to estimate the location and magnitude of gullying and shallow landsliding potential in the Flathead River watershed (**Figure 20**). GEP is an index based on hillslope steepness and convergence (Eq. 1). In this basin, as elsewhere, lithology (rock type) strongly influences erosion. In addition, climate, including the occurrence of fires (see later), influences the types of erosion that are expected. Timber harvest activities, including ground based yarding, can be contributory factors in gully and landslide potential and information about erosion susceptibility could be used for future forest harvest planning. These accessory factors, however, are not addressed in the present analysis. Given the snow dominated and non humid climate of the watershed, gullying (particularly post fire), should be the dominant type of erosion (e.g., Figure 6).

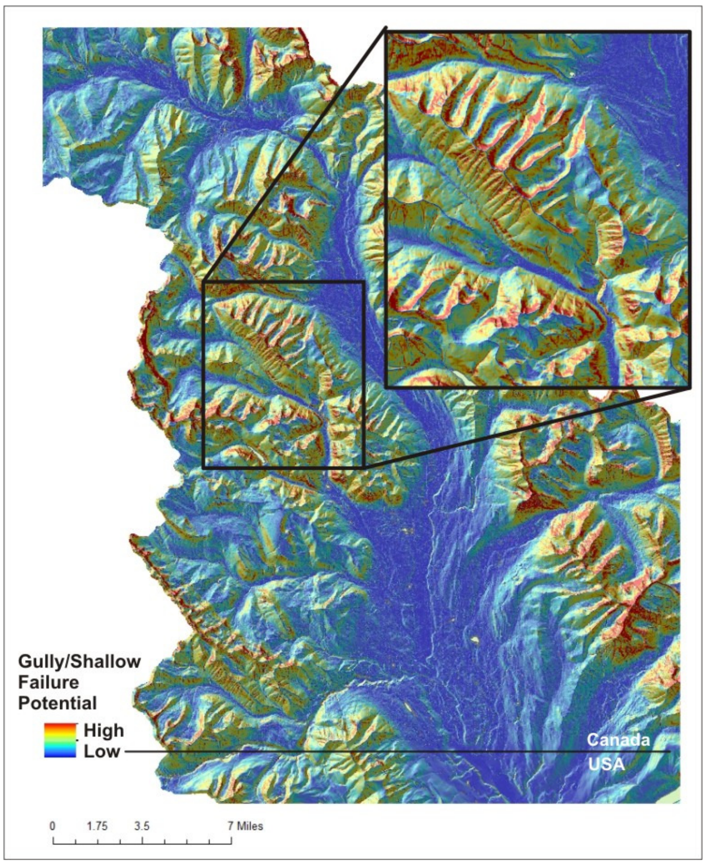

Figure 20. Based on hillslope steepness and curvature, NetMap's Generic Erosion Potential characterizes the gully/shallow landslide potential in the Flathead River watershed. Because of climate, erosion is likely dominated by gullying (Figure 6), particularly post wildfire. To see the full basin results, use NetMap tools with the Flathead River Digital Landscape.

GEP in the Flathead River basin is converted to annual sediment yield (t/km^2/yr) to provide a more intuitive index of relative erosion potential and to provide an estimate of background sediment yield from which to compare predicted road surface erosion (below). Using the data discussed in the Methods

Section, an average annual sediment yield of 20 t/km^2/yr is used. The mapped results reveal how predicted sediment yield (at the scale of individual channels segments and accumulated downstream) varies across the watershed (**Figures 21 and 22**).

The analysis provides a general guide, based on topography alone, where the areas of the highest potential erosion might occur in the basin. This may be useful for considering how disturbances, such as wildfire (see later) and timber harvest, may impact erosion and sediment delivery to streams. For example, predicted wildfire probability and fire severity could be overlaid in NetMap with predicted potential for gully erosion to identify areas most likely to burn by high severity and erode significantly following fires. This information could be used in pre wildfire planning related to reducing fuels and thus reducing fire severity.

NetMap uses its flow direction grids, via drainage wings (Figure 2), to transfer predicted hillside erosion to individual stream segments throughout the basin). Predicted stream segment erosion values ranged between less than one and 54 t/km^2/yr.

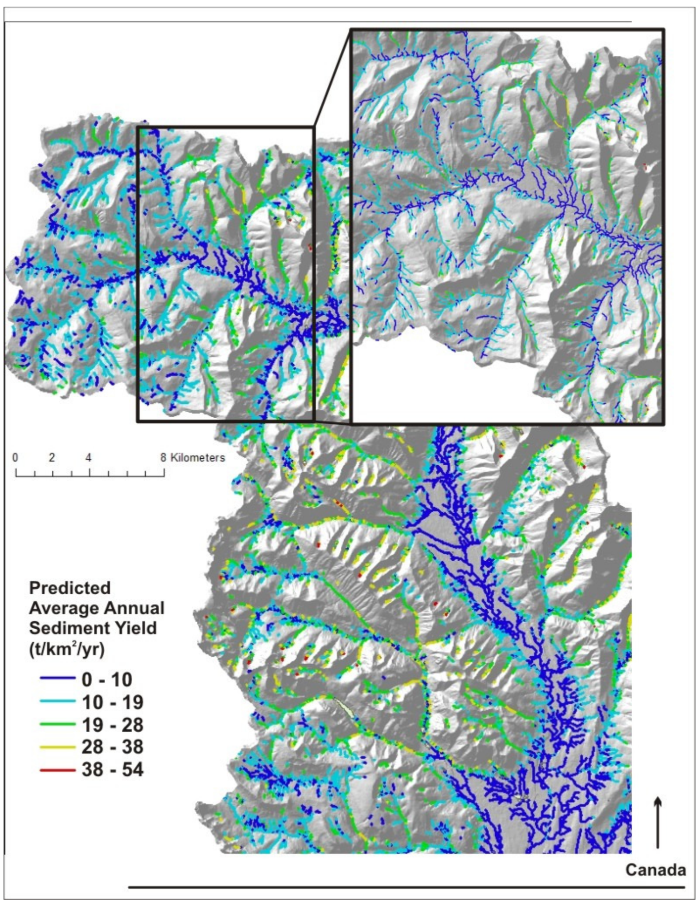

Figure 21. Spatial variation in predicted sediment yield (at the scale of drainage wings, Figure 2) across the Flathead River watershed based on topography (slope steepness and convergence). To see the full basin results, use NetMap tools with the Flathead River Digital Landscape.

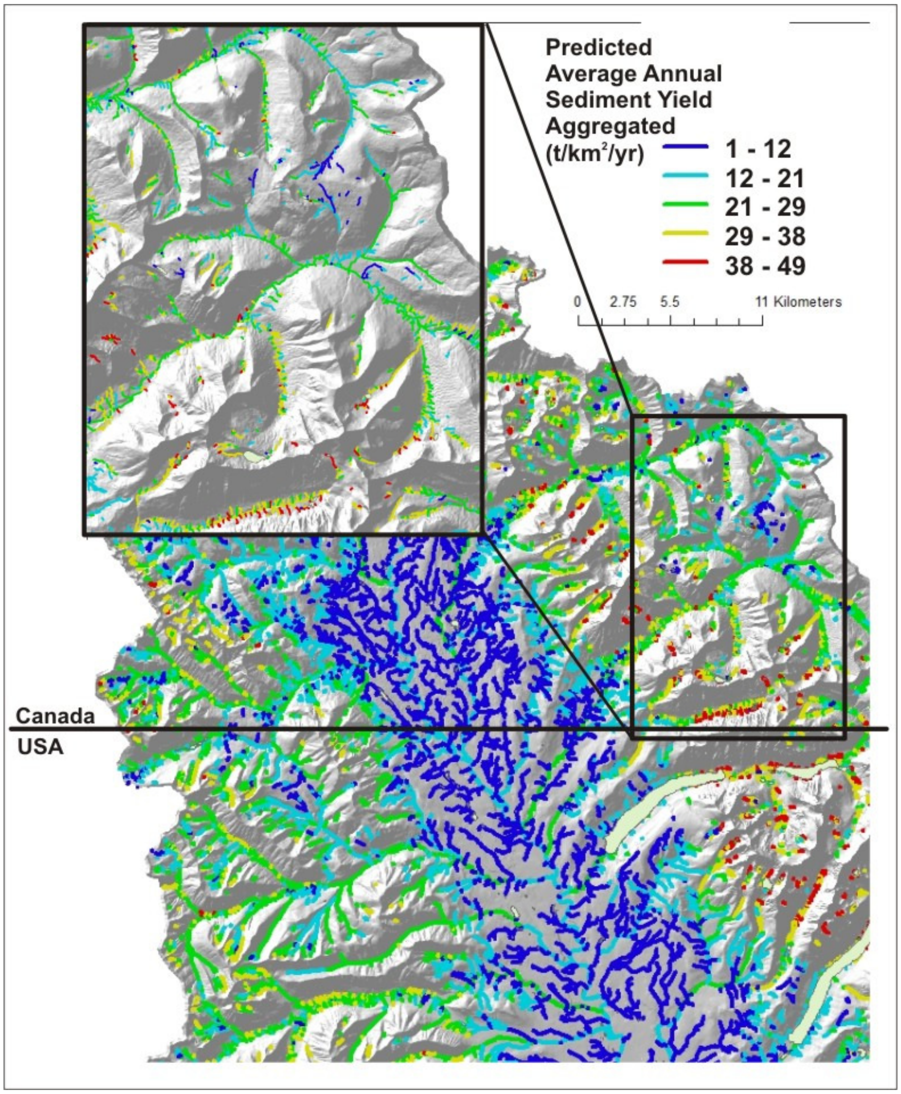

Figure 22. Spatial variation in predicted cumulative sediment yield across the Flathead River watershed based on topography (slope steepness and convergence). To see the full basin results, use NetMap tools with the Flathead River Digital Landscape.

Road Analysis: Road Erosion Comparison to Background Basin Erosion

Two approaches are sued to compare predicted road surface erosion to the predicted background sediment yield. First, estimates for both are compared at the scale of the entire watershed using the total river area at the Canadian border (approximately 1125 km^2) and the total river area in the US (4055 km^2). In this analysis both the WEPP and GRAIP-Lite predictions are used.

At the scale of Flathead River, the predicted road surface erosion compared to background sediment yields in the Canadian portion and in the entire watershed in the US is very small (0.3% to 1.7%) (Table 2). Even using the lower estimate of average basin sediment yields (10 t/km^2/yr), the relative importance of road surface erosion rises to only a maximum of about 4% (but see hillside – channel segment scale analysis below).

Table 2. A comparison between the predicted background sediment yield and the predicted road erosion – sediment delivery.

Drainage Area	**Sediment Yield (background) t/km^2/yr**	**GRAIP Road Surface Erosion (t/km^2/yr)**	**Relative Importance of Road Surface Erosion** ***(but see segment analysis below)***
Canada (1125 km^2)	20 t/km^2/yr	Total cumulative = 0.34 t/km^2/yr	1.7%
USA (4055 km^2)	20 t/km^2/yr	Total cumulative = 0.15 t/km^2/yr	0.8%

GRAIP Lite (and WEPP) predicted sediment yields are for fine sediments only, those moved by flowing water across road surfaces (encompassing fine sands, silts and clays). The predicted sediment yield (background, Figures 21 and 22) encompass the full range of particle sizes (includes bedload sized cobble, gravel and pebbles). It is not feasible to evaluate how the suspended load to total load ratio varies downstream in the Flathead River. In general, however, the proportion of suspended load to total load should increase downstream because of particle attrition (conversion of bedload to suspended load) (Lane and Borland 1951).

There exists spatial variability in both predicted background sediment yields (Figures 21 and 22) and predicted road erosion (Figures 14 and 17) at the scale of individual hillsides and channel segments. Thus, an analysis is conducted that compares road surface erosion with background sediment yields at the scale of individual hillsides and channel segments both locally (local contributing area) and cumulatively downstream. GRAIP-Lite results are used in this analysis; involved stakeholders can conduct similar analyses using WEPP results or other surface erosion modeling results.

At the scale of individual drainage wings and 100 m channel segments, there are numerous locations in the river network where predicted road surface erosion exceeds the predicted background sediment yield by amounts ranging from about 10% to greater than 1000% (average = 32%) (Figure 23).

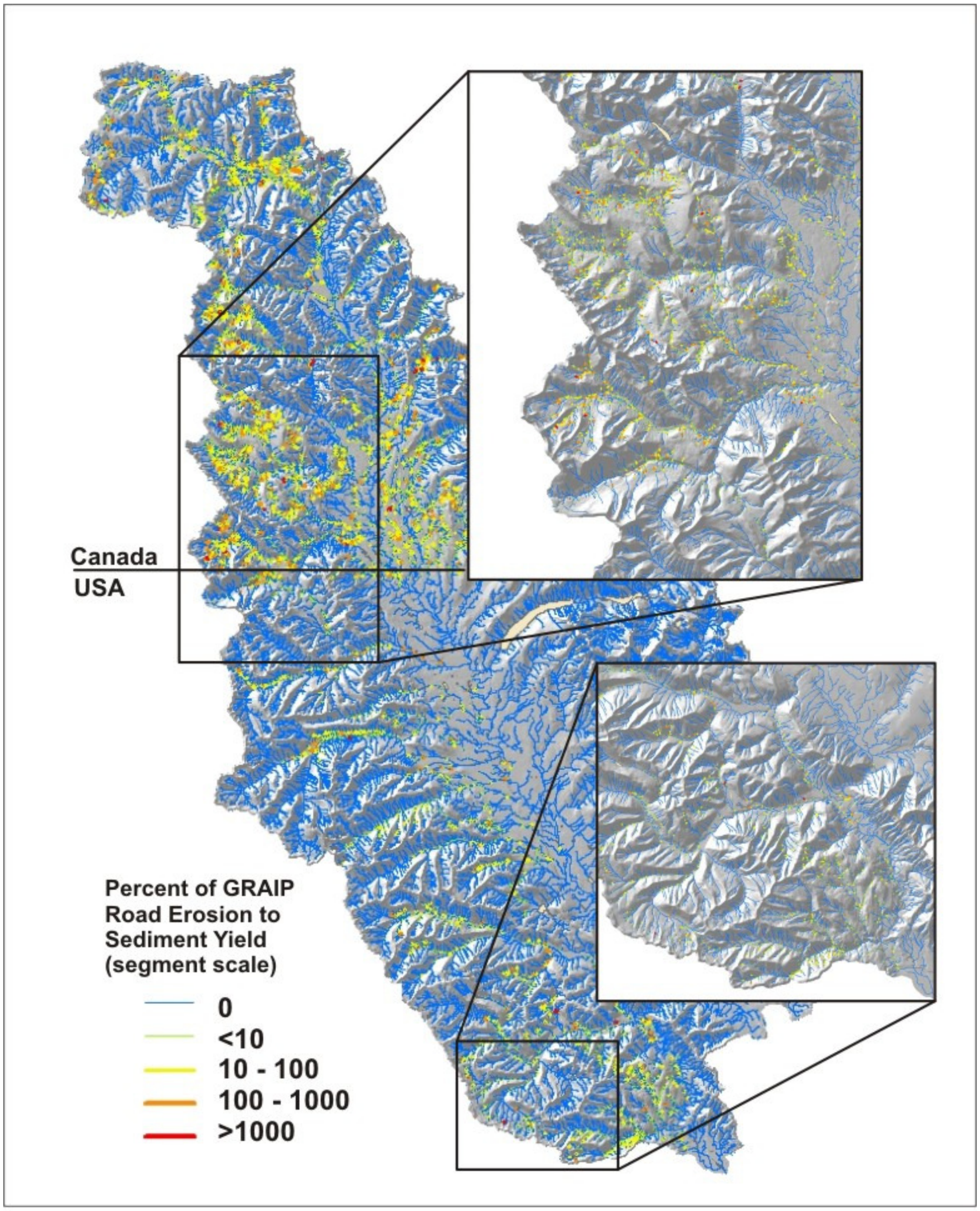

Figure 23. Predicted road erosion (delivered channel segment scale, GRAIP) as a percentage of predicted background sediment yield. The average is 32%. The analysis highlights individual hillsides, road networks and adjacent channels that are exposed to relatively high sediment loading from roads.

A similar comparison using cumulative values of predicted road erosion and background sediment yields (similar to Table 1) reveals that small tributary basins can have cumulative road erosion exceeding cumulative background sediment yield by margins of tens to hundreds of percent (**Figure 24**). The dilution effect of increasing drainage area ensures that larger tributaries (third and higher order) have percentages less than 10% with an average over all reaches of 4%. Nevertheless, this analysis does highlight which small tributary basins are predicted to have cumulative high erosion rates from roads compared to the predicted basin average sediment yield. If one were concerned with only fine sediments and since the suspended load-total load ratio increases downstream, the relative significance of road fine sediment loading compared to background fine sediment production would diminish downstream (and be locally more important in the upper tributaries). However, local scale impacts could be significant, considering important and sensitive fish habitat areas (including spawning) in those areas.

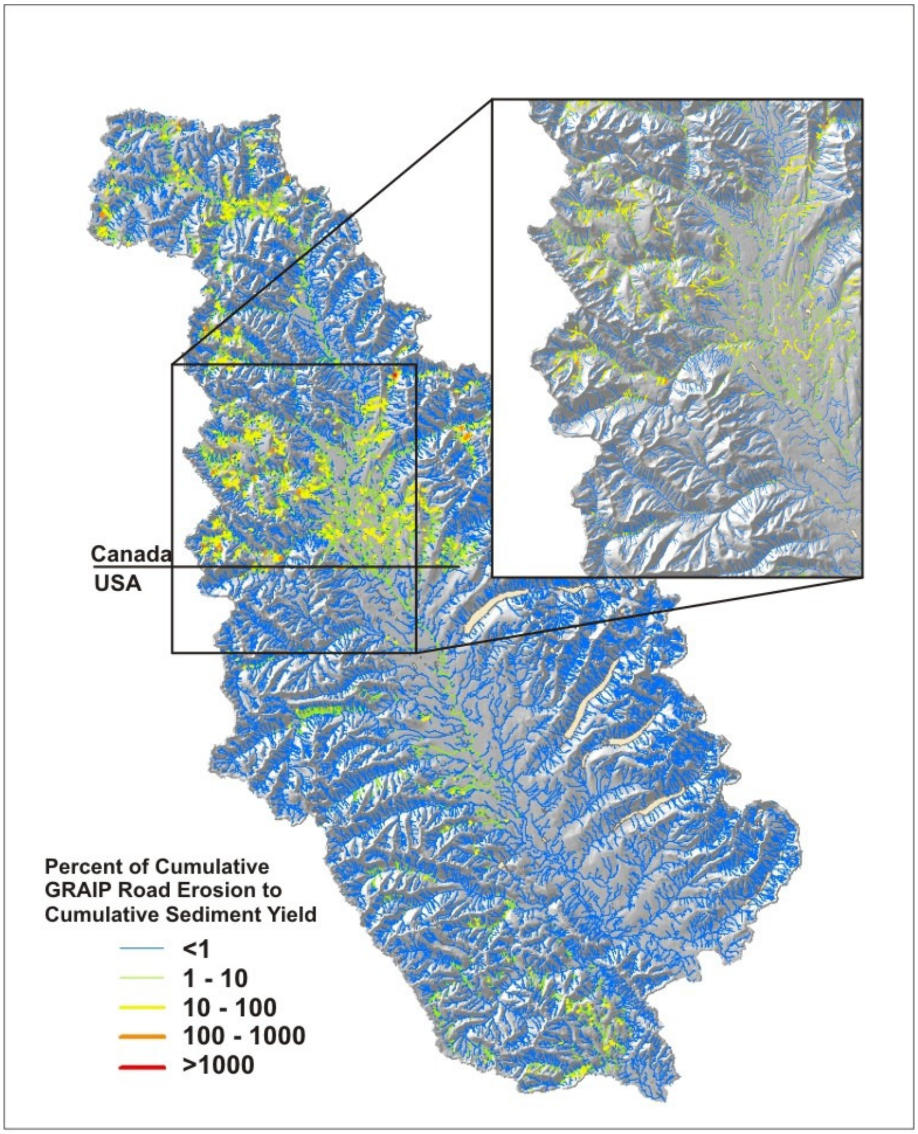

Figure 24. Predicted road erosion (delivered cumulative downstream, GRAIP) as a percentage of predicted background sediment yield. The average is 4%. Higher values (>10-100%) are limited to small tributaries.

Road Analysis: Road-Gully Potential

Road surface erosion does not account for road related gully erosion or the potential for roads to trigger shallow failures. Although the potential for gullying and shallow failure associated with roads in the Flathead River watershed should be less than in humid temperate landscapes such as Oregon and Washington, a risk still exists. Two tools in NetMap can be combined to provide an index of road gully/shallow landslide potential (GEP and gully potential); refer to [NetMap's Technical Help]() to provide background on these tools (**Figure 25**).

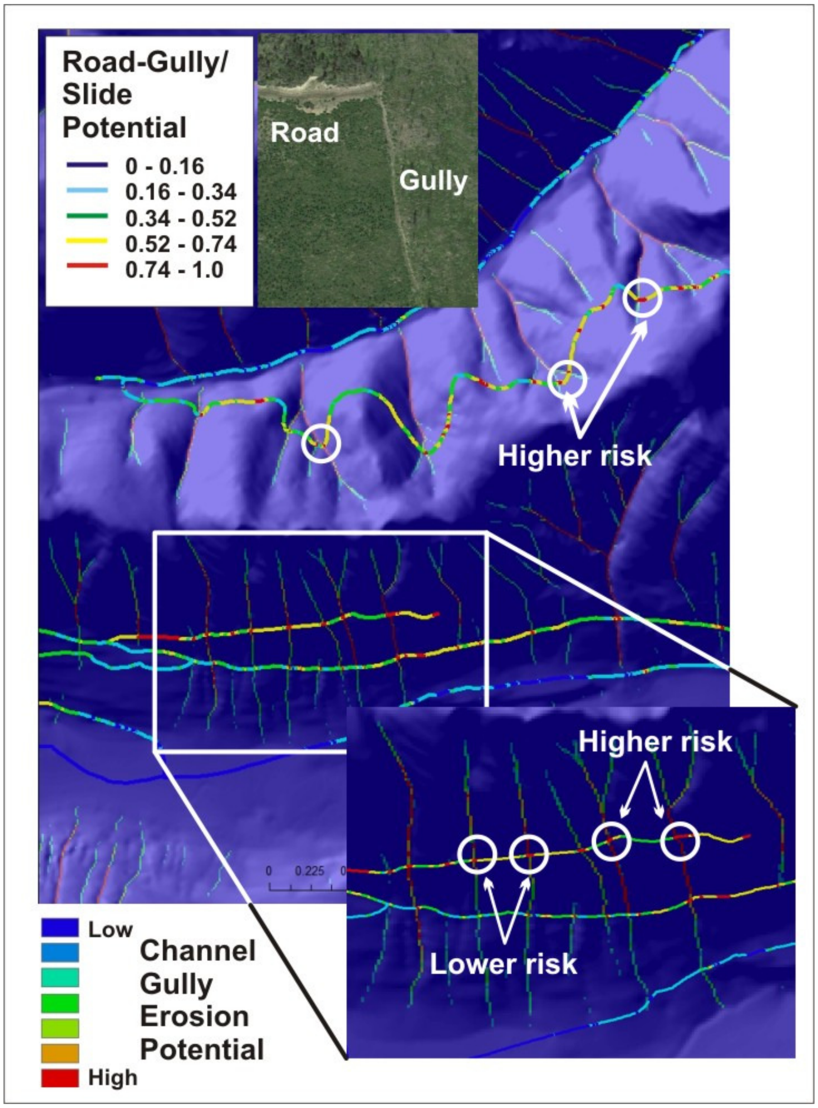

Figure 25. Two NetMap indices are used to evaluate the risk roads pose for gully erosion and to a lesser extent shallow failures. The convergence of both indices indicates those areas at highest potential risk. To see the full basin results, use NetMap tools with the Flathead River Digital Landscape.

Analysis of gully potential (Figure 25) could be used to strategically locate drainage structures and maintenance schedules to lessen the chance of this form of road impact.

Analysis of Floodplains and Channel Migration Zones

Identifying floodplains and associated channel migration zones are often included in watershed scale assessments. Thus, we include that analysis here. There is uncertainty involved with mapping floodplains remotely using DEMs. Consequently in the Flathead River watershed, a range of elevations above the channel (in terms of number of bankfull depths, e.g., Figure 7) are used to classify floodplains and channel migration zones.

NetMap's floodplain tool is applied in increments of 0.5, 1, 2, 3, 4, and 5 X bankfull depths. In the example shown in **Figure 26**, the predicted bankfull depth in the mainstem in the Figure shown is 0.9 m. Thus the sequence of bankfull depths correspond to, 0.5, 0.9, 1.8, 2.7, 3.6 and 4.5 m above the channel.

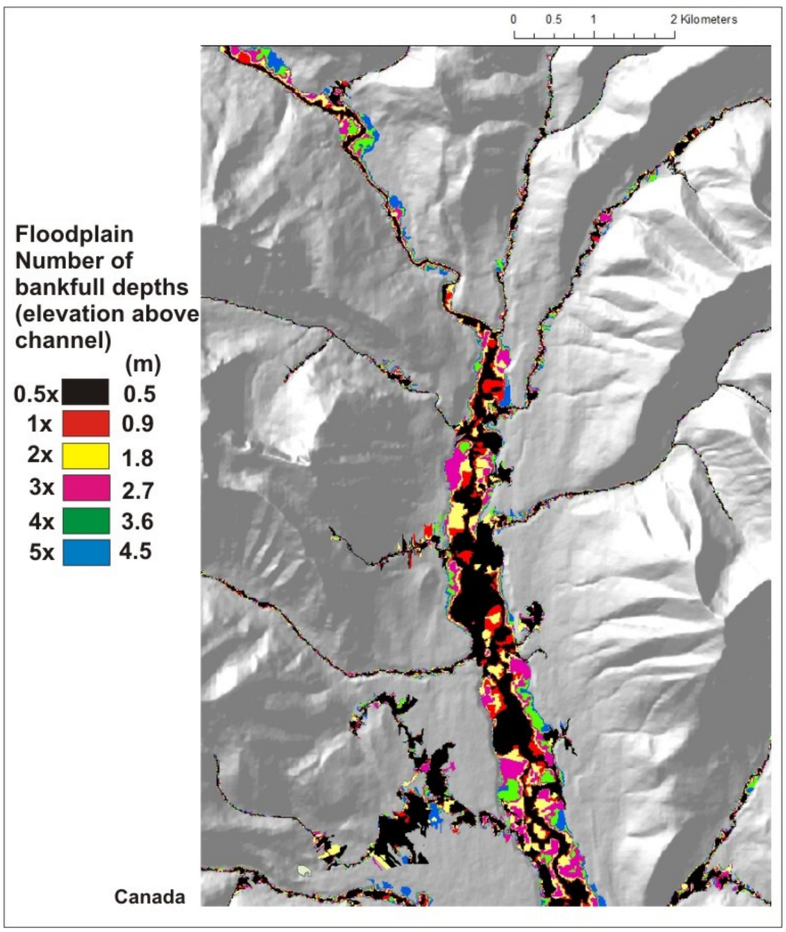

Figure 26. NetMap's floodplain tool is used to map the distribution of floodplain and terrace surfaces, shown as a landform mosaic corresponding to a range of bankfull channel depths above the channel elevation (0.5x – 5x). Using a predicted bankfull depth of 0.9 m, the predicted surfaces range from 0.5m to 4.5 m above the channel. To see the full basin results, use NetMap tools with the Flathead River Digital Landscape.

In the example located in the upper portion of the mainstem Flathead River in Canada, the predicted floodplains and terraces form a mosaic of surfaces (Figure 23). From a comparison of the predicted surfaces and the mapped floodplains and channel migration zones along the example reach (using Google Earth), a predicted floodplain at 3x bankfull depth appears to capture the majority of those landforms (**Figure 27**).

The mapping of floodplains, terraces and channel migration zones using DEMs (10-15m in this application) should be considered approximate. Floodplains are most accurately mapped at site specific locations using field surveys. However, NetMap's floodplain tool allows a rapid evaluation of floodplain and channel migration surfaces at the scale of large watershed, particularly where field information is lacking.

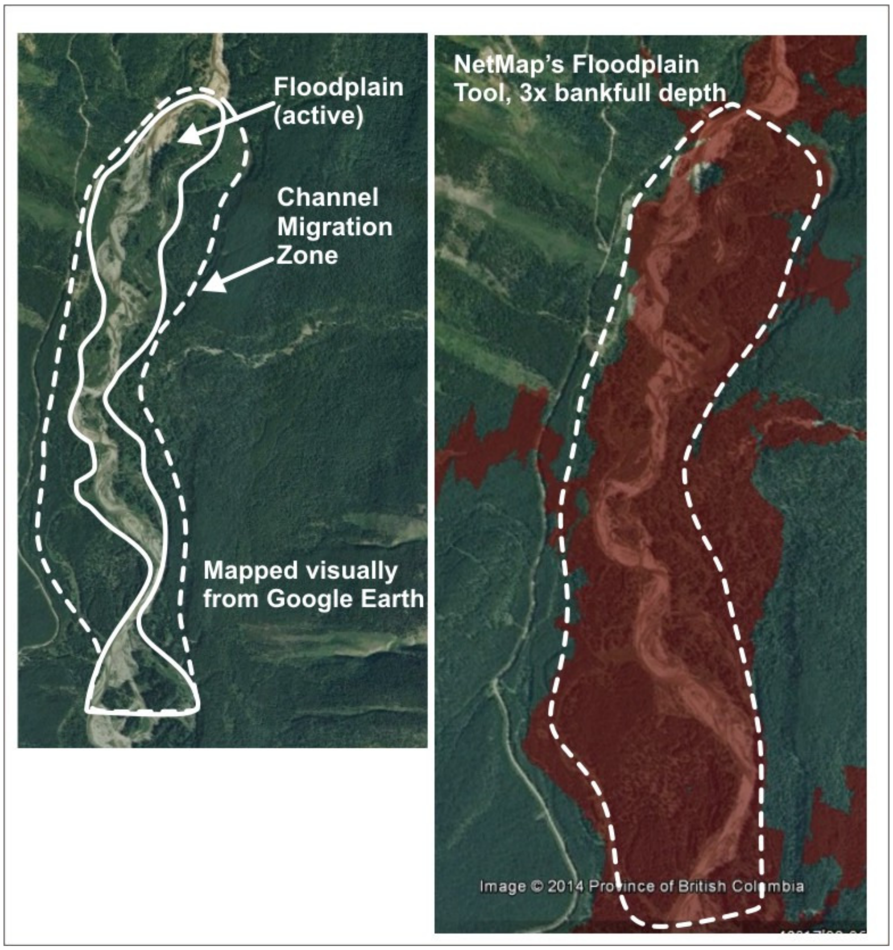

Figure 27. (Left Panel) The floodplain was mapped visually using Google Earth based on evidence of gravel bars and young vegetation. The channel migration zone was similarly interpreted based on older vegetation, evidence of side channels or older channels and erosional features along high terraces or hillsides. (Right panel) NetMap's mapped floodplain using 3x bankfull depth captures the majority of the combined floodplain-channel migration surface.

Once floodplains (or channel migration areas) are mapped, NetMap contains a tool for identifying road segments that are located within or close to the predicted zones. **Figure 28** shows an example of road segments that might be contained with the predicted floodplain. However, use of 10-15 m DEMs adds uncertainty about the prediction. Such analyses are used as a coarse screen to quickly identify which road segments may be at risk of damage during large floods, or which road segments may be impacting the aquatic system.

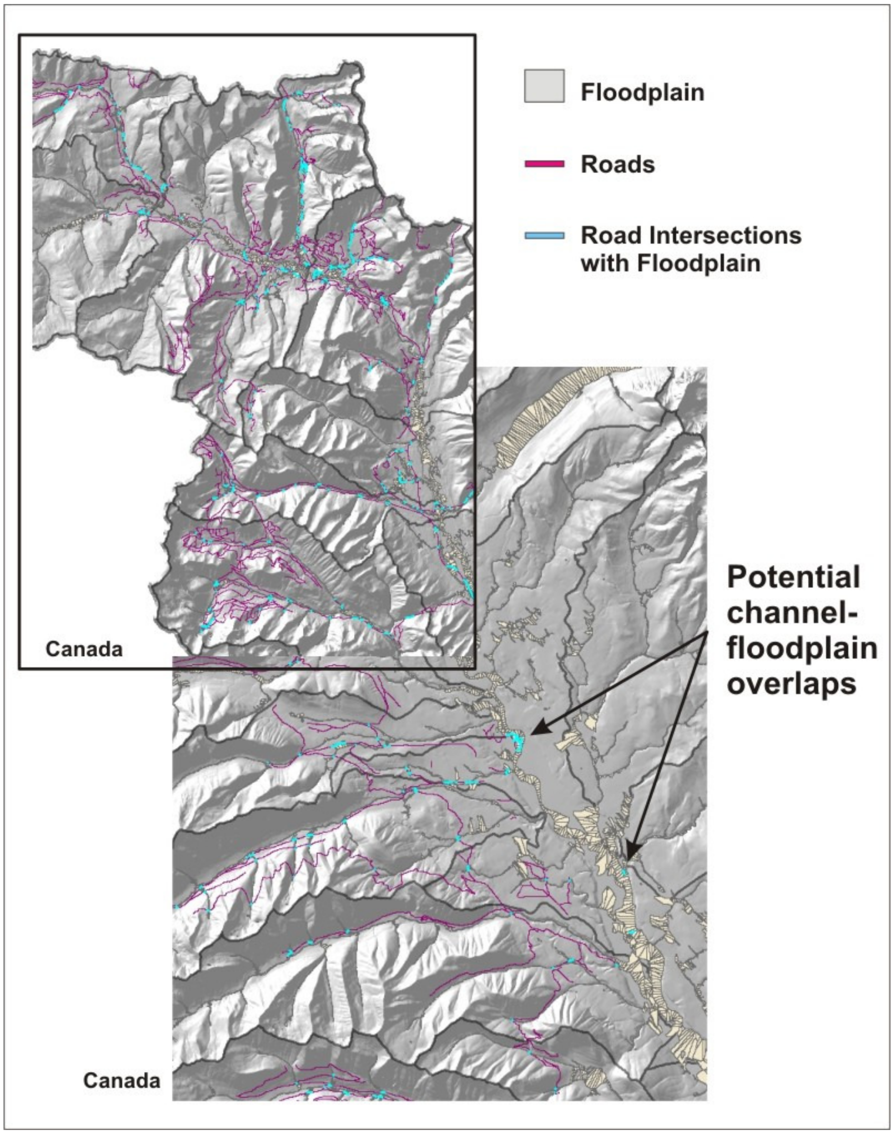

Figure 28. Locations where roads may be intersecting potential floodplain areas are shown for two areas in the Flathead River watershed.

Fish Habitats: Bull Trout and Westslope Cutthroat Trout

Mapping of sensitive fish habitats in the Flathead River watershed can be used to better understand how land use activities, such as road surface erosion, or wildfire and climate change can impact aquatic habitats and to delineate habitat-stressor intersections. Data on the fish distribution (NOAA, http://www.nwfsc.noaa.gov/trt/mapsanddata.cfm) are used to define the spatial extent of Bull Trout and Westslope Cutthroat Trout in the Flathead River basin (**Figures 29 and 30**). Westslope cutthroat trout has a larger range in the watershed compared to Bull Trout. Mapping of Bull Trout and Westslope Cutthroat Trout habitat extent could be improved and extended into Canada using available field information on fish distribution; data that can be transferred to NetMap's synthetic stream layer.

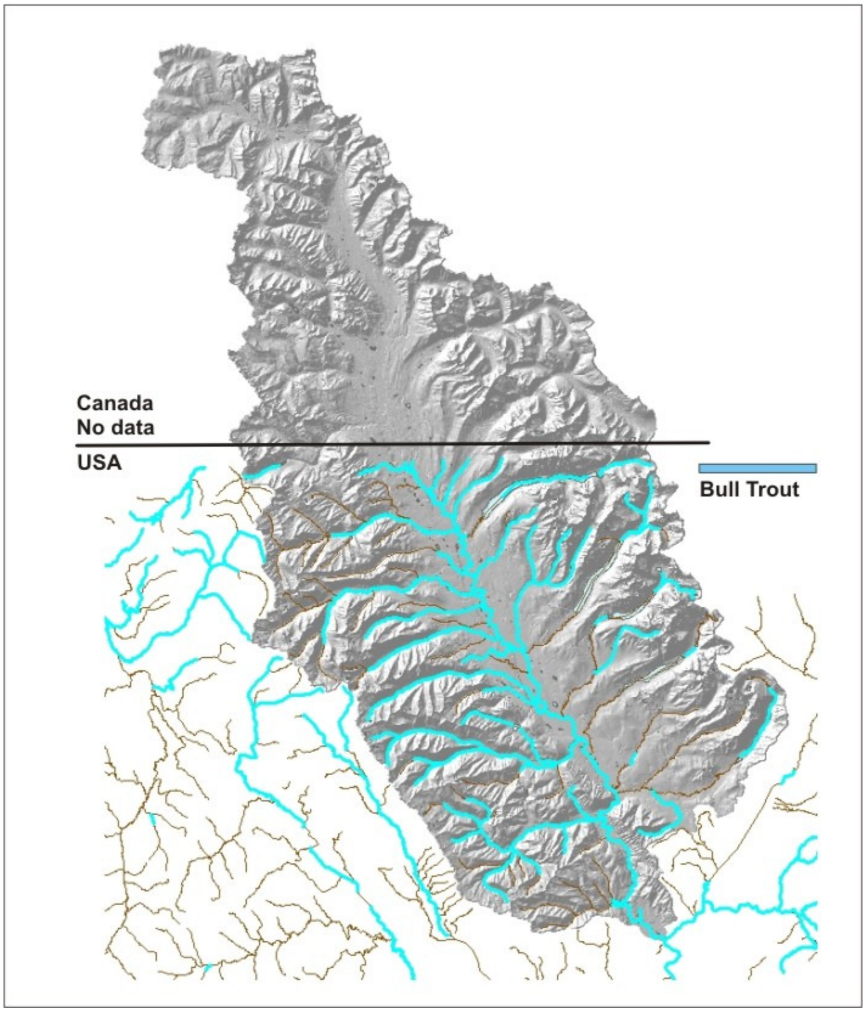

Figure 29. Data from NOAA (http://www.nwfsc.noaa.gov/trt/mapsanddata.cfm) are used to define the spatial extent of Bull Tout in the Flathead River basin. Data not available in Canada. However, these data can be calibrated, improved and expanded upon with the use of available field survey data that can be incorporated into the NetMap platform. Data on fish distribution and quality can also be added in Canada, depending on data availability.

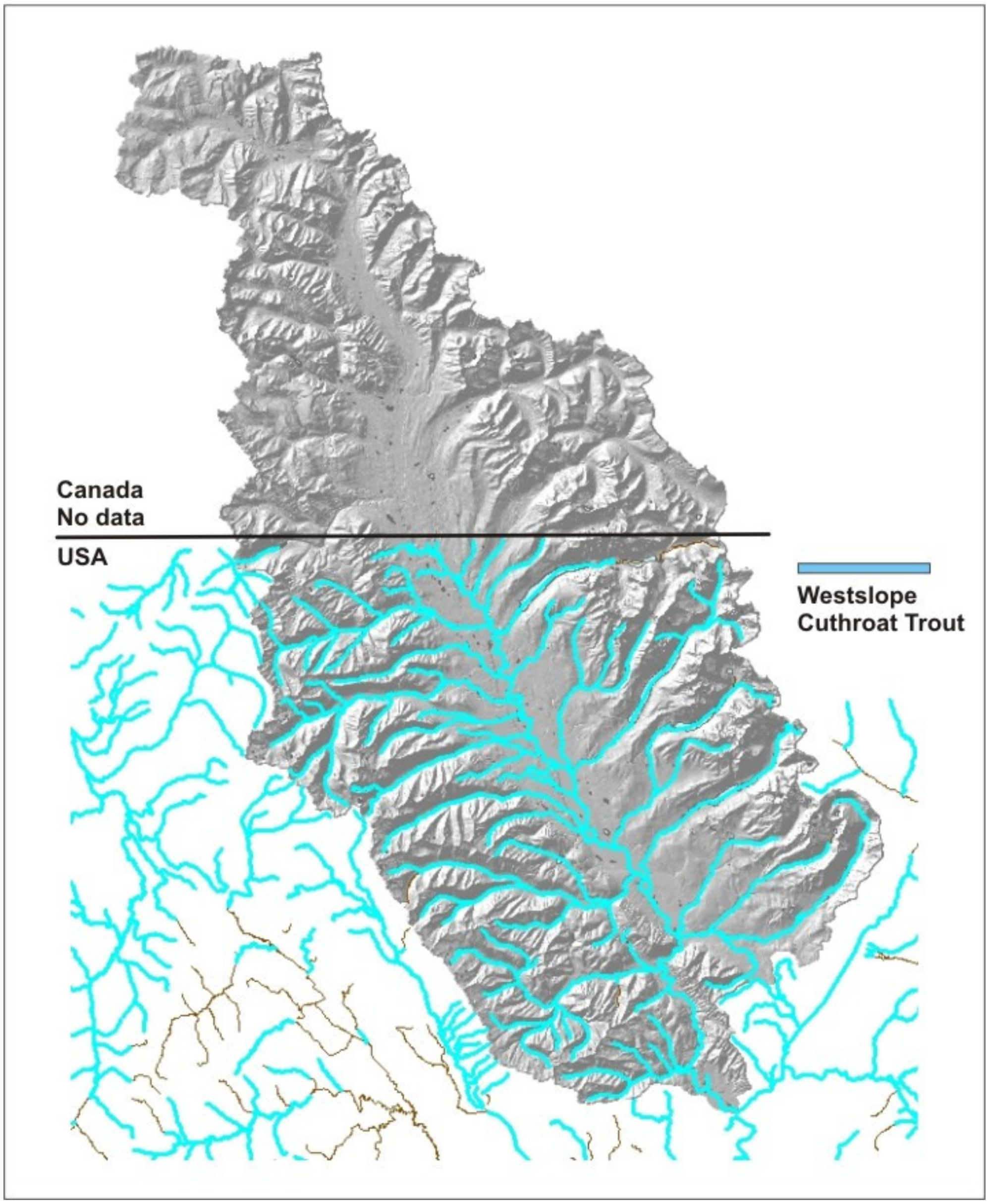

Figure 30. Data from NOAA (http://www.nwfsc.noaa.gov/trt/mapsanddata.cfm) are used to define the spatial extent of westslope cutthroat trout in the Flathead River basin. Data not available in Canada.

NetMap contains fish habitat modeling capabilities that are used to create provisional maps of fish habitat habitat quality across the Flathead River. An intrinsic potential model for westslope cutthroat trout (Peterson et al. 2008) is used in this analysis (**Figure 31**).

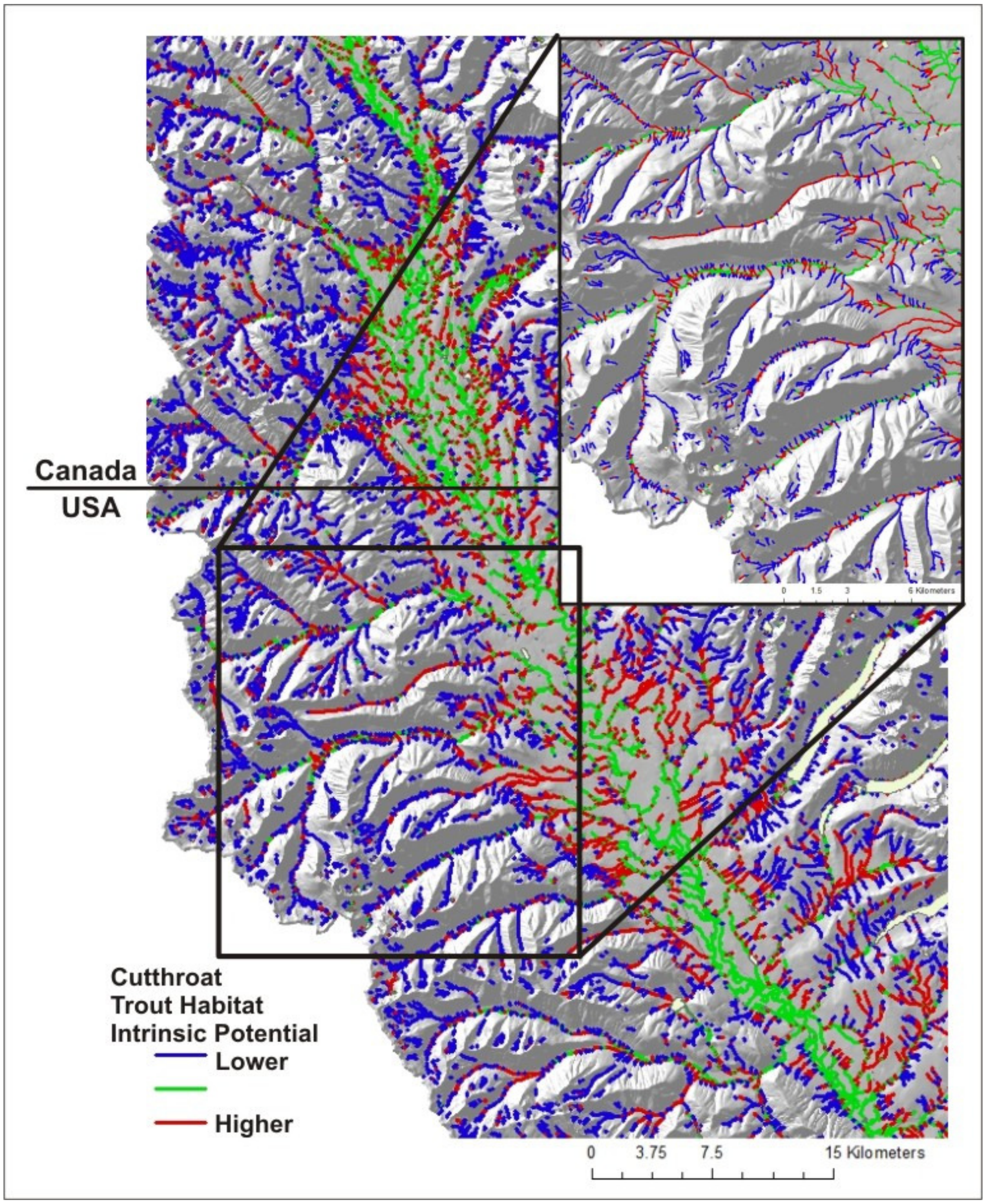

Figure 31. A habitat intrinsic potential model for westslope cutthroat trout (Peterson et al. 2008) is applied across the Flathead River basin revealing spatial variation in habitat quality.

Wildfire Analysis

NetMap's Fire Cascade tool was applied as part of the Flathead River watershed assessment. Fire probability and fire severity (flame length) were accessed from federal wildfire predictions (WWETAC). The post fire erosion prediction (surface erosion using the WEPP model) used results from Miller et al. (2011). For more site specific analysis of pre and post wildfire conditions and the erosion associated with it, users can apply NetMap's fire-erosion tool.

Wildfire probability and severity forecasts were available for only the US portion of the Flathead River watershed. **Figure 32** shows the spatial data (grid) on forecasted wildfire probability (1/p = fire recurrence intervals) and the predicted fire severity (flame length in feet).

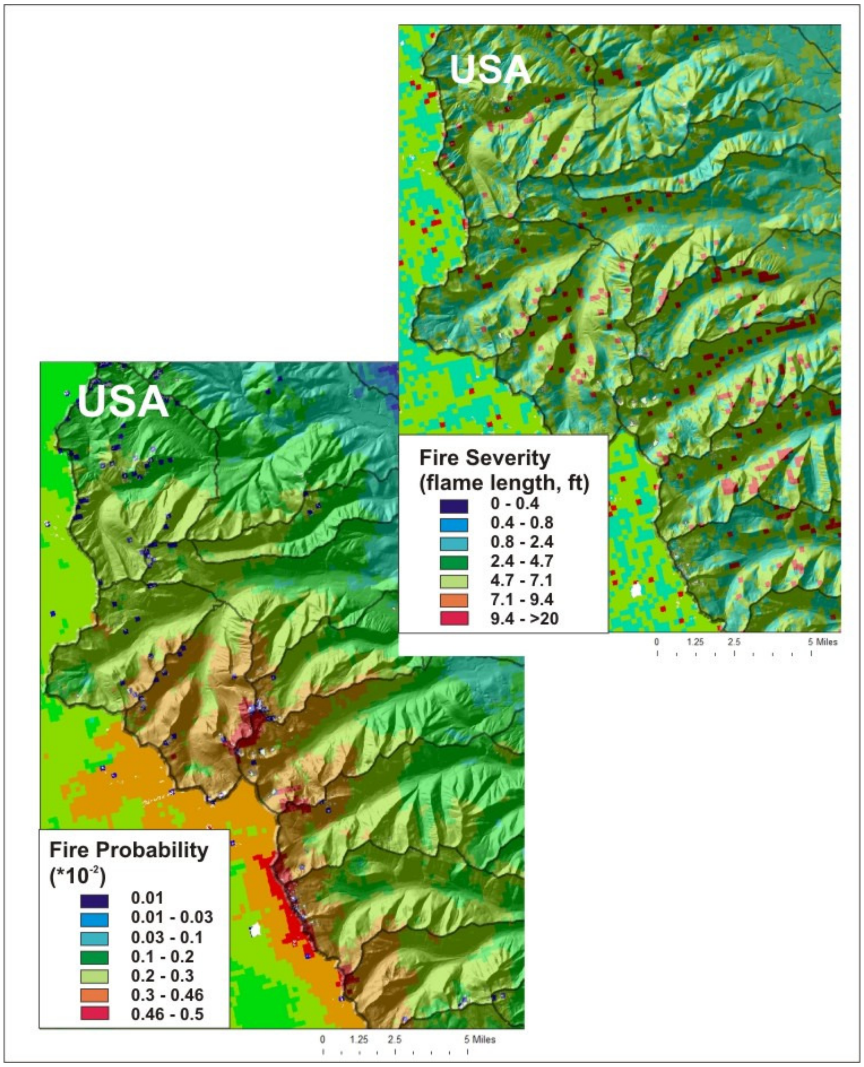

Figure 32. The predicted fire probability (lower) and fire severity in terms of flame length (upper) are mapped across the US portion of the Flathead River watershed. See Figure 33 for a fish eye view of fire severity. To see the full basin results, use NetMap tools with the Flathead River Digital Landscape.

Using the channel segment scale drainage wings in NetMap (Figure 2), predicted fire severity is reported to stream segments, offering a channel- or fish-eye view of fire severity (**Figure 33**). In addition, the channel segment values are aggregated (summed and area weighted) downstream in NetMap, providing a means to examine predicted fire severity at any spatial scale defined by the channel network (**Figure 34**). NetMap's Fire Cascade tool is used to quickly identify locations in the Flathead River watershed where the highest fire probability overlaps with the highest fire severity, and where that pair of stressors intersect with cutthroat trout habitat (**Figure 35**).

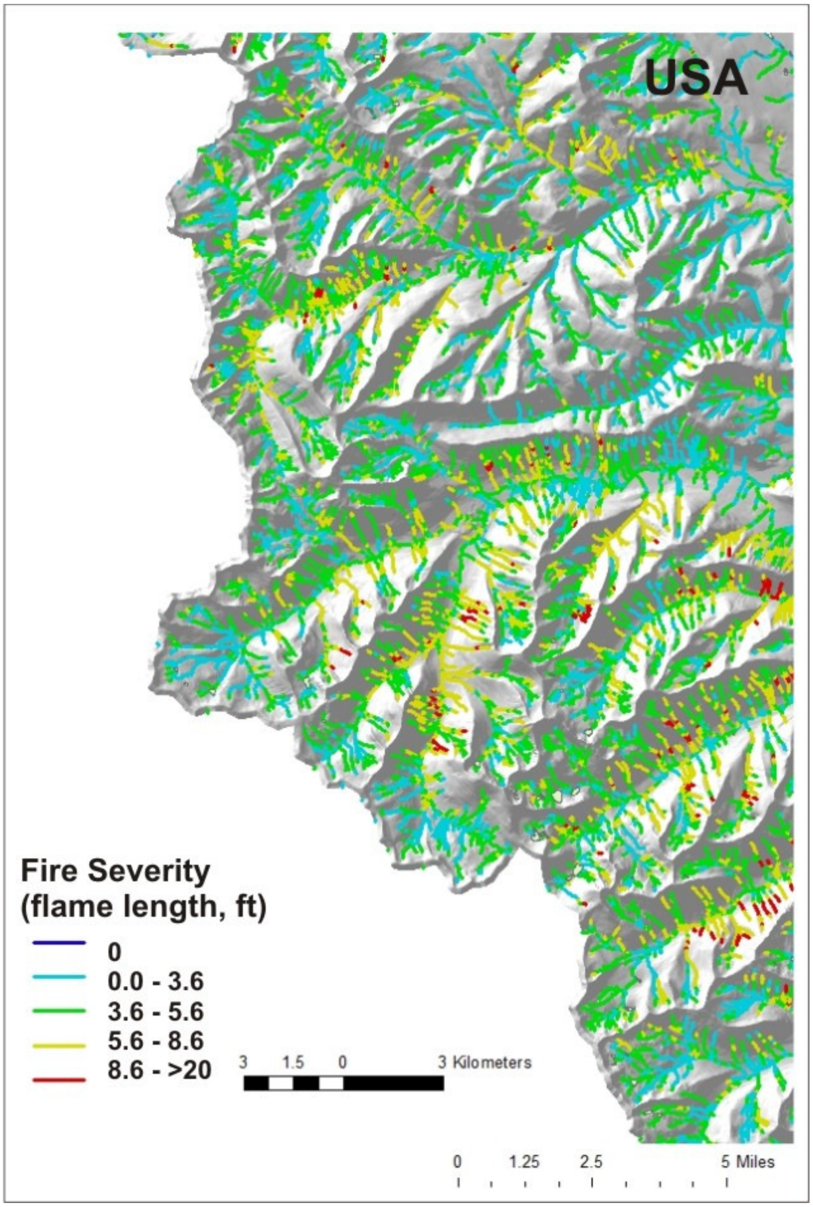

Figure 33. Predicted fire severity in terms of flame length is mapped onto individual channel segments using NetMap's reach scale local contributing area, providing a fish eye view of fire severity. To see the full basin results, use NetMap tools with the Flathead Digital Landscape.

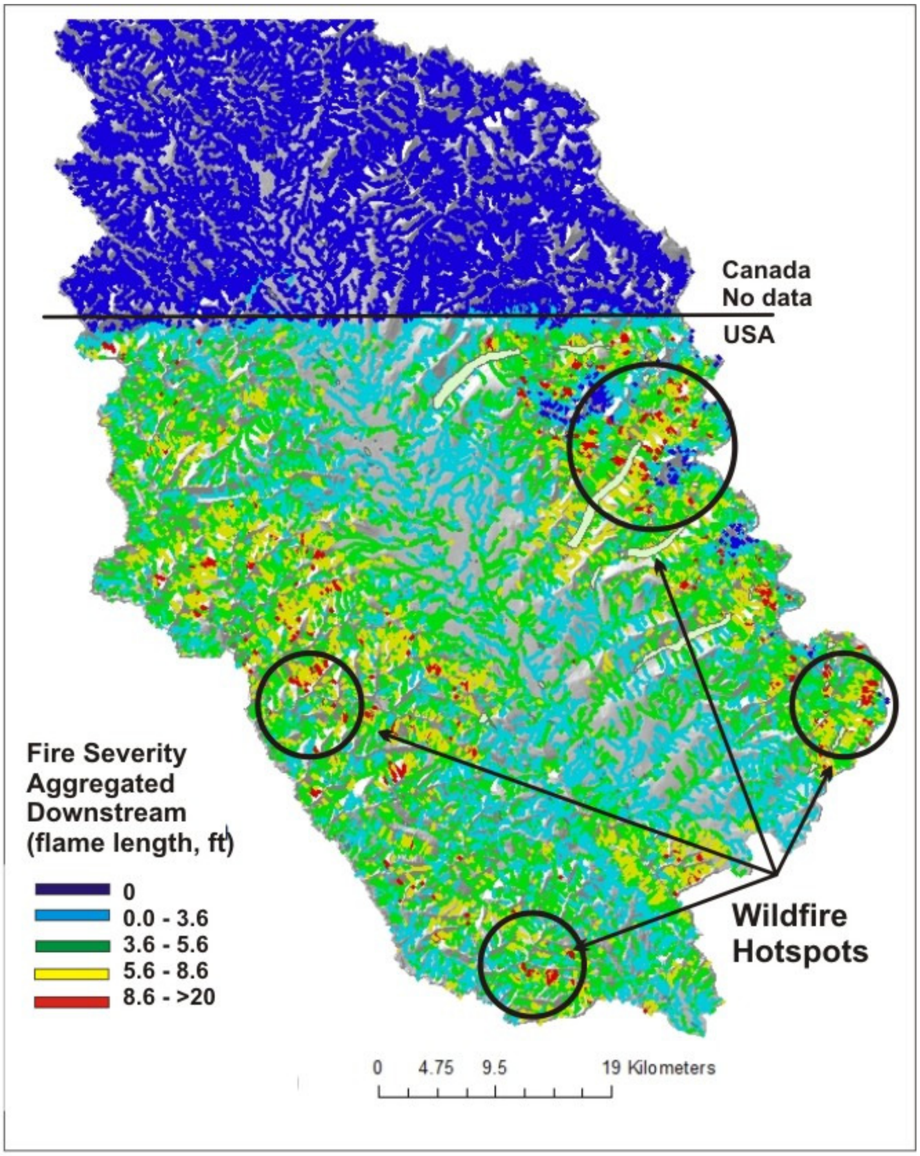

Figure 34. Predicted fire severity (flame length) is aggregated downstream revealing tributary scale patterns of fire severity across the US portion of the watershed. The smaller tributaries with the highest fire severity are shown in red indicating general geographic areas with higher fire severity potential.

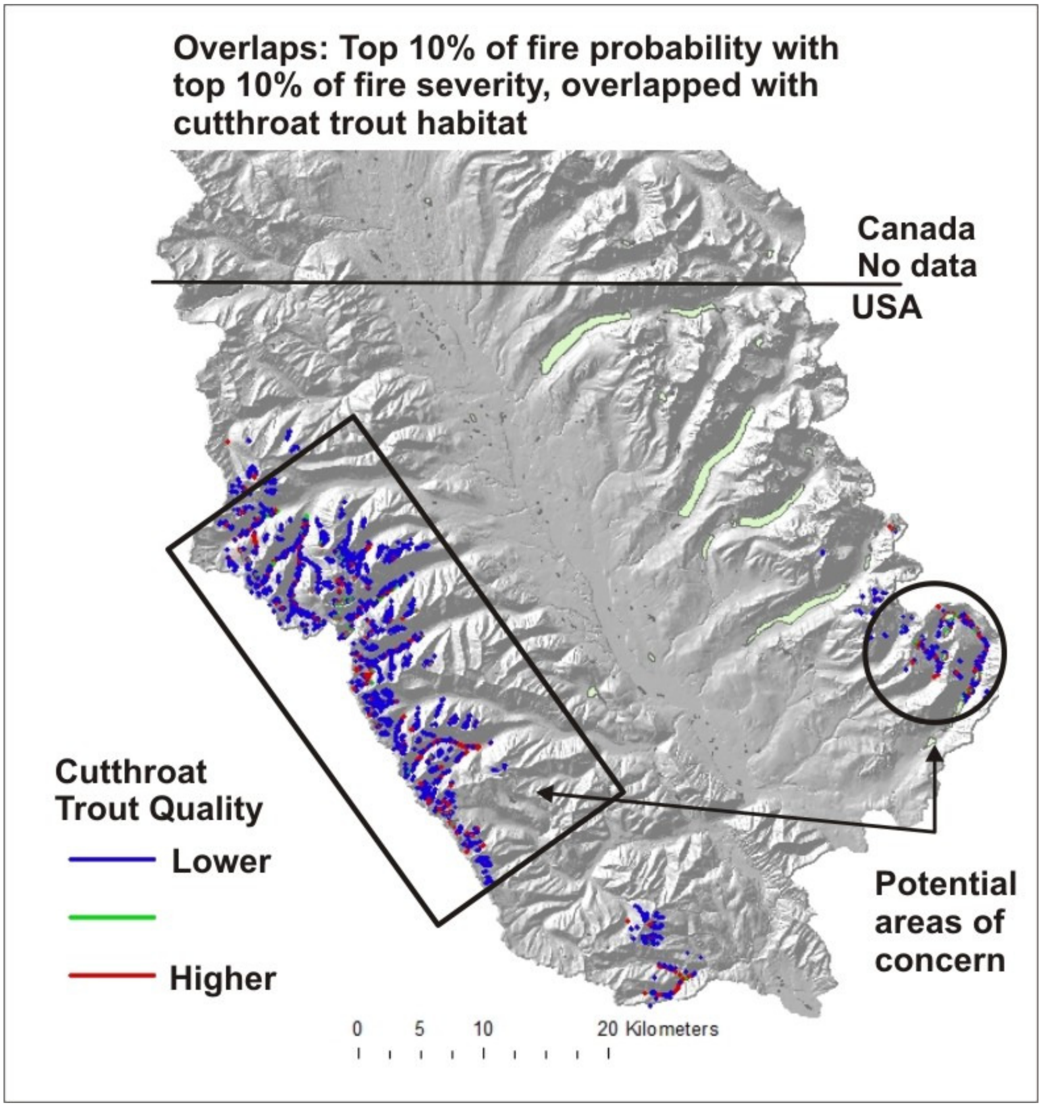

Figure 35. NetMap's Fire Cascade Tool is used to identify intersections among various watershed attributes. Illustrated here are the intersections between the highest 10% of fire probability and the highest 10% of fire severity. These areas as represented at the channel segment scale (4% of all segments) are mapped (color coded) according to the predicted Westslope Cutthroat Trout habitat intrinsic potential score (habitat quality). Certain areas of the Flathead River watershed are highlighted (no data in the Canadian portion). This information, among other NetMap analyses, could be used in pre wildfire planning activities (e.g., fuels reduction, prescribed fire etc.).

An analysis of the highest predicted fire severity and the highest predicted post fire erosion (using results from Miller et al. 2011) reveal where the intersections exist between these two stressors (**Figure 36**).The area of the greatest risk is located in the southeastern portion of the higher elevation areas of the Flathead watershed. Such information could be used to help guide wildfire mitigation efforts, including fuels reduction.

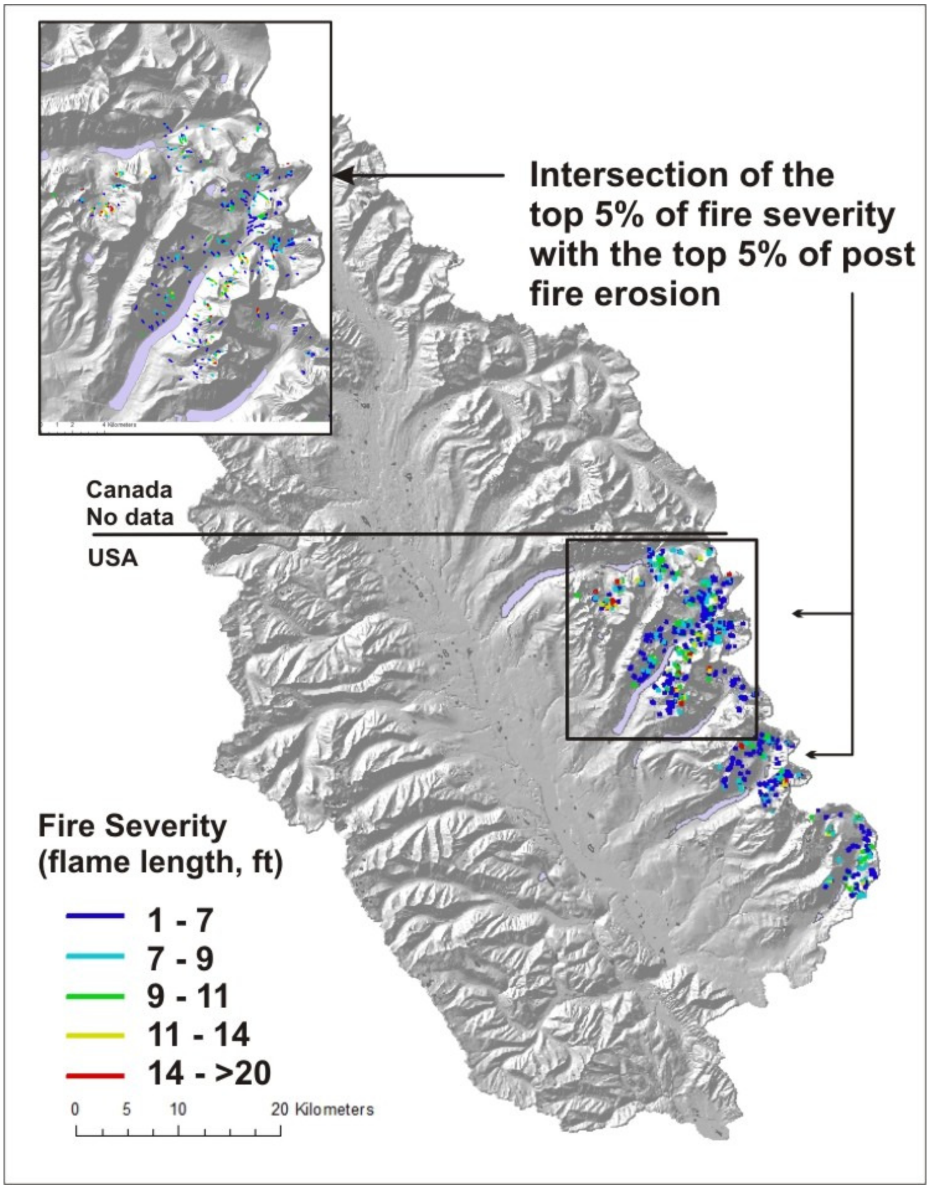

Figure 36. NetMap's Fire Cascade Tool is used to identify intersections between the highest 5% of fire severity and the highest 5% of post fire erosion potential (surface erosion). This type of information could be used to inform pre wildfire planning strategies.

Such stressor analyses can include fire probability, fire severity and post fire erosion, providing additional data to inform pre wildfire planning (**Figure 37**).

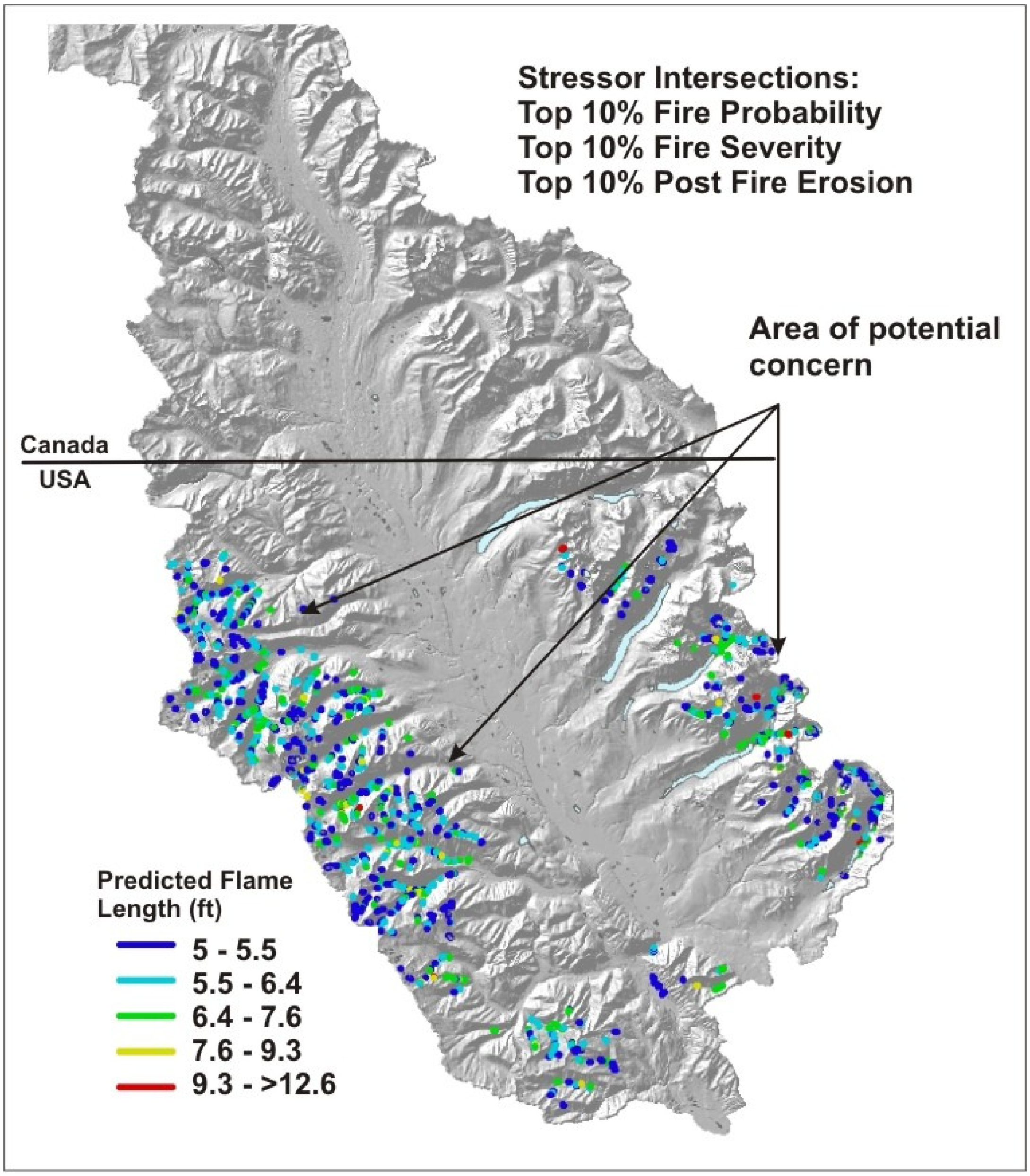

Figure 37. Locations (as reported in channels but representing adjacent hillside, via drainage wings, Figure 2) in the Flathead River basin where the highest (top 10%) fire probability, fire severity and post fire erosion overlap.

Climate Change Vulnerability

NetMap's climate change vulnerability tool utilizes downscaled forecasts available from the University of Washington Climate Impacts Group. Predictions are for one greenhouse gas scenario (A1B, a middle of the road scenario for future emissions). Results are in percent change from historical (1916-2006) to forecasts in 2040.

NetMap's tool is used to search for landscape vulnerability to climate change by examining intersections among climate change, wildfire risk, and in-stream habitat and channel sensitivity indicators. Forecasts pertaining to mean annual temperature, precipitation, snow accumulation, and summer and winter flows are presented. Forecasts are available for both the US and Canadian portions of the Flathead River watershed. Additional background information is available from Littell et al. (2011).

Projected air temperature increases are not uniformly distributed across the basin (Figures 38 and 39).

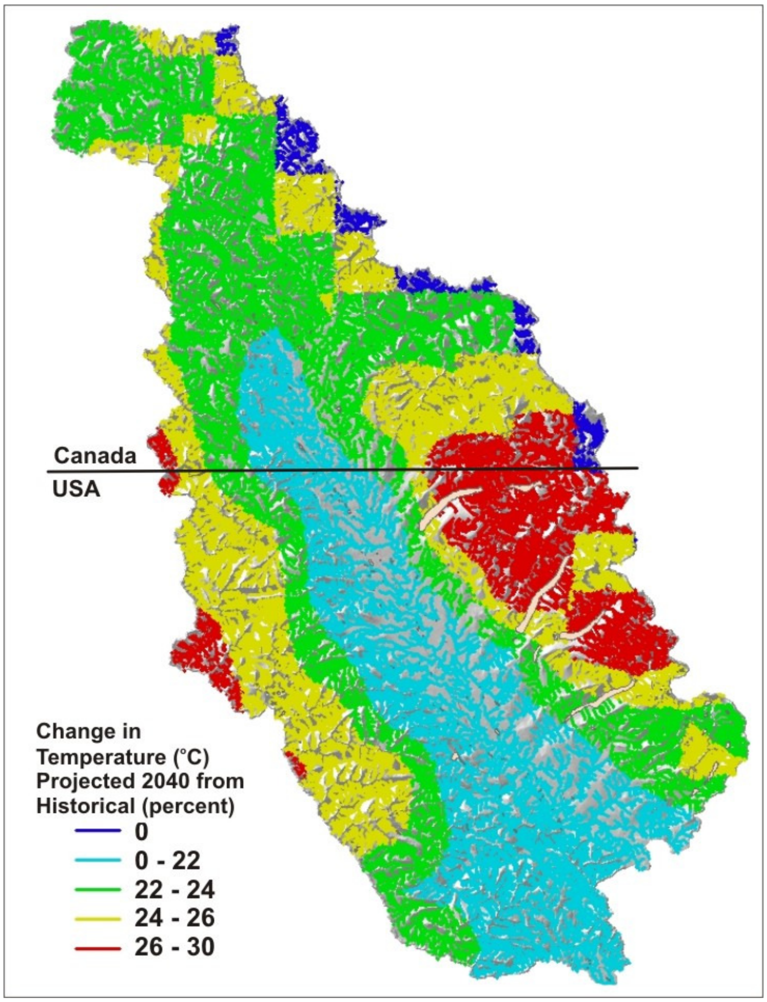

Figure 38. Downscaled predictions for mean annual air temperature mapped as percent change from year 2040 compared to historical (1916 – 2006). Although the raw data are in grid form, NetMap converts those values to channel segment values. The highest predicted increases in temperature are located in the US and Canadian portions of the basin along the eastern boundary. Small changes in predicted temperature (°C) can lead to high percent changes, as illustrated here. See Figure 39 for predicted absolute changes in temperature.

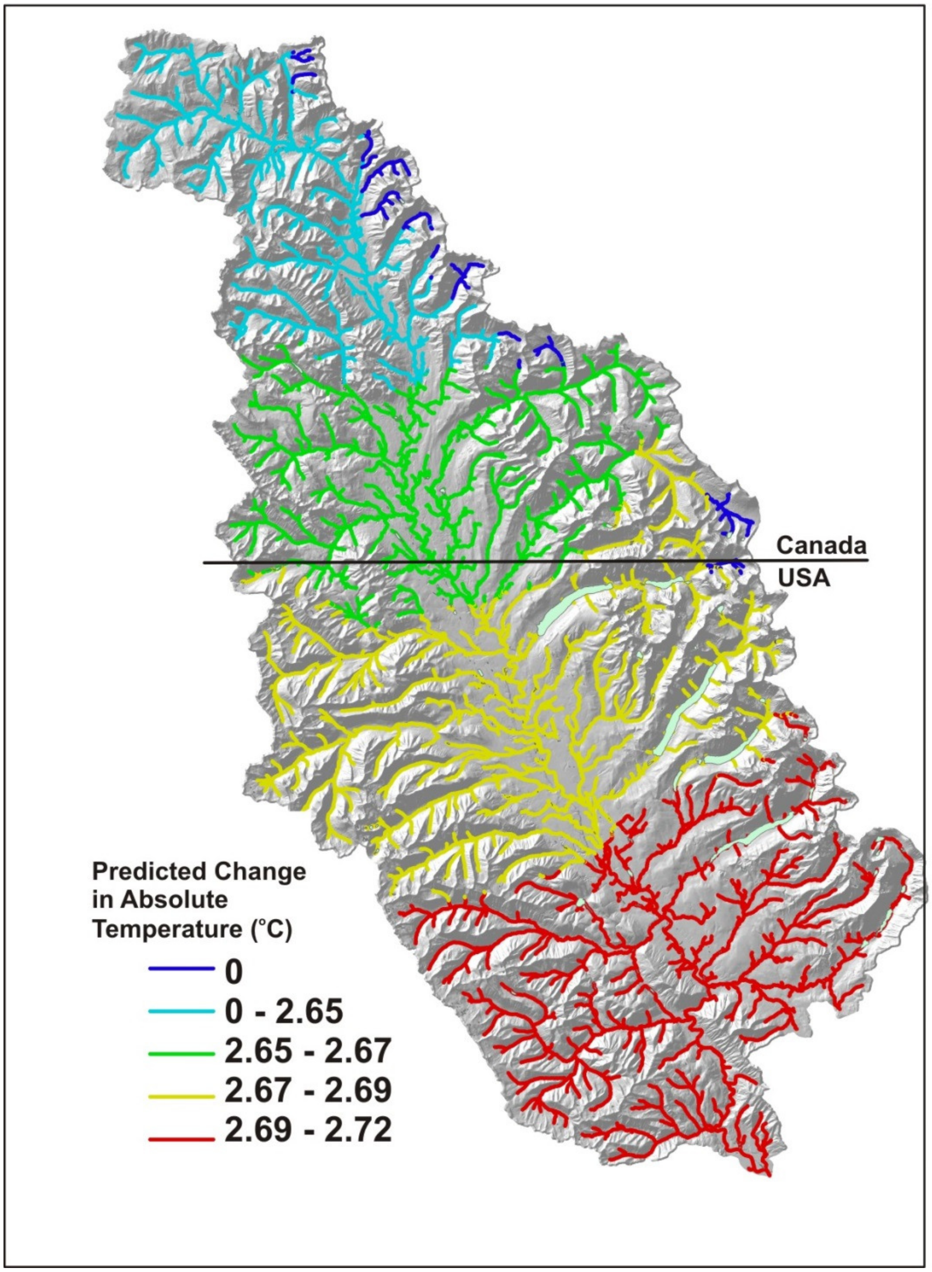

Figure 39. Downscaled predictions for mean annual air temperature (June, July, August) are mapped in absolute degree C, year 2040 compared to historical (1916 – 2006).

The downscaled climate change predictions also reveals that average annual precipitation may increase (rain and snow combined), although non-uniformly across the watershed (**Figure 40**). However, GCM predictions do not consider orographic effects of westerly winds and these are decreasing, leading to declines in mountain precipitation and thus to potentially lower flows (Luce et al. 2013).

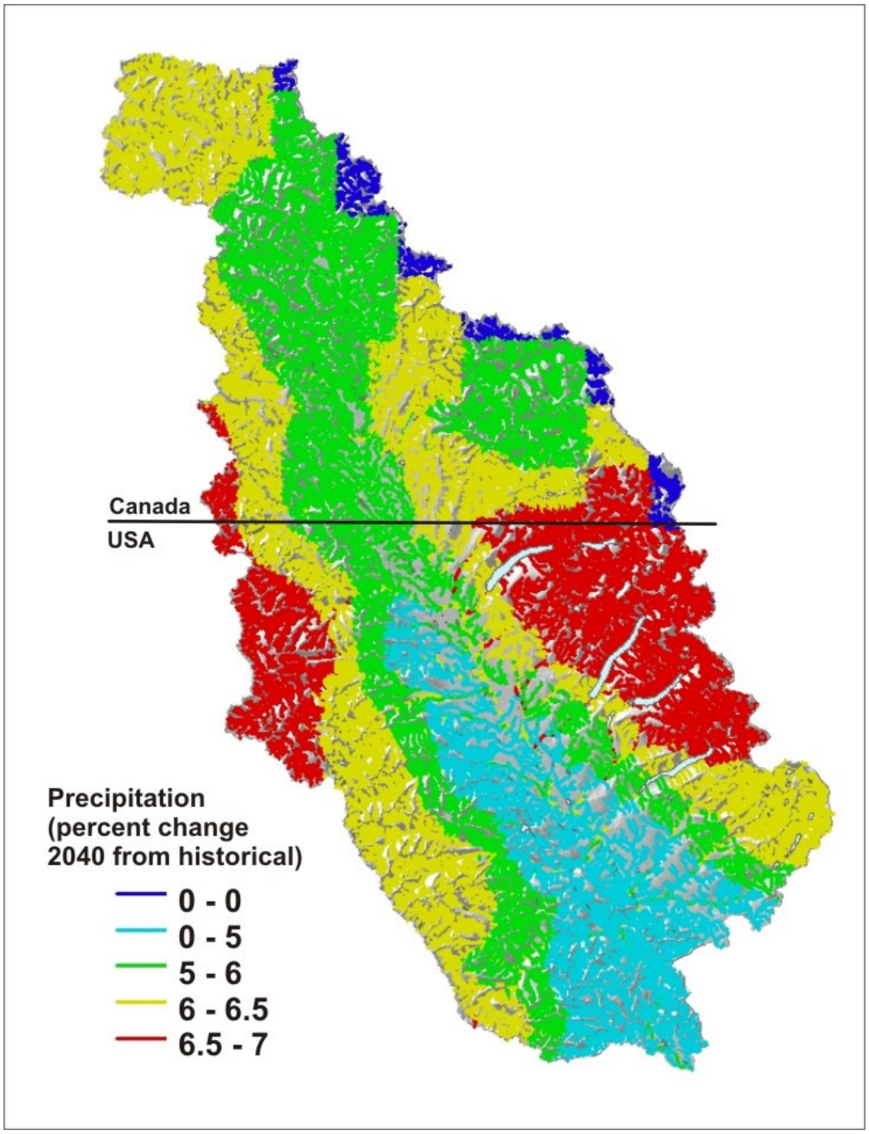

Figure 40. UW Climate Impacts Group GCM projections (downscaled) reveal a spatially variable increase in annual precipitation across the Flathead River watershed.

Wildfire is an important environmental stressor in the Flathead River watershed and the incidence of fire may increase in a warming climate. NetMap's climate change vulnerability tool is used to search for locations where the highest 10% of projected low summer flow reductions overlap the highest 10% of predicted (present day) fire severity (**Figure 41**).

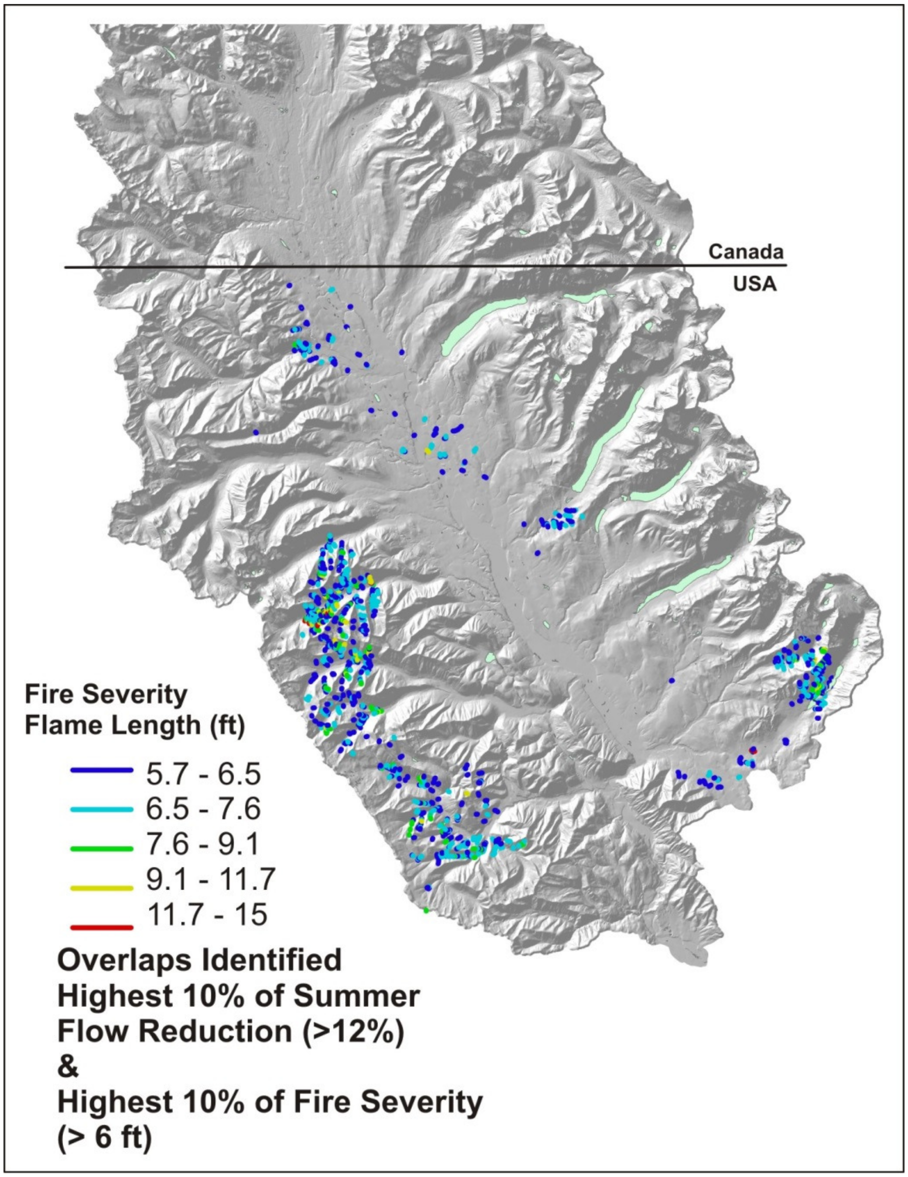

Figure 41. NetMap's climate change vulnerability tool is used to identify locations in the Flathead River watershed where the highest 10% of climate change induced reductions in summer flow overlap the (present day) highest 10% of fire severity. Such potentially sensitive areas are concentrated in the southwestern portion of the basin on the US side of the border (no fire risk data in Canada was used in this analysis).

Downscaled climate change projections also reveal significant reductions in snow accumulation days across the watershed, with the highest predicted reductions in the US side of the border. The forecasts defines elevation bands surrounding the N-S Flathead River mainstem with reductions that increase from **higher** to lower elevations ranging from less than a few percent to a maximum of greater than 30% along the mainstem in the US portion of the basin (**Figure 42**).

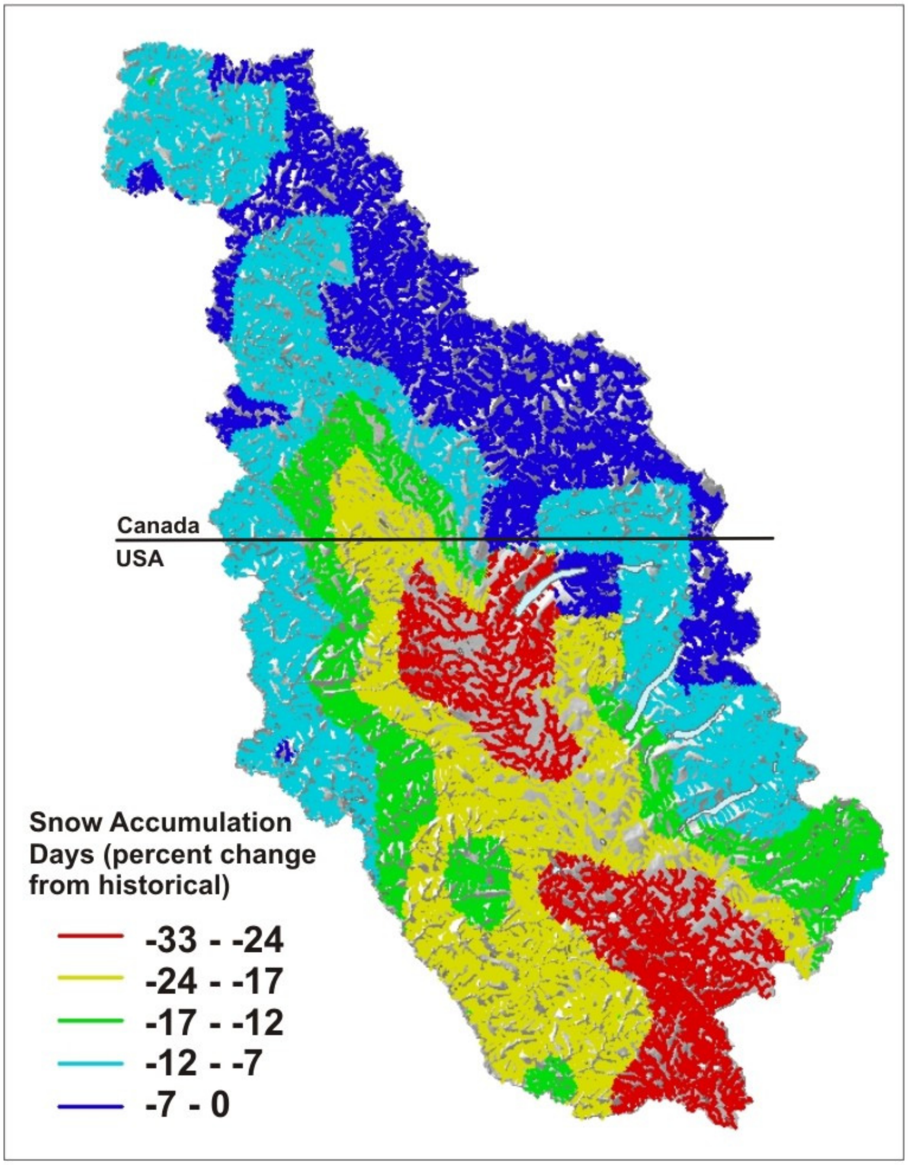

Figure 42. UW Climate Impact Group climate change forecasts for reductions in snow accumulation days in the Flathead River watershed.

Total precipitation is forecasted to increase across the Flathead River watershed due to climate change (although modestly to a maximum of 7% by 2040). However, the significant change in winter precipitation as snow (Figure 42) leads to forecasted reductions in summer runoff of up to 12 to 17% (**Figure 43**). But see the recent work of Luce et al. (2013) on decreased orographic effects leading to reduced flows in the northwestern US.

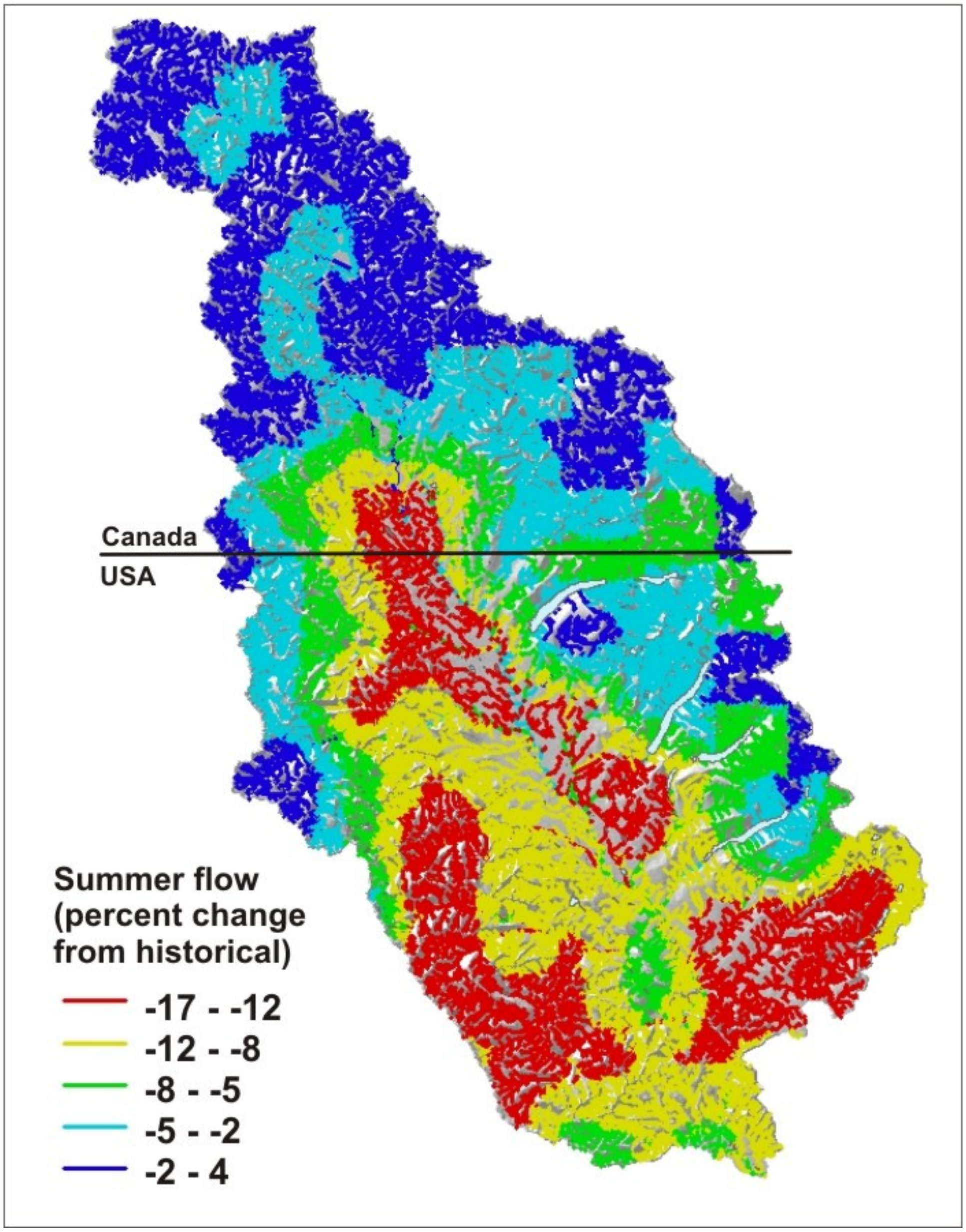

Figure 43. UW Climate Impacts Group predictions of reductions in summer flow show the largest impacts occurring in the US side of the border and along the lower western and eastern basin boundaries.

The predicted conversion of winter snow to winter rain (Figure 42) due to a warming climate (Figure 38) in the Flathead River watershed can result in increases in winter flows (**Figure 44**). This could yield an increase in rain dominated floods or rain-on-snow floods with the greatest potential impacts along the mainstem river and adjacent lowland tributaries (Figure 44).

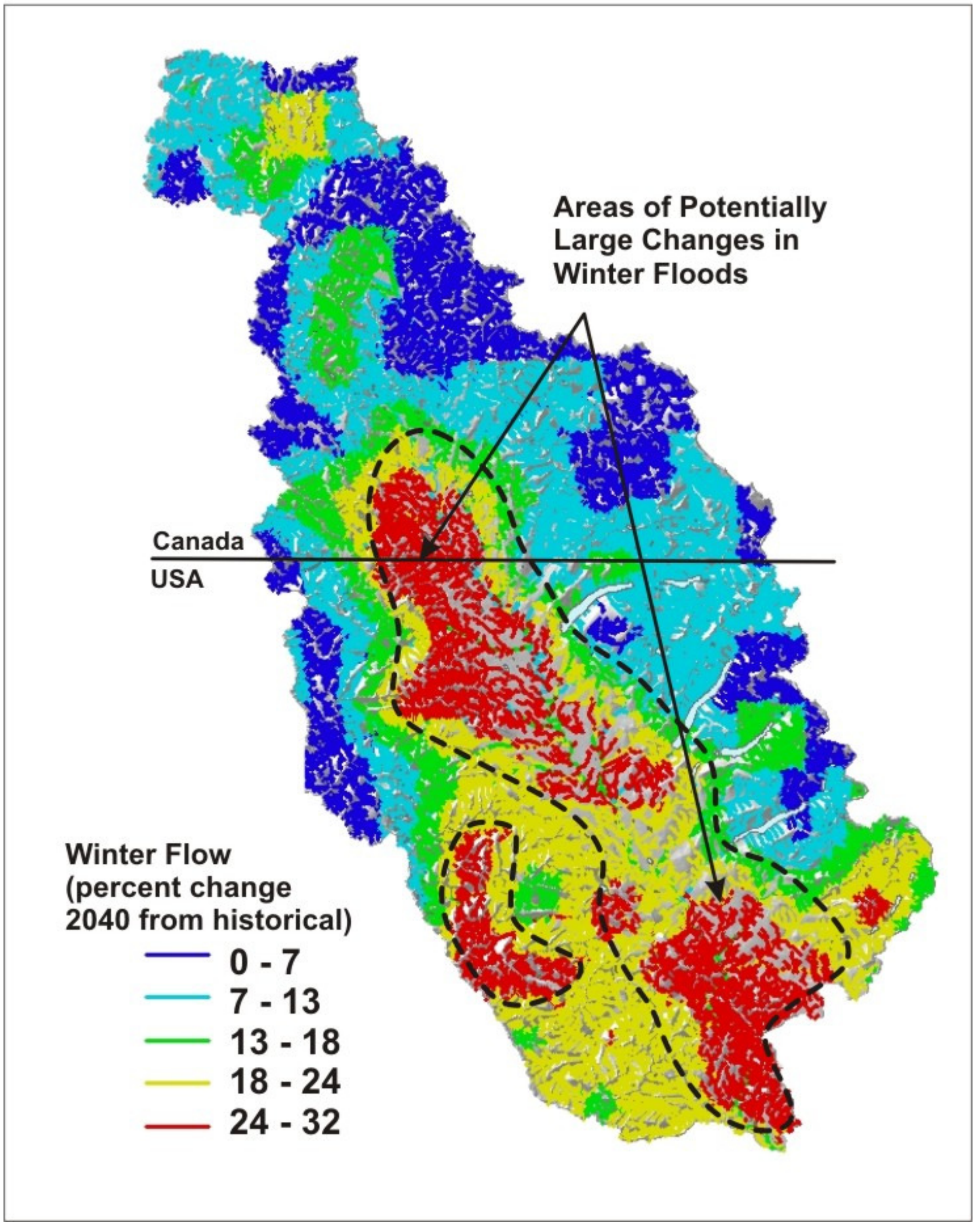

Figure 44. UW Climate Impact Group forecasts for increases in winter flow. The largest changes are forecast for the mainstem and adjacent lowland tributaries on the US side of the border.

Summary

Results contained in the Flathead River watershed assessment (Figures 9 – 44, and see Appendix 1) represent snapshots of various types of analyses contained within the full NetMap analysis available in the Digital Landscape accessed via NetMap tools. For more detailed and comprehensive analyses that span the entire Flathead watershed, refer to NetMap tools and the Flathead Digital Landscape (contact the US Fish and Wildlife Service or www.terrainworks.com for additional details). A key aspect of a

NetMap analysis is the ability of interested stakeholders to conduct their own custom analyses using the analysis tools.

A series of preliminary conclusions (1-14) are derived from NetMap's computer based analysis of the Flathead River watershed. Since analyses are model based, they could be used at the level of coarse screening. For example, which road segments have the potential to be the largest contributors of sediment to stream channels? Which road segments have the greatest potential for damaging the best habitats? Where is fire risk considered to be most extreme and where does that overlap the greatest forecasted climate change?

Conclusions:

(1) Road densities at the subbasin scale (HUC 6) range from zero to 2.5, with the highest densities located in the Canadian portion of the watershed (Figure 9).

(2) Road densities at the individual hillside and channel segment scale range from zero to 100 (Figure 10). The highest road densities (top 10%) are located in the Canadian portion of the watershed (Figure 11).

(3) Predicted road surface erosion (delivery to streams) is substantial and highest in Canada (Figures 13–17). Both models (GRAIP-Lite and WEPP) reveal the specific hillside locations of the highest predicted road surface erosion (delivered to streams). Predicted values are similar to independent field measurements of road sediment production (Table 1). Users can import a set of geo-referenced drain points representing culverts and secondary drainage structures (rolling dips, water-bars) to improve predictions of road hydrologic connectivity and road surface erosion.

(4) An average annual background sediment yield of 20 t/km^2/yr is estimated for the watershed using very approximate data from other sources. The value was distributed spatially across the Flathead River watershed using an index of hillslope steepness and curvature (Figures 20-22).

(5) A comparison between predicted road surface erosion (both models) and the estimated background sediment yield, at the watershed scale (the Canadian portion of 1125 km^2 and the full basin in the US at 4055 km^2) revealed that predicted sediment yield comprised a very small proportion of the total basin sediment yield (0.3% to 1.8%, Table 2). Even using the lower end of the estimated average basin sediment yield (10 t/km^2/yr), proportions only increase to a maximum of 4%. But see (6) below.

(1) A comparison between predicted road surface erosion (WEPP model) and the estimated background sediment yield at the scale of individual hillsides and channel segments (locally and cumulative downstream) revealed that in many locations, predicted road erosion can exceed background sediment yield by tens to hundreds of percent (Figure 23). When considered cumulatively downstream, road erosion exceeds background sediment yields (by high margins) only in the uppermost tributaries (Figure 24). *Users can import a set of geo-referenced drain points representing culverts and secondary drainage structures (rolling dips, waterbars) which are used to inform drain point location in the models; due to lack of data this enhancement was not done in the Flathead Watershed Assessment (but could be done later by stakeholders using NetMap tools).*

(6) NetMap tools were used to evaluate the potential for roads to cause gully erosion (Figure 25). There are numerous locations in the watershed where road related gully erosion may be cause for concern.
(7) An analysis of floodplain and terrace surfaces (including within the river migration zone) reveals a mosaic of surfaces along the Flathead River mainstem and its tributaries (Figure 26). This analysis could provide a provisional mapping of floodplains and channel migration areas (Figure 27). It can also be used to identify which road segments may be at risk within that zone (Figure 28).
(8) The distributions of Bull Trout and Westslope Cutthroat Trout were mapped across the US portion of the watershed (Figures 29-30). An intrinsic potential habitat model (Peterson et al. 2008) was also applied across the basin revealing spatial patterns of variable habitat quality (Figure 31). Mapping of Bull Trout and Westslope Cutthroat Trout habitat extent could be improved (in the US portion) and extended into Canada using available field information on fish distribution/quality; data can be transferred to NetMap's synthetic stream layer.
(9) NetMap's Wildfire Cascade Tool was applied to the watershed using Western Environmental Threat Assessment Center predictions for fire probability and fire severity (flame length). Predictions were mapped to individual channel segments and routed downstream revealing spatial patterns of varying fire risk and severity (Figures 32-34). An example of a habitat-stressor analysis revealed locations in the watershed where the highest 10% of fire probability overlaps the highest 10% of fire severity and where that pair intersects cutthroat trout habitat quality (Figure 35).
(10) As an example risk assessment, NetMap is used to identify intersections between the highest 5% of fire severity and the highest 5% of predicted post fire erosion (Figure 36). Another illustrative analysis revealed where the highest 10% of fire probability, highest 10% of fire severity overlaps with the highest 10% of post fire erosion (Figure 37). Areas of concern are concentrated in the US northeastern portion of the Flathead River watershed (fire data not made available in Canada).
(11) Using NetMap's Climate Change Vulnerability tool, predictions for changing temperature, precipitation, snow accumulation days and runoff were mapped across the Flathead River watershed using downscaled GCM forecasts (UW Climate Impacts Group, results in percent change from historical [1916-2006] to 2040) (Figures 38-40)
(12) An illustrative risk assessment revealed where the highest 10% of projected reduction in summer low flows overlaps with the top 10% of predicted fire severity (Figure 41). This type of analysis can be used to help inform pre wildfire planning (fuels reduction, prescribed fire etc.).
(13) Significant reductions in snow accumulation days are forecasted and highly dependent on elevation patterns in the watershed (Figure 42). This prediction, along with forecasted changes in temperature and precipitation, leads to forecasted reductions in summer flow (Figure 43) and increases in winter flows and floods (Figure 44).

Analyses conducted in the Flathead River basin, using NetMap's Digital Landscape and Analysis Tools (www.terrainworks.com), can be used for natural resource planning involving forestry, fisheries, wildfire and climate change or for planning restoration projects. NetMap tools combined with readily available data were used to create a multi-scale analysis to provide insights into road, channel, and watershed scale attributes pertinent to aquatic systems. Field visits/measurements are recommended to be used in conjunction with the NetMap analyses. No field work was conducted during this study.

Acknowledgements

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Appendix 1: Road Surface Erosion Predictions using WEPP and Comparison of WEPP to GRAIP-Lite Predictions

In addition to GRAIP-Lite road erosion predictions (Figures 13 – 17), the WEPP road surface erosion model was also applied in the Flathead River basin (Figure 1-1).

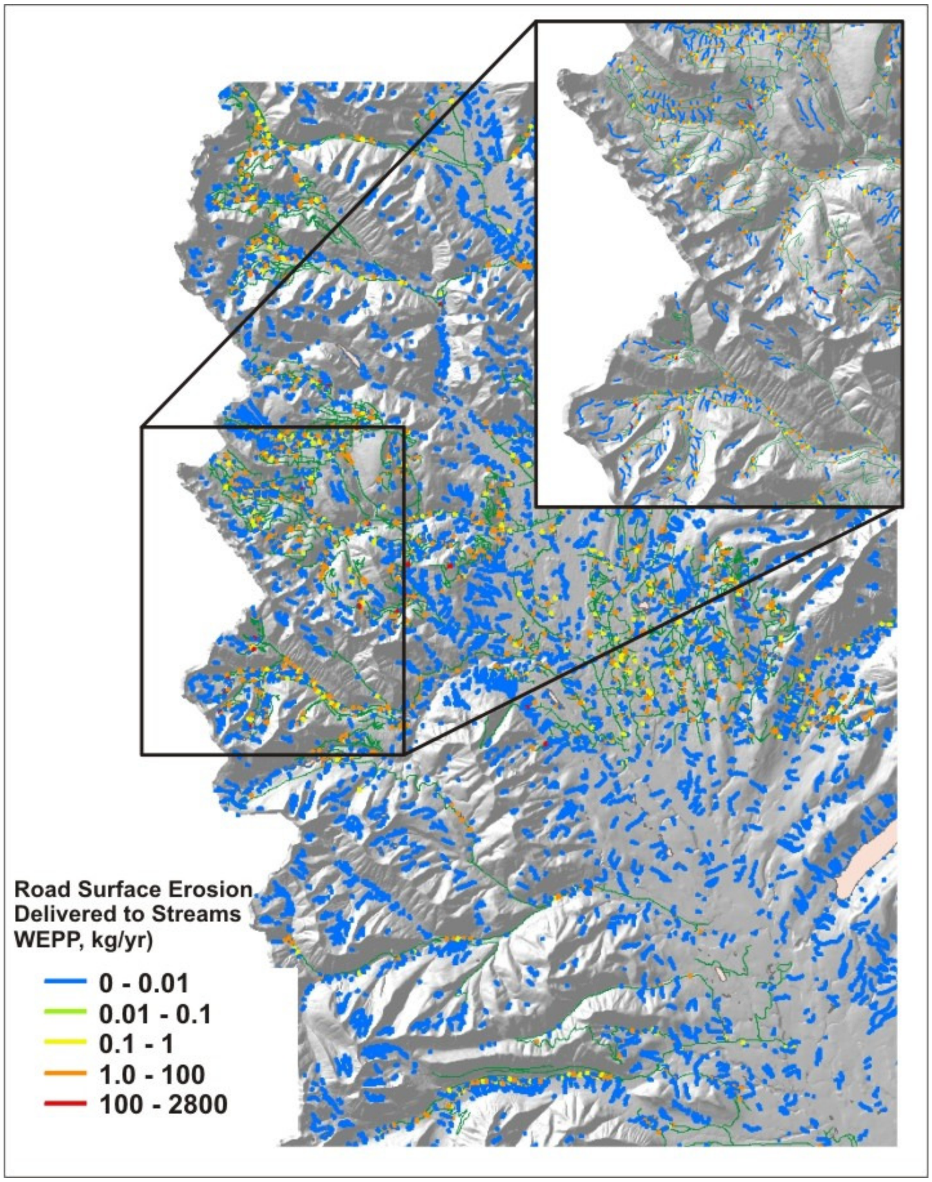

Figure 1-1. Predicted WEPP road surface erosion – delivery to streams is less compared to GRAIP-Lite predictions (e.g., Figure 17).

A comparison between GRAIP-Lite and WEPP sediment *production* values reveals that the majority of WEPP predictions are up to 100% less than the corresponding GRAIP-Lite predictions, per channel segment (**Figure 1-1**). The predicted road hydrologic connectivity segments are identical in both models). However, note that the WEPP model is applied using "low traffic" levels; increasing the traffic levels to “high”, particularly on steeper gradient roads increases the WEPP erosion predictions by 300% to 500%.

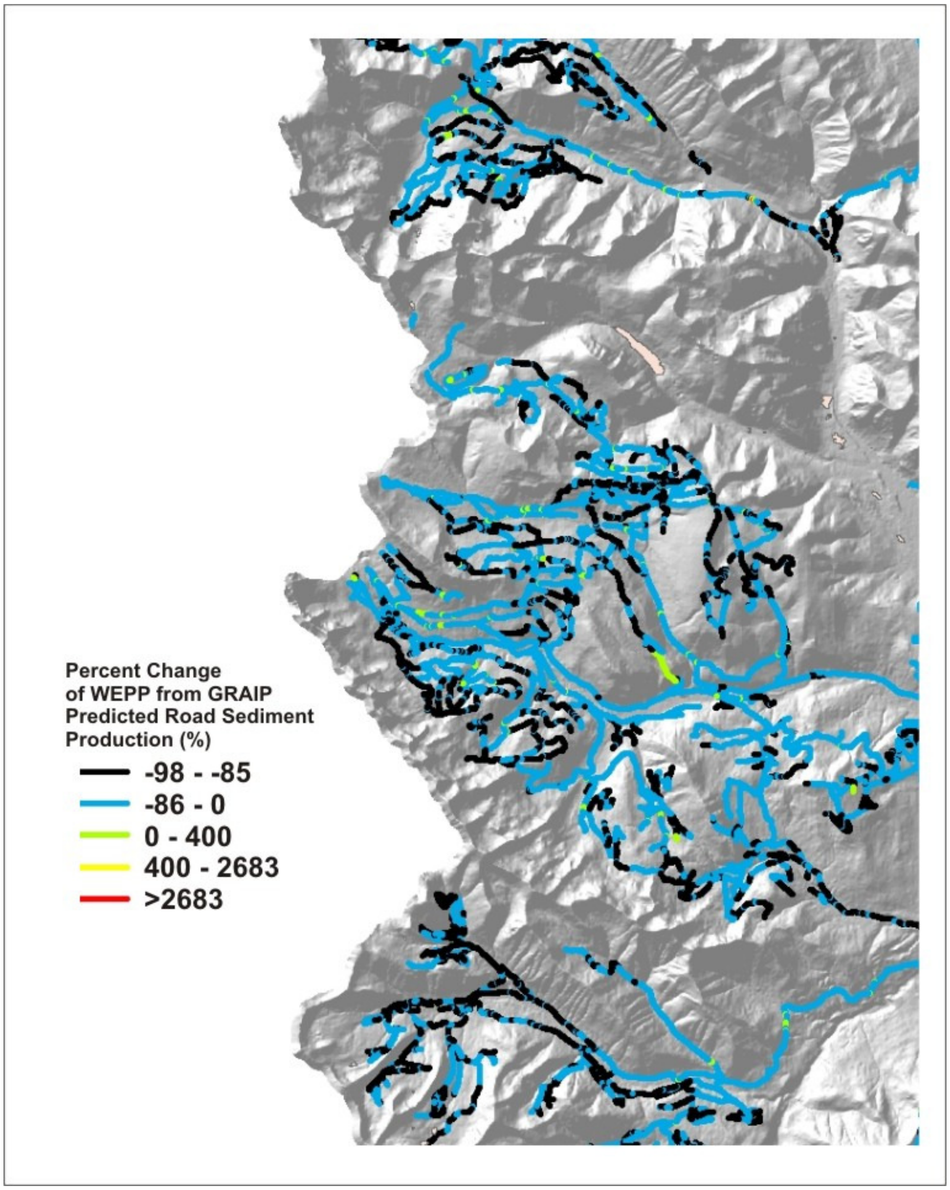

Figure 1-2. A comparison between WEPP and GRAIP-Lite road erosion predictions ([[Wepp – GRAIP]/GRAIP] X 100 = change in %) reveals that, in general, WEPP sediment production is less than GRAIP-Lite sediment production (does not include sediment delivery to stream channels).

A comparison between WEPP and GRAIP-Lite road surface erosion - delivery to streams shows the same discrepancy, although even larger (**Figure 1-3**).

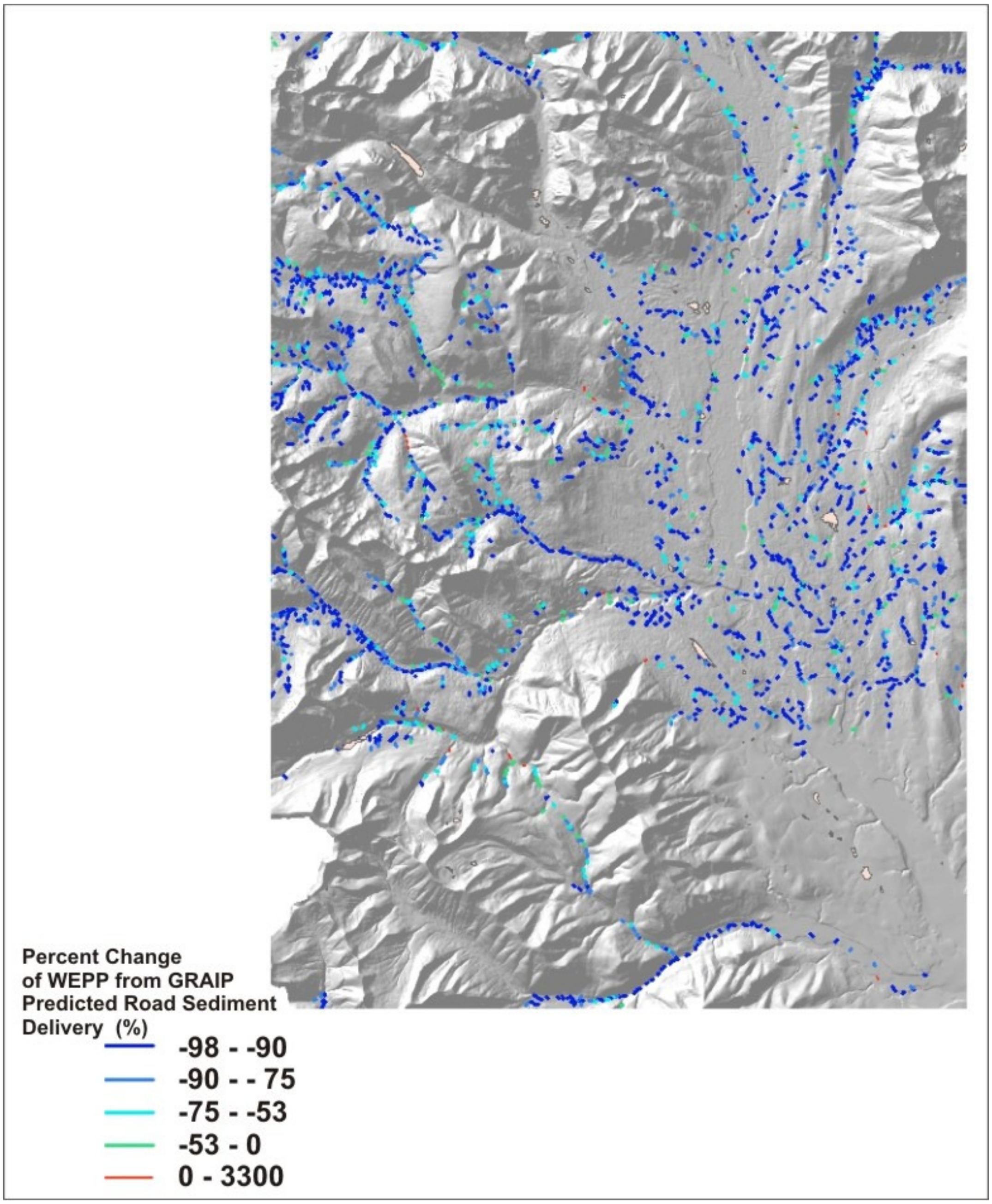

Figure 1-3. A comparison between WEPP and GRAIP-Lite road erosion – sediment delivery to streams ([[Wepp – GRAIP]/GRAIP] X 100 = change in %) reveals that, in general, WEPP sediment delivery is less compared to GRAIP-Lite sediment delivery.

There are differences in the WEPP and GRAIP-Lite models that could lead to the differences in predicted erosion and sediment delivery to streams. First, their modeling structures are different; see NetMap-GRAIP Lite model and documentation for the WEPP road surface erosion model for more details. GRAIP-Lite is an empirical model. WEPP is more theoretical and it contains parameters for road width, soils, traffic levels and site specific climate. GRAIP-Lite does not contain these variables but it does rely on field measured road surface erosion (referred to as the base road surface erosion rate, see Eq. 1). WEPP was run using a "low" traffic level (no data on traffic level were available); running WEPP with "high" traffic can increase predicted road surface erosion on steeper roads by a factor of 3 to 5. In addition, there are numerous road segments in the Flathead where GRAIP sediment delivery predictions are greater than zero compared to WEPP predictions that equal zero, including even when roads are located hundreds of meters away from streams (the erosion decay curve used in GRAIP-Lite allows small proportions of sediment [<5%] to be delivered over distances of up to a few thousand meters).

Refer to Table 1 and the accompanying discussion about comparison of GRAIP-Lite and WEPP results to field measured road erosion production in western Montana. Also note that despite the differences in absolute values of predicted surface erosion and sediment delivery, the