WIN-System: A Decision Tool for Cumulative Watershed Effects Assessment in Alberta

Forest Program Management Section/Forest Management Branch of Alberta Government

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WIN-System: A Decision Tool for Cumulative Watershed Effects Assessment in Alberta

Executive Summary:

A decision support tool for cumulative watershed effects assessment (CWE) in Alberta was developed for the Forest Program Management Section/Forest Management Branch of Alberta Government. The CWE assessment combined two advanced technologies, the Wet Areas Mapping (WAM) stream line delineation and NetMap's Virtual Watershed with tools; the WAM integrated NetMap system is referred to as the '*WIN-System'*. The purpose of this work is not to duplicate previous efforts that developed watershed assessment protocols and manuals created prior to advanced numerical watershed modeling capabilities and the advent of high resolution digital data. Rather, the Win-System represents an evolution in CWE assessment because it incorporates new GIS-based modeling advances in watershed processes and it utilizes the highest resolution digital elevation data, including LiDAR. Alberta's *WIN-System* is designed to be multi-functional and cost effective in its support of numerous resource management activities involving forestry, beetle-kill salvage logging and remediation, oil and gas development, fisheries management, post-wildfire salvage logging and restoration, pre-wildfire fuels reduction, restoration of existing impacted areas and applied research. It can be applied across diverse landscapes by government and corporate stakeholders.

As a demonstration, the *WIN-System* was applied to the 1270 km^2 Whitemud River watershed located in northwestern Alberta. Three general types of CWEs can be addressed by the *WIN-System* including: i) one or more land use stressors occurring at multiple locations in a watershed overlapping sensitive or high quality aquatic or terrestrial habitats, ii) one or more land use stressors occurring at multiple locations and that accumulate downstream and iii) shifting distributions of watershed conditions over time, such as temporal changes in forest ages, road densities and other watershed attributes. Six functional elements of the *WIN-System* include: 1) LiDAR DEMs and a derived synthetic river network, ii) multiple types of terrestrial – river connections, iii) downstream and upstream routing or transfer of information, iv) terrestrial and river network discretization, v) landform delineation (rivers, floodplains, riparian areas, erosion source areas etc.) and vi) attribution of key watershed characteristics. Multiple scales of analysis are supported, including: i) hillside pixel scale (1 – 2 m), ii) stream segment (~100 m), iii) stream buffers (multi-pixel), iv) stream segment - local hillside contributing areas (~0.1 km^2), v) multi-scale basin areas as defined by the channel network, ranging from the top of a first-order stream to the bottom of a 7th-order river, vi) roads/pipelines from pixel scale to any length scale and vii) various sub basin scales. In the Whitemud River watershed, twelve WIN-System datasets were created. To

demonstrate the *WIN-System*, four types of cumulative effects were analyzed that were pertinent to the Whitemud River watershed, including: i) forest/energy road surface erosion and sediment delivery to streams, ii) erosion from harvest cut blocks, iii) beetle kill forests and impacts on shade – thermal energy to streams and iv) post fire impacts on erosion potential (surface erosion, gullying, landsliding).

1.0 Conceptual Framework

Cumulative watershed effects involve interactions between natural processes, including disturbances (e.g., landslides, floods, fires, beetle outbreaks), and land uses (e.g., transportation systems, timber harvest, energy development) that can negatively affect ecosystem processes both in space and time (Reid 1998, MacDonald 2000, Noble 2011). Environmental impacts can arise due to spatial overlaps of land use stressors with sensitive habitats in a watershed, such as increased thermal loading in streams due to loss of riparian forests across many locations. Another form of cumulative effects is the accumulation of impacts downstream from many point sources, such as the accumulation of sediment pollution from a network of forest roads (Gucinski et al. 2001) (Figure 1). Cumulative effects can also be represented as shifts in frequency distributions of certain watershed attributes over time, such as the conversion of forests to farms or loss of floodplains (**Figure 1**) (Benda et al. 1998).

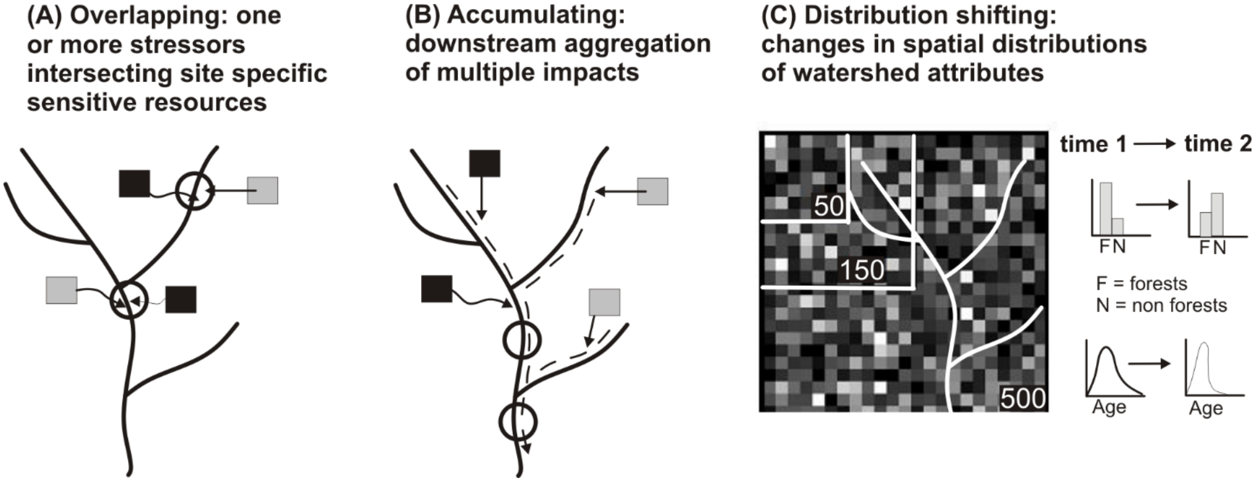
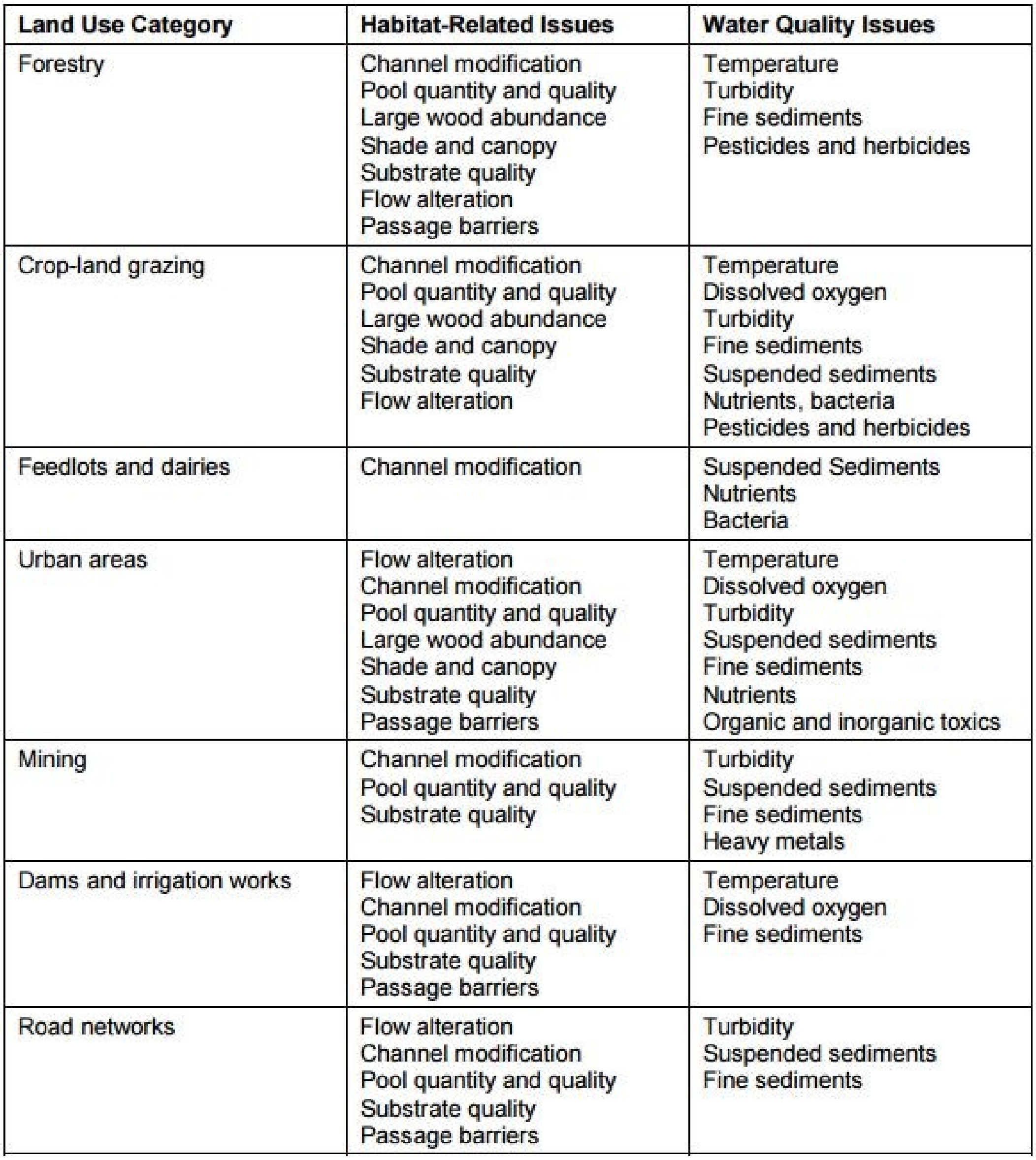


Figure 1. Three different types of cumulative watershed effects analysis.

The study of cumulative watershed effects often incorporates a historical perspective, one that focuses on the time series of past events and impacts using a combination of historical data, such as inventories of erosion including landslides, reconstruction of wildfires, land clearing by land uses, and water and sediment gage data (Reid 1998 and OWEB 1999). A historical perspective provides information about how the past is the key to the present. For example, historical aerial photographs are often used to document how land uses are linked to erosion such as landslides and debris flows (Sidle et al. 1985). Historical maps and records, in combination with older photography, can be used to document how riparian areas and even floodplains have been diminished over time (Collins et al. 2002). However, it is often a challenge to de-convolve the myriad of processes and land uses, and their complex interactions and accumulations, over decadal time frames and over thousands of hectares; the complexity of the scientific study of cumulative watershed effects has been referred to as the "UFO's of Hydrology" (Swanson 1986) and has led to calls for simplification in analysis (MacDonald 2000, Benda et al. 2002).

An alternative perspective acknowledges the value of historical reconstructions in watersheds, but focuses on what already is known about the cause and effect of land use impacts, specifically on aquatic and terrestrial systems. The spatially deterministic approach relies on existing knowledge about how land uses can impact various watershed processes including erosion, removal of riparian vegetation, road impacts on aquatic systems, invasive species, nutrient loading to rivers and lakes etc. Hence, many well-documented environmental impact causes and effects can be considered first-order principles that can underpin analysis of cumulative effects in a watershed (**Table 1**). Such first-order principles can be used to craft resource management prescriptions designed to lessen impacts from land uses and to improve water quality and terrestrial and aquatic habitat conditions in the future. This spatially deterministic perspective in the study of cumulative effects aims to identify, site specifically, where potential land use impacts overlap sensitive terrestrial and aquatic resources. For example, where does the highest road surface erosion and sediment delivery potential overlap channels that have the highest value aquatic habitats or have domestic water supply intakes? Where does the highest landslide potential overlap with areas undergoing intensive timber harvest? With this geospatial information in hand, resource managers and planners can devise land use guidelines and site-specific prescriptions for limiting future environmental impacts and also plan restoration and conservation strategies.

Table 1. An example of well-studied and well-recognized cumulative watershed effects involving various land uses (from Oregon Watershed Assessment Manual 1999).



Land Use Category	Habitat-Related Issues	Water Quality Issues
Forestry	Channel modification Pool quantity and quality Large wood abundance Shade and canopy Substrate quality Flow alteration Passage barriers	Temperature Turbidity Fine sediments Pesticides and herbicides
Crop-land grazing	Channel modification Pool quantity and quality Large wood abundance Shade and canopy Substrate quality Flow alteration	Temperature Dissolved oxygen Turbidity Fine sediments Suspended sediments Nutrients, bacteria Pesticides and herbicides
Feedlots and dairies	Channel modification	Suspended Sediments Nutrients Bacteria
Urban areas	Flow alteration Channel modification Pool quantity and quality Large wood abundance Shade and canopy Substrate quality Passage barriers	Temperature Dissolved oxygen Turbidity Suspended sediments Fine sediments Nutrients Organic and inorganic toxics
Mining	Channel modification Pool quantity and quality Substrate quality	Turbidity Suspended sediments Fine sediments Heavy metals
Dams and irrigation works	Flow alteration Channel modification Pool quantity and quality Substrate quality Passage barriers	Temperature Dissolved oxygen Fine sediments
Road networks	Flow alteration Channel modification Pool quantity and quality Substrate quality Passage barriers	Turbidity Suspended sediments Fine sediments

The purpose of this work is not to duplicate previous efforts that developed watershed assessment protocols and manuals (e.g., WDNR 1997, OWEB 1999, U.S Forest Service – Reid and McCammon 1993). Most, if not all, watershed procedural manuals that address cumulative watershed effects were developed prior to advances in numerical modeling of watershed processes and the advent of high resolution digital elevation models, including LiDAR (Benda et al. 2009). Thus, our objective is to take advantage of new GIS based analysis technologies, combined with newly available high resolution digital elevation data (LiDAR in Alberta) and create an advanced system that can be applied across very large areas (of Alberta) relatively rapidly by provincial and other corporate stakeholders.

The Decision Tool for cumulative watershed effects assessment in Alberta integrates Alberta's Wet Areas Mapping (WAM) technology (White et al. 2012) with the NetMap system of "virtual watersheds" and tools (Benda et al. 2007). A virtual watershed is a geospatial simulation of riverine landscapes used to enumerate watershed processes and landforms, and human interactions over a range of scales (Barquin et al. 2015, Benda et al. 2015). The "WAM-Integrated-NetMap" analysis system (*WIN-System*) employs a synthetic stream layer mirrored on WAM stream lines and coupled to the Alberta's LiDAR digital elevation model (DEM). A prototype *WIN-System* was built in a portion of the Simonette River basin in conjunction with Alberta Environment and Sustainable Resource Development in 2015.

The *WIN-System* decision support tool addresses multiple land uses, landforms, and physical and biological process acting over multiple scales, with diverse connections and overlapping interactions (**Figure 2**). It serves as the numerical foundation to consider cumulative effects, to design remediation, and to provide day-to-day decision support for resource management. In the context of the *WIN-System*, one strategy would be to avoid cumulative effects (Figure 1) by mapping sensitive and valuable parts of the landscape (such as high quality fish habitats, riparian zones etc.) and identifying the anthropogenic stressors that overlap them, including roads (sediment delivery, landslide risk) and erosion potential etc.

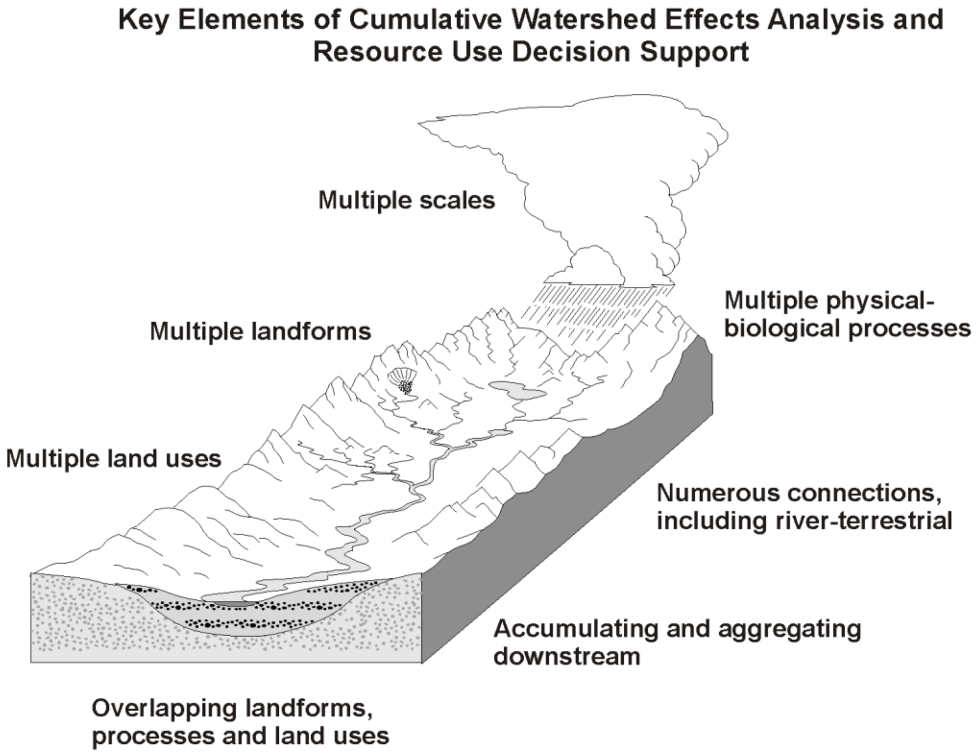


Figure 2.Key elements of the *WIN-System* Cumulative Watershed Effects Analysis Framework.

Key elements include: i) multiple scale analysis (pixel to sub-watershed to full watershed, including local channel drainage areas, linear features [roads and pipelines] at any length scale [pixel to larger], terrestrial-channel network attributes – at any scale defined by the channel network); ii) multiple landforms (erosion source areas, valleys, floodplains), iii) multiple land uses (cut blocks, roads, pipelines); iv) multiple physical and biological processes (shade-thermal energy, wood recruitment, erosion), v) multiple connections between land use and watershed processes; vi) river network downstream aggregation of patterns and processes and vii) overlaps among landforms, processes and land uses.

In this User's Guide to cumulative watershed effects analysis and decision support (commissioned by Alberta's Forest Program Management Section, Forest Management Branch) we begin with a description of a virtual watershed, its analytical capabilities and the spatial scales involved with assessments. The main types of cumulative effects analysis that can be readily addressed within the

WIN-System are outlined. We then describe a range of disciplinary components covered by embedded tools including aquatic habitats, riparian processes and zonation, road (and pipelines) analysis, erosion processes, wildfire and climate change. Others could be added. Several components of the *WIN-System* are applied in one sub-basin of the Whitemud River watershed located in northwestern Alberta as a demonstration.

2.0 Virtual Watershed Spatial Framework

2.1 Building the Seamless Synthetic Stream Network

Two advanced watershed analysis technologies, Alberta's Wet Areas Mapping (WAM, White et al. 2012) and NetMap's virtual watershed coupled to tools (Benda et al. 2015, Barquin et al. 2015), are combined to create a state of the art platform for cumulative watershed effects analysis in Alberta. To accomplish the integration, the WAM D8-flow direction and flow accumulation grids, and its synthetic stream layer, are integrated with NetMap's node-based stream delineation technology to create a river network wide, seamless, attributed and routed synthetic stream layer in conjunction with Alberta's one meter LiDAR DEM. This required matching WAM flow direction and accumulation grids across multiple, rectangular 14 km by 16 km WAM LiDAR-based tiles (e.g., from tile to tile). The result is a seamless grid of flow direction and accumulation (and synthetic stream lines) across all DEM tiles, with WAM flow-lines and NetMap's channel nodes matching exactly (**Figure 3**).

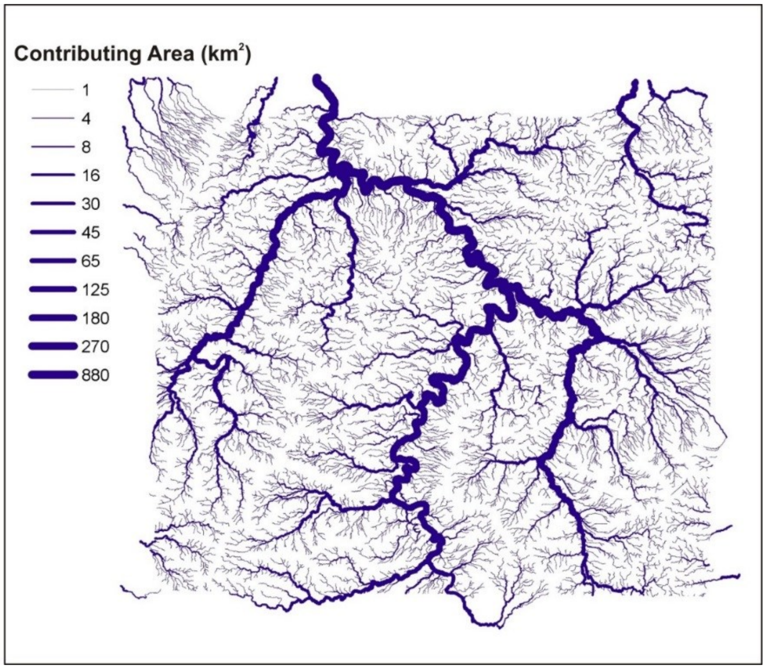


Figure 3.A completed and routed river shape file is constructed from WAM-LiDAR tiles.

The composite *WIN-System* synthetic river network is comprised of a node based data structure, delineated at the scale of the 1 m LiDAR (**Figure 4**). From the nodes, individual channel reaches are created at a length scale that ranges between about 100 to 150 m (adjustable to any length scale during creation of the synthetic stream layer). Each stream reach delineates its local contributing watershed area draining to both sides of the channel, an attribute called 'drainage wings'. Drainage wings allow information within the wing (forest type and age, erosion potential, roads, wildfire risk etc.) to be summarized and reported to each reach, allowing linkages among terrestrial, riparian and riverine systems to be identified in the context of CWEs and associated resource management activities.

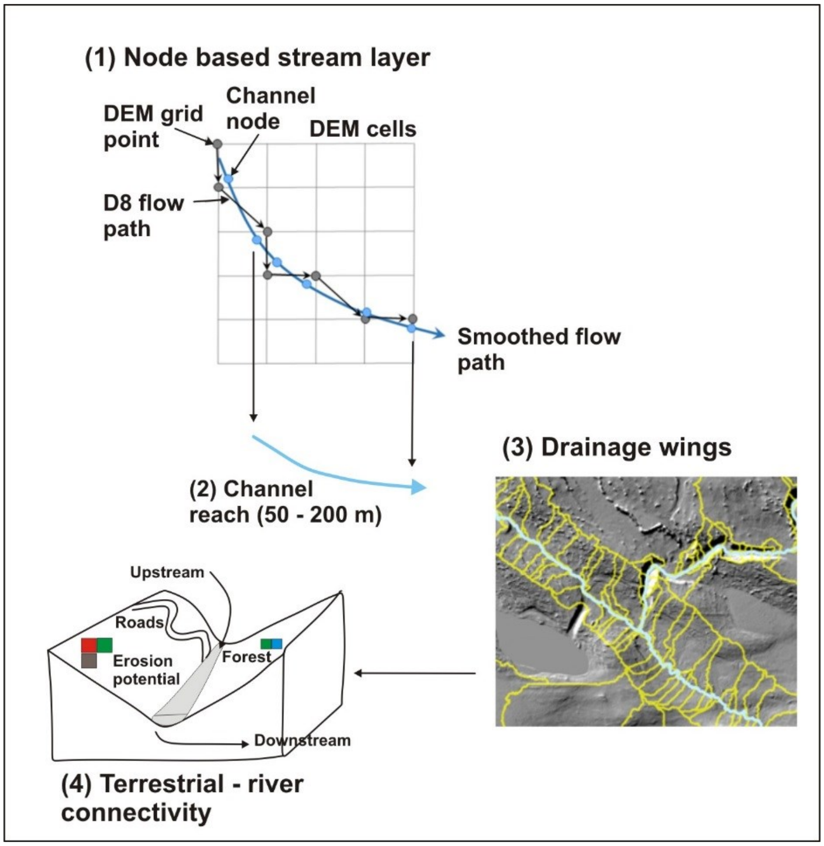


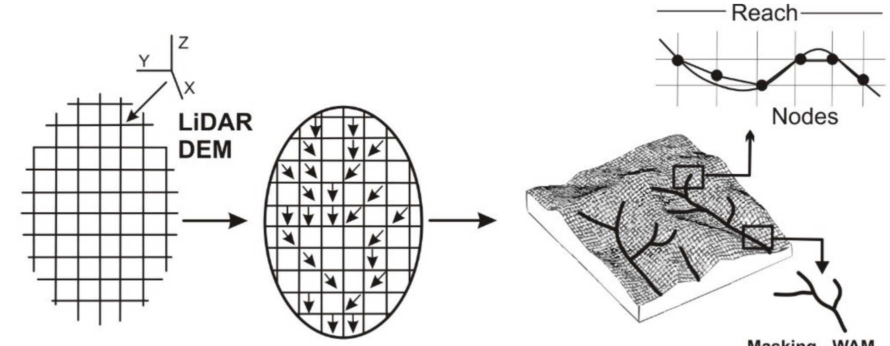
Figure 4.The *WIN-System* node based synthetic stream layer with drainage wings.

2.2 Analytical Capabilities of the *WIN-System*

The *WIN-System* contains six analytical capabilities that are required for CWE analysis and resource management decision support in Alberta: 1) <u>delineating</u> watershed scale synthetic river networks using 1-m LiDAR DEMs (Figure 4), 2) <u>connecting</u> between river networks and terrestrial environments, and with other parts of the landscape, 3) routing of watershed information downstream (such as sediment) and upstream (such as fish), 4) discretizing landscapes and land uses into facets of appropriate scales to identify interactions and effects, 5) characterizing landforms and 6) attributing river segments with key stream and watershed information (**Figure 5**).

Flow direction and accumulation grids are used to define several different types of connectivity within *WIN-System's* virtual watershed: i) river connected, ii) Euclidean distance, iii) slope distance, iv) gravity driven flow paths and v) modified slope distance (**Figure 5, #2**). A river connected pathway allows upstream and downstream transfer of information, such as sediment moving down rivers or fish moving up them. Euclidean distance is a straight line connecting two points, such as defining the extent or gradient of a groundwater field. Slope distance refers to straight lines that follow hillslope profiles and may be used to consider energy gradients pertinent to mass movements. Gravity flow paths refer to downslope directions taken by sediment and water over undulating topography. Modified slope distance is adjusted by additional factors, such as topographic ruggedness affecting animal movements (Ganskopp et al. 2000). Modeling connectivity enables understanding of how landforms and processes interact with land uses. For example, each river node is linked to specific floodplain areas, thereby linking activities in floodplains to the reaches most affected. Predictions of heighted hillside erosion due to land use can be related directly to the channel reaches that would receive additional sediment.

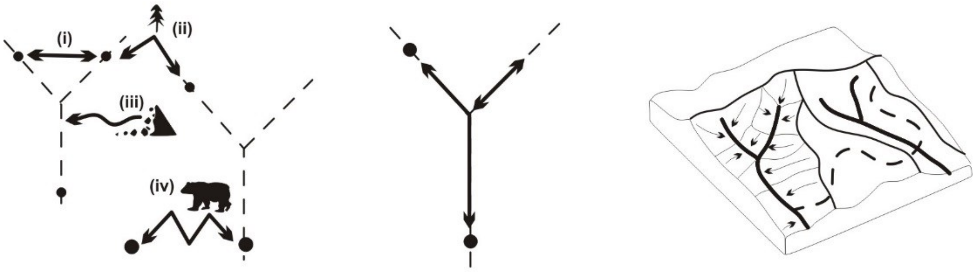
Using the *WIN-System*, spatial patterns of processes and landforms, (e.g., aquatic habitats, slope stability, erosion-sediment supply, shade-thermal energy, floodplain extent etc.) and land uses (e.g., roads, timber harvest, energy developments, wildfires, bark beetle related tree mortality etc.) are aggregated downstream (or upstream) through the synthetic network, revealing cumulative (effects) patterns at any spatial scale defined by river networks (e.g., from the bottom of a first-order channel to the bottom of a seventh-order river).



(1) Building river network

Flow direction/ accumulation

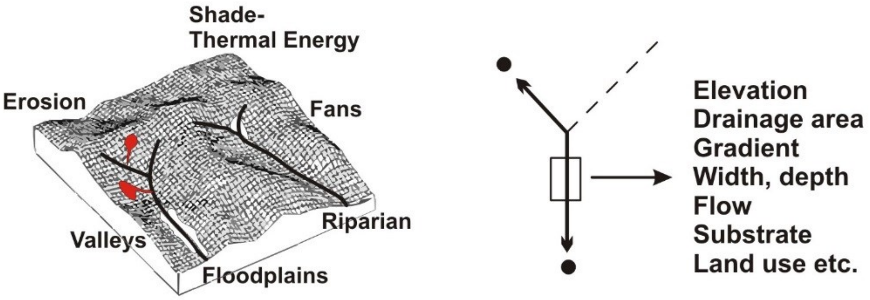
Node-based Network



(2) Connecting

(3) Routing

(4) Discretizing



(5) Landforms

(6) Attributing

Figure 5.The *WIN-System* contains six levels of capabilities required for CWE analysis.

A key element in the *WIN-System* for evaluating interactions among watershed processes, landforms and land uses in the *WIN-System* is “drainage wings”, defined as the local contributing area to each channel segment. Drainage wings are used to transfer terrestrial information, such as upland and riparian vegetation, roads, and erosion potential, to stream reaches (**Figure 6**). Drainage wings are used to identify critical overlaps among reach scale attributes (~100 m length scale, or down to the 1-m resolution of LiDAR DEMs), such as fish-habitat potential, and watershed landforms (e.g., floodplains, erosion source areas), processes (e.g., road sediment delivery, pollutant spills), and land uses (e.g., roads, pipelines, timber harvest blocks, beetle-related tree mortality, engineered structures).

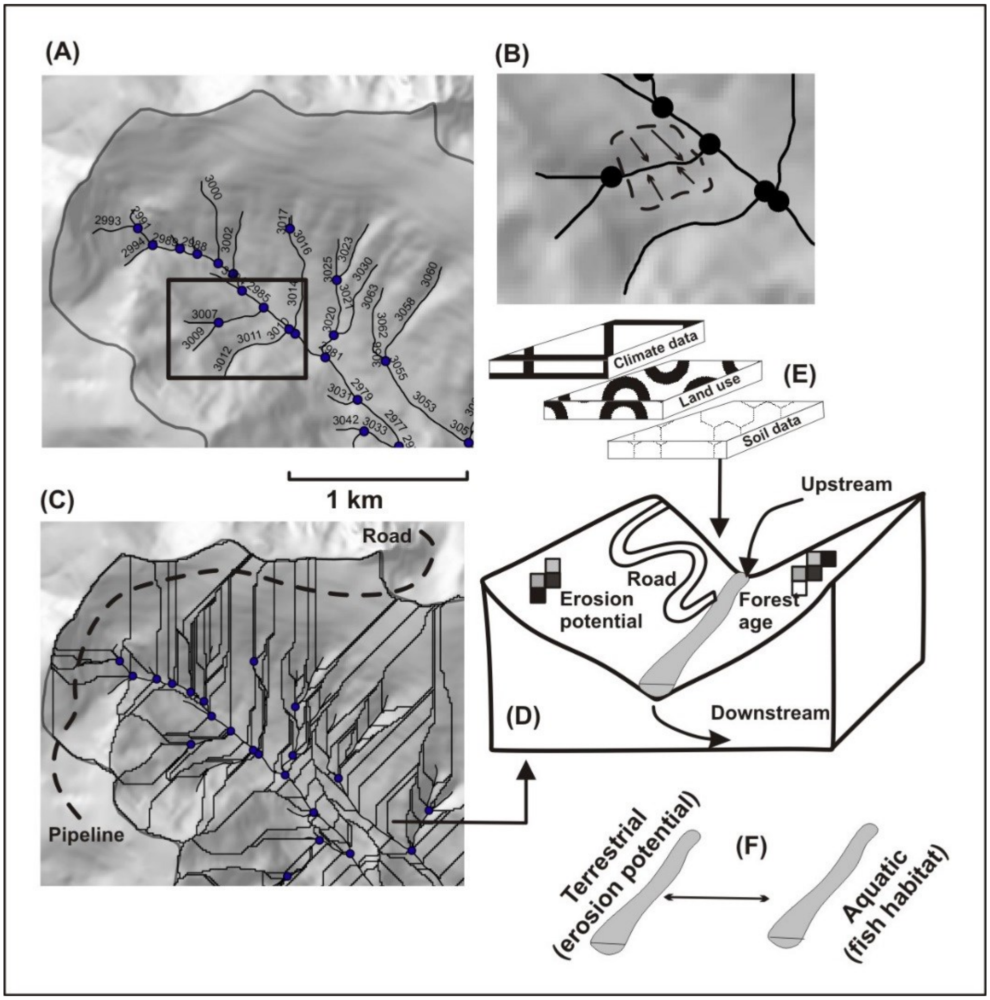


Figure 6.*WIN-System* channel and landscape discretization components.

In **Figure 6**, the *WIN-System* contains: (A) a synthetic, attributed and routed river network with individual river segments delineated (black dots denote tributary confluences). (B) Each river segment delineates a local contributing area, called “drainage wings”, on both sides of the channel. (C) Terrestrial environments are discretized at appropriate scales; river segments of 100 to 200 m create drainage wings of approximately 0.1 km^2. Linear features such as roads and pipelines are discretized at pixel scales and associated with similarly scaled indices of other attributes such as erosion. (D) Drainage wings contain similarly scaled terrestrial information including roads, erosion potential, wildfire risk and climate change attributes etc. depending on the models and tools used. (E) Other data layers can be added such as water bodies, basin boundaries, lithology, soils, vegetation (including beetle-killed trees) and climate and treated as landscape features to be discretized, routed, and analyzed via connectivity pathways. (F) Terrestrial attributes are mapped as channel data and overlaid onto stream attributes such as sensitive habitats. All types of data can be routed downstream (or upstream) revealing patterns at any spatial scale defined by the network.

2.3 Attributes and Landforms in the *WIN-System*

The *WIN-System* can contain more than 100 parameters derived from multiple analysis tools. **Table 2** provides a sample listing of channel attributes and landform and process characterizations. More specifically, **Table 3** summarizes the parameters that can be used to analyze riparian zone processes and to delineate riparian zones. For a full listing and discussion of all tools and parameters within the *WIN-System*, go to the online Technical Help.

Table 2. A partial list of *WIN-System* channel attributes and landform and process characterization.

Channel Attributes	Landform and Process Characterization
Gradient	Floodplains
Elevation	Terraces
Distance to outlet	Alluvial fans
Drainage area	Hillslope-gradient and convergence (mass wasting)
Mean annual flow	Tributary confluences
Stream order	Erosion potential
Channel width and depth	Hillslope–slope profile
Bed substrate	(surface erosion)
Channel sinuosity	Valley width and transitions
Channel classification	Debris flows
Fish habitats	Earthflows
Radiation loading	Floodplains
Mean annual precipitation	Terraces
Gradient	Alluvial fans

Table 3. List of attributes in the *WIN-System* to support spatially explicit riparian zone delineation and environmental settings.

Riparian Process/Delineation Parameters (units)	Environmental Settings Parameters (units)
Synthetic Stream Layer (Integrated WAM-NetMap)	Channel Classification (types)

Depth to Water (WAM, in meters)	Stream order (Strahler 1952)
Drainage area (km^2)	Channel confinement (LL^{-1})
Elevation (m)	Entrenchment ratio (LL^{-1})
Gradient (LL^{-1})	Hillslope erosion potential (GEP)
Azimuth (0 – 360°)	Sinuosity (LL^{-1})
Bankfull width (m)	Tributary confluence effects (P)
Bankfull depth (m)	Thermal refugia (watt-hours/m^2 or indexed by contributing area)
Valley Elevations/Floodplain width (n=5, m)	Channel Migration Zone (m)
Topography (slope, curvature, distance to stream)	Maximum downstream gradient (LL^{-1})
Mean annual flow (m^{3}s^{-1})	Aquatic (Fish) Habitats
Mean annual precipitation (m)	Mean annual flow (m^{3}s^{-1})
Thermal Energy to Channels (Bare Earth, watt-hours /m^2)	Summer habitat volume (m^3)
Current Shade (tree height and basal area)	Wildfire risk
In-stream wood recruitment (tree height, stand density, diameter classes)	Climate change forecasts
Riparian vegetation (basal area, average tree height, average stand density, quadratic mean diameter)	

2.4 Analysis Tools Included in the *WIN-System*

There are approximately 100 analysis tools that can be incorporated and used within the *WIN-System* (**Table 4**). New tools and capabilities can be added by collaborative engagements among the Alberta Provincial Government, Universities and TerrainWorks. There are 800 pages of online technical help that covers all current tools, their functions and example applications (see here).

Table 4. A listing of analysis tools available in the *WIN-System*. New tools can be built and incorporated in the future.

***WIN-System* Analysis Tools**	37) Westslope cutthroat habitat
Module: Analysis Tools	38) Coastal cutthroat habitat
1) Define fish distribution	39) Habitat diversity
2) Calculate channel gradients (multiple length scales)	40) Cumulative habitat length and quality
3) Query watershed databases (n=5)	41) Beaver habitat
4) Profile graphing (longitudinal and x-sectional)	42) Channel disturbance index
5) Attribute aggregation, downstream – upstream, routing of buffer and hillslope attributes	43) Piscidide tool
6) Google Earth zoom and map data transfer	

7) Data management (n = 5)	**Module: Riparian**
8) Risk analysis (n = 2)	44) Delineate variable width riparian zones
9) Sub-basin classification (n=2)	45) In-stream wood recruitment, project scale
10) Watershed delineation	46) In-stream wood recruitment, watershed scale
11) Construct drainage wings	47) Upslope wood recruitment
	48) Thermal energy sensitivity
Module: Fluvial Processes	49) Shade-thermal energy
12) Flow calculation	50) Thermal refugia (4 types)
13) Mean annual flow	
14) Stream power	**Module: Erosion**
15) Bankfull flow	51) Hillslope gradient
16) Channel width	52) Shallow landsliding
17) Channel depth	53) Debris flows
18) Flow velocity	54) Flash floods
19) Bed shear stress/D50	55) Gully erosion
20) Channel sinuosity	56) Earthflow/deep seated
21) Reach gradient adjustment	57) Convert to sediment yields
22) Maximum downstream gradient	58) Sediment delivery adjustment
23) Drainage area	59) Hillslope gradient
24) Stream order	
25) Stream power	**Module: Roads**
26) Tributary confluence effects	60) Import road layer
27) Valley width	61) Road density – basin scale
28) Azimuth	62) Road density – channel segment scale
29) Channel classification (4 types)	63) Road hydrologic connectivity
30) Drainage and tributary junction density	64) Road erosion and sediment delivery (n = 3)
31) Valley floor elevation mapping	65) Optimized drain locations
32) Floodplain mapping	66) Optimized road surface erosion remediation
33) Landslide – channel interactions	67) Road stability
34) In-stream wood accumulation types	68) Roads in floodplains
	69) Habitat upstream of crossings
Module: Aquatic Habitats	
35) Create aquatic habitats (HIP model builder)	**Module: Wildfire/Climate change**
36) Bull Trout habitat	70) Wildfire Cascade
	71) Climate change vulnerability

2.5 Multiple Scales of Analysis

A key element in the *WIN-System* is the ability to examine land-use, landform, and process interactions over multiple spatial scales that include: 1) DEM pixel scale (e.g., such as erosion potential), 2) stream segment scale, nominally 100 m length scale, but can be adjusted ranging from the grain of the LiDAR DEM (1 m) and upwards during creation of the synthetic stream layer, 3) buffer scale, such as vegetation patches and riparian zones, 4) hillside drainage wings (stream reach local contributing area, approximately 0.1 km^2 associated with 100 m stream segments), 5) terrestrial and channel reach information aggregated downstream (or upstream) at any spatial scale defined by the channel network (e.g., bottom of a first-order stream to the bottom of a seventh-order river), 6) linear features, such as road or pipeline networks, broken at pixel-cell boundaries (1 m) and then re-aggregated to any length scale to support various analyses, such as road hydrologic connectivity, road surface erosion, and pipeline infrastructure, and 7) watershed and land use data can be summarized at the scale of sub-watersheds of various scales (Figure 7).

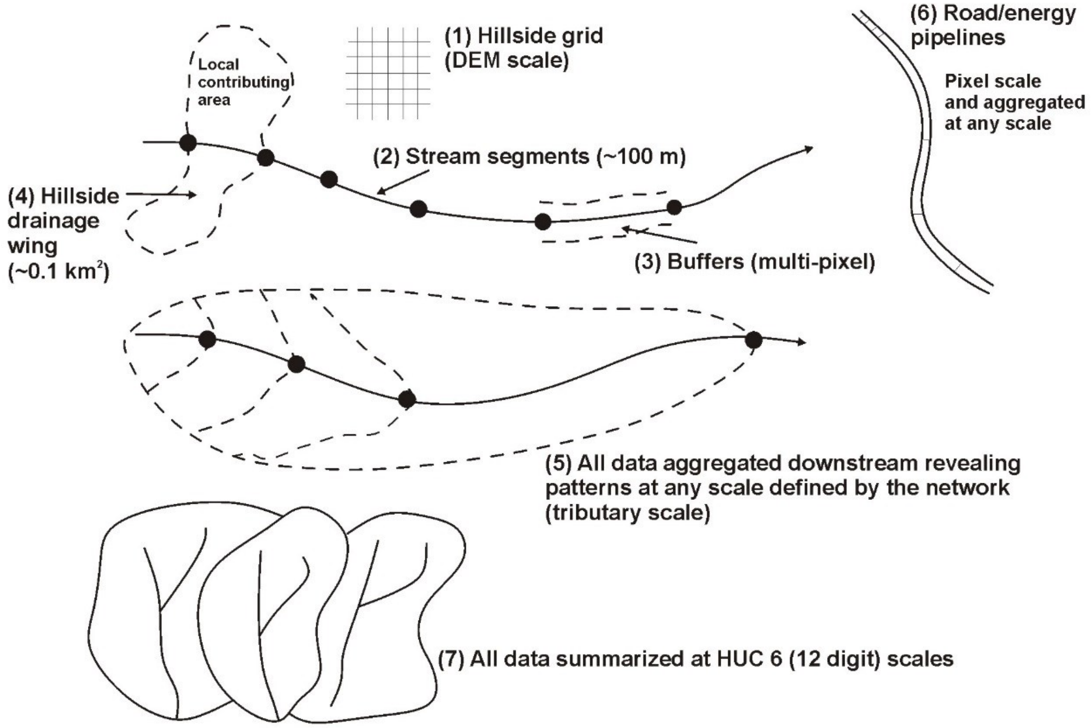


Figure 7.*WIN-System* multiple scales of analysis.

3.0 DEMONSTRATION ANALYSIS

3.1 Location: Whitemud River Watershed, Alberta

The Whitemud River watershed (1230 km^2) located in northwestern Alberta was selected by the Alberta Government to demonstrate application of the *WIN-System* in the analysis of CWEs (**Figure 8**). The Whitemud River watershed was divided into twelve *WIN-System* datasets to ease computations (**Figure 9**). This report demonstrates elements of the CWE analysis using only one of the datasets (WM1).

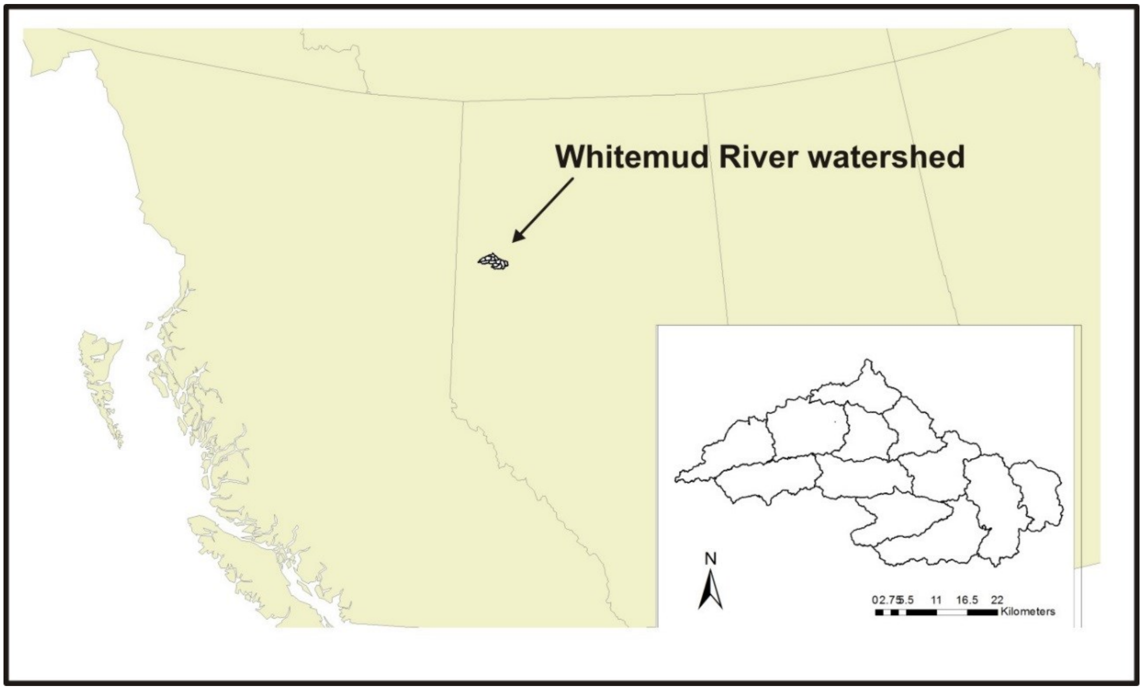


Figure 8. The Whitemud River watershed is located in northwestern Alberta.

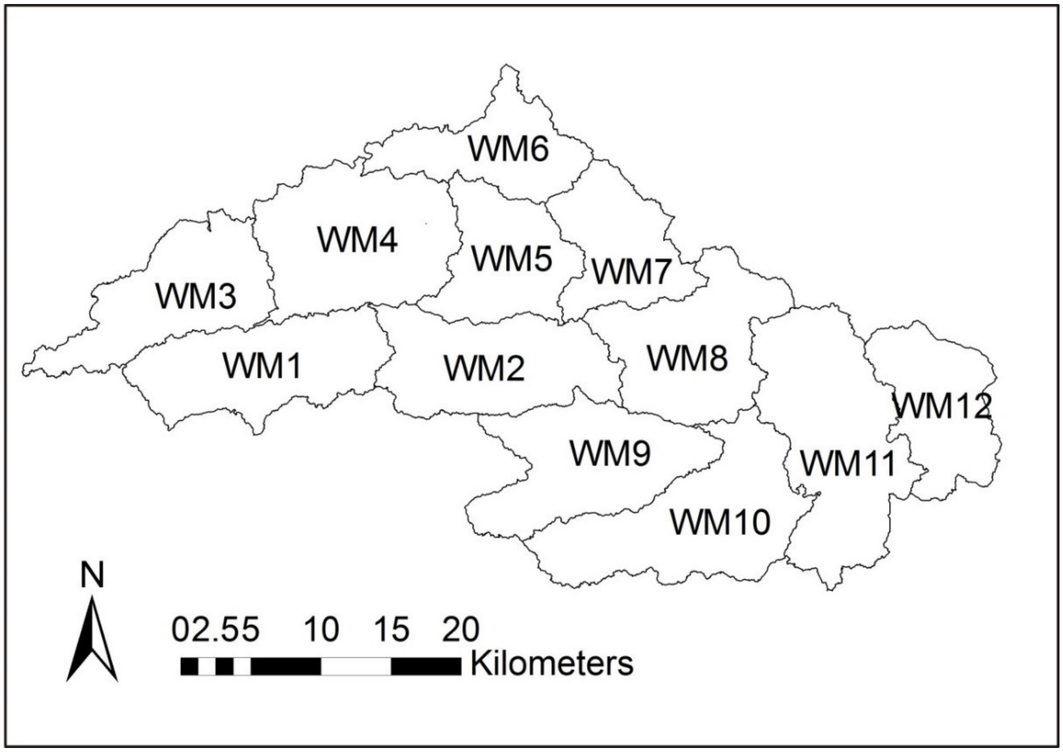


Figure 9.The *WIN-System* Whitemud CWE analysis consists of 12 individual sub-watershed datasets.

The CWE analysis in the WM1 *WIN-System* dataset consists of 16 primary components (**Table 5**). The *WIN-System* demonstration analysis in the Whitemud River watershed can be considered from two management perspectives: (1) remediation/restoration of existing potential impacts and (2) future CWE avoidance.

Table 5. The *WIN-System* CWE analysis that is demonstrated within the Whitemud River watershed addressed land uses associated with: 1) forest/energy sector road construction, use and maintenance, 2) forestry - timber harvest, 3) energy development (road infrastructure), 4) post-fire salvage logging, 5) pre-fire fuels reduction, and 6) beetle kill salvage logging.

Components of Cumulative Watershed Effects Analysis	**Remediation/ Restoration Opportunities**	**Future Avoidance Opportunities**	**Importance in CWE Analysis**
(1) Location (distribution) of fish habitats	Unknown[1]	Yes	Moderate – habitat sensitives unknown
(2) Channel sensitivity to disturbances	Unknown[1]	Yes	Most larger channels are sensitive
(3) Location of floodplains/flood zones	Unknown[1]	Yes	High
(4) Location of wet areas (WAM)	Unknown[1]	Yes	High
(5) Location of variable width, high value riparian zones	Unknown[1]	Yes	High
(6) Unpaved forest road sediment production and delivery to streams	Yes	Yes	High
(7) Forest road drainage optimization	Yes	Yes	High
(8) Forest road surface improvement optimization	Yes	Yes	Moderate
(9) Ground disturbance – surface erosion and sediment delivery potential	Unknown[1]	Yes	High to low, emphasis on steep areas adjacent to streams
(10) Ground disturbance – gully potential	Possible, but very local	Minor	Mostly low, locally moderate
(11) Ground disturbance – shallow landslide potential	Possible, but very local	None to minor	None to low
(12) Timber harvest cut blocks erosion potential	Possible	Yes	High to low, emphasis on steep areas adjacent to streams
(13) Beetle kill trees – shade/thermal energy impacts	Yes	na	Low to moderate
(14) Wildfire – erosion potential impacts	Yes	In a pre-fire context	Low to moderate

[1] Requires site specific field observations/measurements, information not available during this study.

3.2 Stream and Aquatic Habitat Classification

There are no existing published models of channel morphological classification and fish habitats applicable to the Whitemud River watershed. However, there are GIS fish distributions available for 15 species of fish (**Table 6**). Channel classification schemes developed elsewhere, such as in the western U.S. (Montgomery and Buffington 1997, Rosgen 1996), are likely not suitable to the Whitemud River watershed because of its very fine grained soils, lack of significant coarse sediment, Boreal wet soils and generally low relief. Additional field information would be required to develop more site specific channel type classification systems.

Table 6. Species and ArcMap field names of fish in the Whitemud River watershed. These attributes are included within the *WIN-System* Whitemud River datasets.

Species	**ArcMap Field Name**	**Species**	**ArcMap Field Name**
Arctic grayling	ARGR	Lakechub	LKCH
Brook stickleback	BRST	Longnose dace	LNDC
Burbot	BURB	Longnose sucker	LNSC
Emerald shiner	EMSH	Northern pike	NRPK
Flathead chub	FLCH	Redside shiner	RDSH
Finescale dace	FNDC	Trout perch	TRPR
Fathead minnow	FTMN	Walleye	WALL
Lakechub	LKCH	White sucker	WHSC

An important ecological principle underlying stream classification is the hierarchical spatial nature of channel morphology and aquatic habitats. Fluvial environments can be viewed as a nested set of spatial features ranging from the watershed (10^2 – 10^3 km^2), valley segment (10^2-10^3 m), reach (10^1-10^2 m), and micro habitats that include individual pools, riffles, gravel bars and log jams (10^0 – 10^1 m) (**Figure 10**, Frissel et al. 1986). This concept informs how stream classification can be applied using a range of data obtained from remote sensing to field measurements. Classification at the scale of entire watersheds or landscapes (like the Flint Hills ecoregion) that involve thousands to millions of stream reaches (the terms reaches and segments are used interchangeably in this report) require the use of remote sensing data, such as channel gradients derived directly from DEMs using a synthetic river network. However, field data collected at the scale of reaches and micro habitats could also be used to classify individual channel segments, or they can be coupled to remote sensing data for their extrapolation across entire watersheds and landscapes.

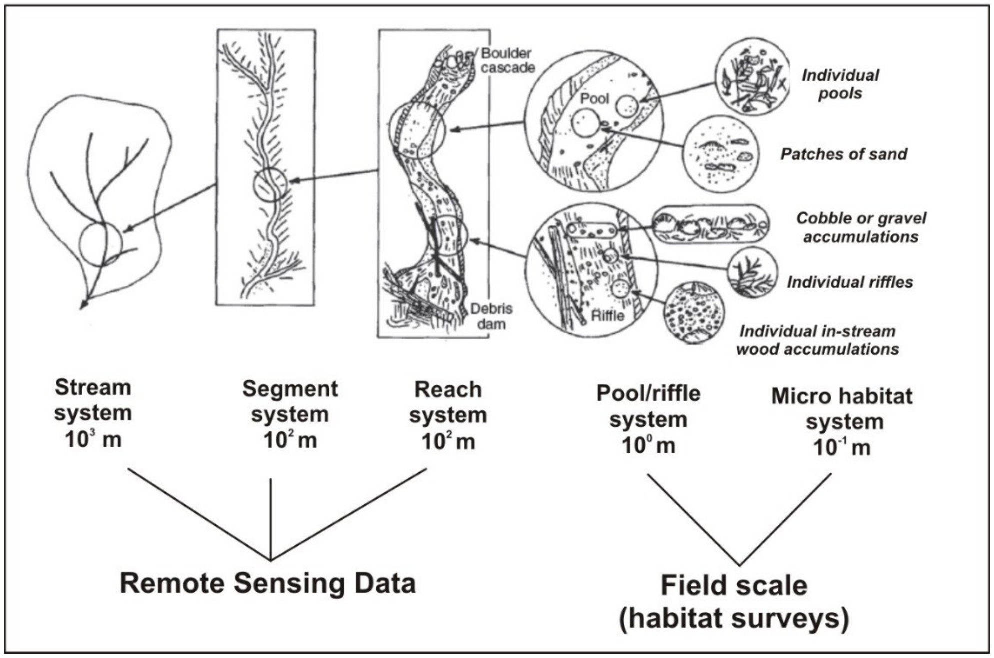


Figure 10. Hierarchical classification of streams (Frissel et al. 1986).

There are different types of channel classification approaches. Strahler (1952) applied a stream ordering approach on channel networks based a numerical measure of channel branching or sequence of tributary intersections. For example, the highest channel segment in a network is considered 'first order'. Where two first order channels intersect, a 'second order' channel is formed. A 'third order' occurs where two second order channels confluence, and so on. Although stream order is a handy way to organize channels by branching patterns, one limitation is that the largest order of any network or watershed is dependent on the location of the initiating stream order, which can vary significantly depending on how channel networks are mapped, either by hand using photos or derived by computers using DEMs. For example, many USGS blue line topographic maps do not include the smallest headwater, first-order channels (Heine et al. 2004). Stream order is one of the remote sensing attributes in the Flint Hills that can be used for classification.

Other stream classification techniques include classifying channel planform patterns (meandering, braided, and straight) based on bankfull discharge and gradient (Leopold and Wolman 1957). This concept was expanded to include width to depth ratios, sediment caliber and bedload to total load ratio by Schumm (1963). Other classification systems focused on the interactions between channels and their floodplains, including their response to disturbances (Church 2006).

Using a large sets of field observations, measurements and general fluvial geomorphic principles in mountain terrains in the western U.S., Montgomery and Buffington (1997) created categories of stream types (alluvial, colluvial, step pool, plane bed, pool riffle and braided) based on width depth ratio, gradient, substrate size, sinuosity, sediment supply and valley morphology. The classification evolved and is currently expressed using two parameters, channel gradient and width to depth ratios (Buffington and Montgomery 2013) (**Figure 11**).

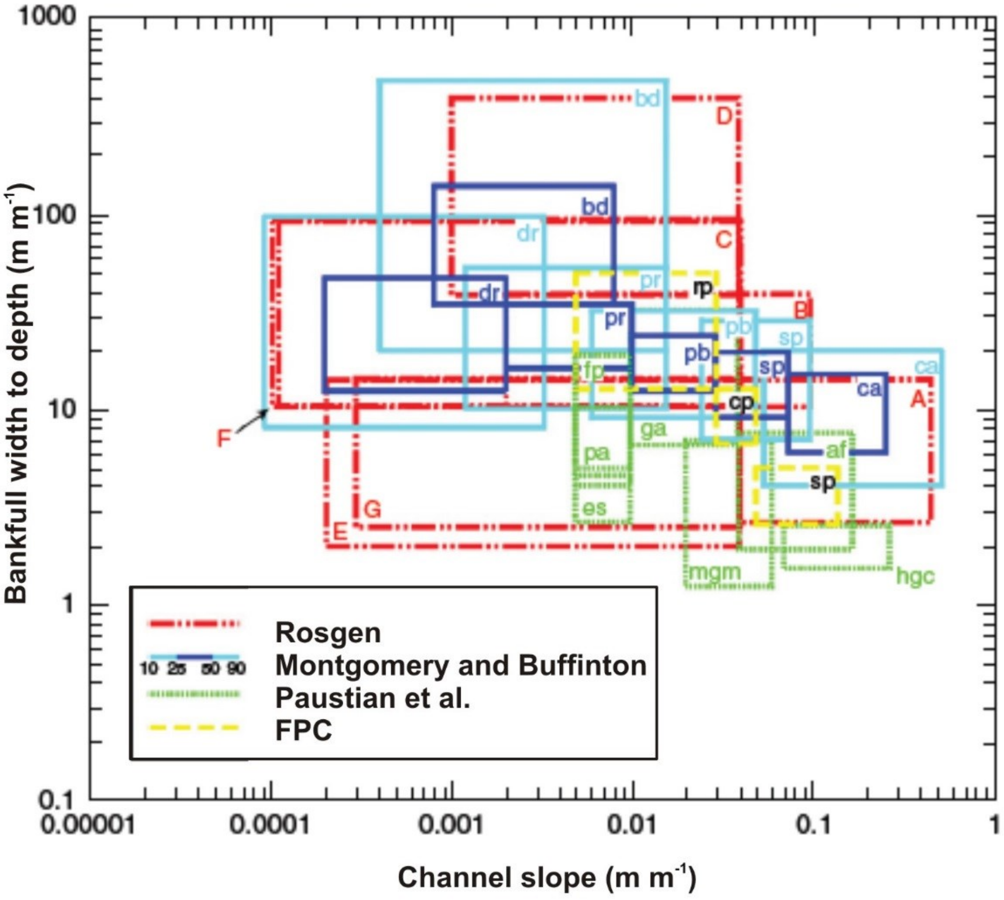


Figure 11. Montgomery and Buffington channel domains.

David Rosgen also assembled a large range of field observations and measurements of channels in the semi-arid western U.S., and combined those with fluvial geomorphic principles (Leopold et al. 1964) to create the Rosgen classification system (Rosgen 1996). The Rosgen stream classification system uses entrenchment ratio (floodplain width divided by channel width), width to depth ratio, sinuosity, channel gradient and substrate size (**Figure 12**). The classification system, that has an alphabetic nomenclature (A, B, C, D etc.), subdivides channel types primarily by slope gradient, sinuosity, single to multi thread and cross sectional geometry. The Rosgen classification system is applied to the Flint Hills ecoregion using the remote sensing data of entrenchment ratio, width to depth ratio, and sinuosity.

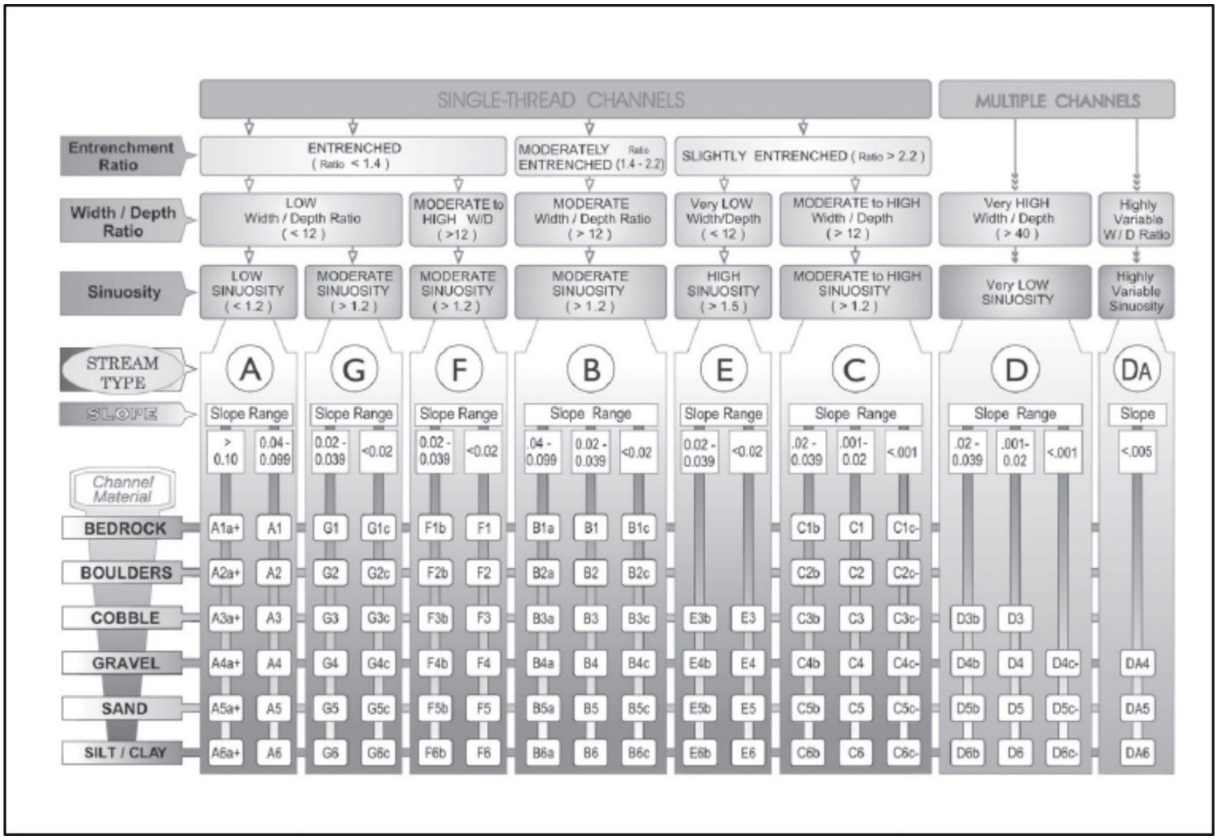


Figure 12. Rosgen (1996) channel classification scheme.

In Alberta, McCleary et al. (2011) develop a classification system for the Foothills Region near Hinton. Attributes in the synthetic river required for channel and habitat classification included drainage area, channel gradient, mean basin slope, and channel longitudinal profiles (McCleary et al. 2011). The regional-scale stream classification included uplands, swales, seepage-fed channels, and fluvial channels and can be used to apply variable width vegetation buffers along water courses to protect water quality and aquatic habitats. The Whitemud River watershed is sufficiently different in lithology and geography that McCleary’s classification system would need to be adjusted. This was not attempted here due to absence of field data on channel morphology, including substrate.

The *WIN-System* has the capability to build unique and site specific classifications in the Whitemud River watershed and elsewhere in Alberta. It contains three types of channel classification tools: 1) “Parameter Nesting” that uses nested sets of parameters to ensure classification to the upstream-downstream limits of river networks and data, 2) “Selection Grouping” that allows for flexible classification using data ranges of attributes, 3) Rosgen classification. For additional information, see here. The *WIN-System* provides core attributes that can be used in channel classification, including channel gradient (**Figure 13;** to learn more about how channel gradients are measured, see here), and floodplain extent (**Figure 14**), among others (see Table 4).

Bankfull Channel Width

Bankfull channel width, depth and mean annual flow are predicted by statistical regression and modeled as a power function of mean annual flow, drainage area and or precipitation (e.g., Leopold and Maddock 1953 and Clarke et al. 2008). Statistical regressions for the Alberta Rocky Mountain Foothills (Hinton area) are used in this analysis but NetMap contains a tool to recalculate bankfull channel width.

Bankfull width (m) = a* (drainage area^b)* (Precip^c) =0.966, b=0.5353, c=0

Bankfull Channel Depth

Bankfull channel depth is predicted by statistical regression and modeled as a power function of mean annual flow, drainage area and or precipitation. Statistical regressions for the Alberta Rocky Mountain Foothills (Hinton area) are used in this analysis but NetMap contains a tool to recalculate bankfull channel depth.

Bankfull depth (m) = a* (drainage area^b)* (Precip^c) a=0.4427, b=0.2866, c=0

Mean Annual Flow

Mean annual flow is predicted based on the flow regression in Table 2. Analysts can use other statistical relationships to inform this parameter in the Integrated WAM-NetMap using this tool.

Mean Annual flow (m^3s-1) = a* (drainage area^b)* (Precip^c) a=0.0216, b=0.933, c=0

Mean Annual Precipitation

Mean annual precipitation (m yr^{-1}) is often used in the statistical regressions for bankfull width, depths and mean annual flow. For the Whitemud River, mean annual precipitation gridded data were obtained from PRISM.

Floodplain Width/Channel Confinement

To characterize valley-floor surfaces in NetMap, DEM cells are classified according to elevation above the channel. 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. To learn more about mapping floodplain width and channel confinement, go here.

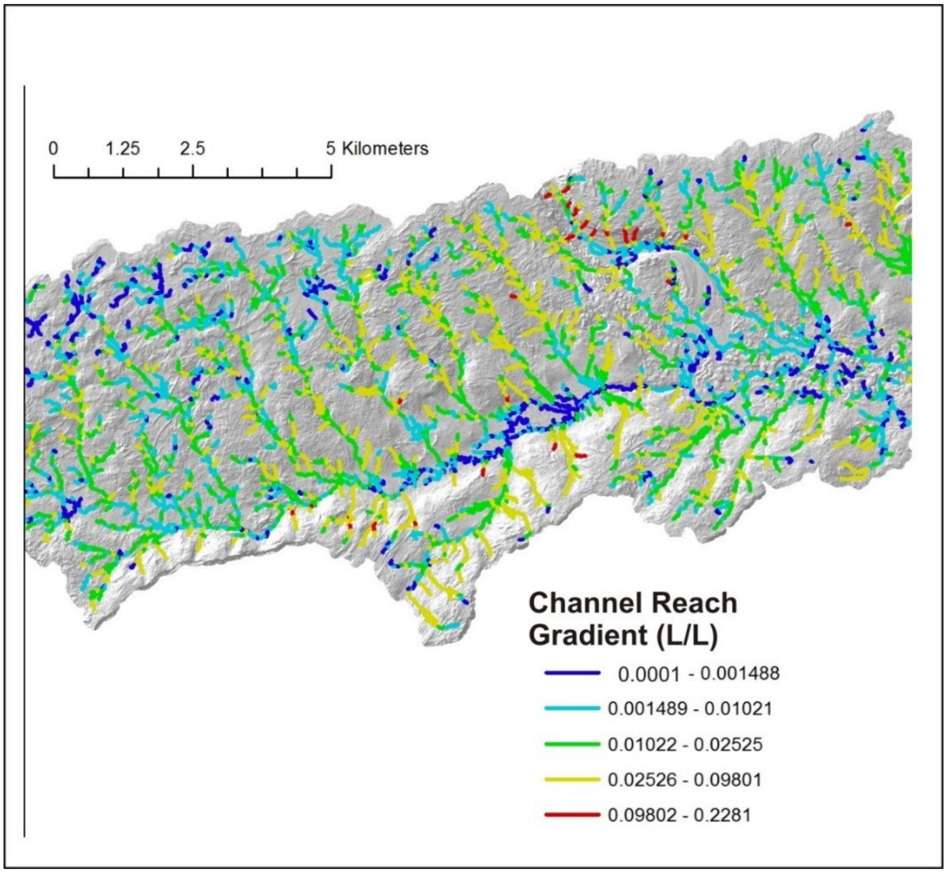


Figure 13. Channel reach gradients in the WM1 *WIN-System* dataset.

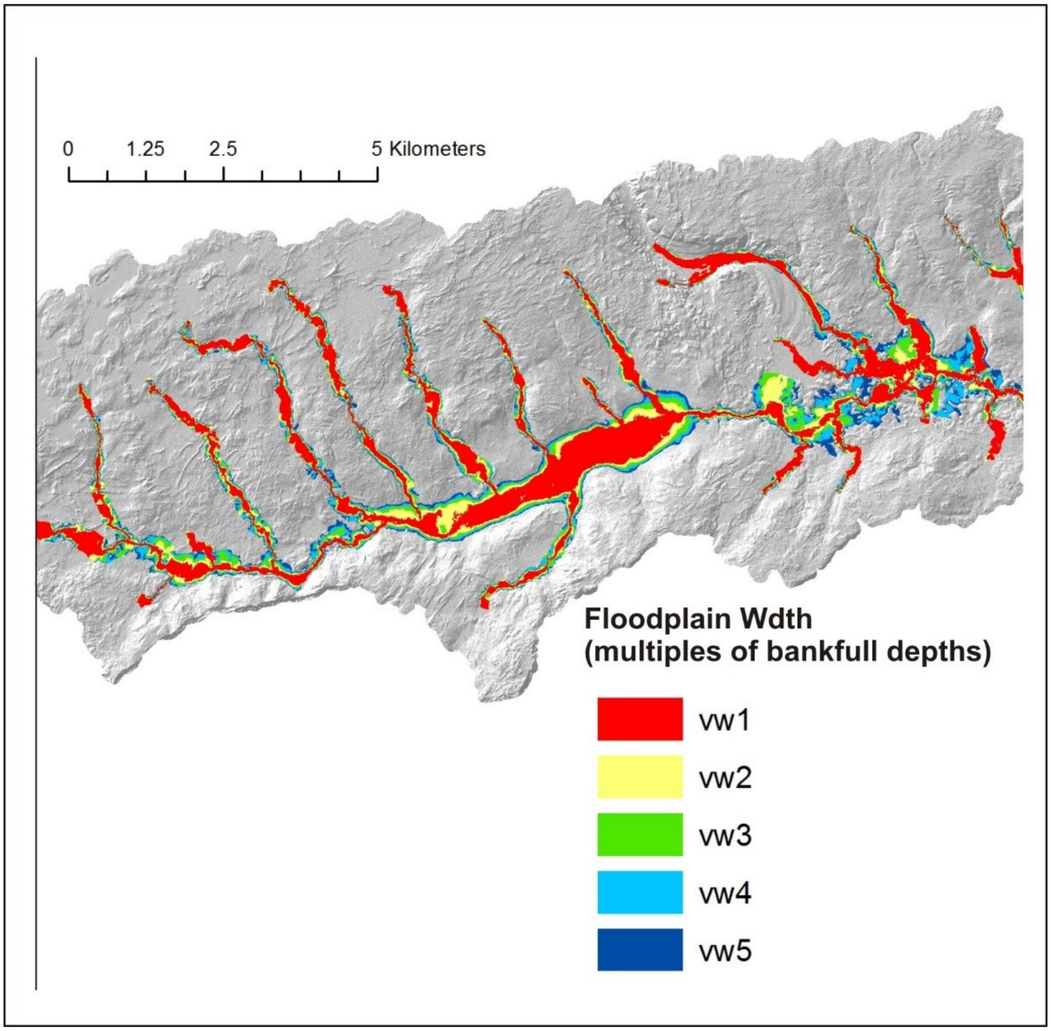


Figure 14. Floodplain widths scaled to bankfull depths in the WM1 dataset.

Channel Sensitivity Index

Based on channel gradient alone, an index of channel sensitivity to increases in sediment (coarse or fine) was developed based on general fluvial geomorphic principles (Montgomery and Buffington 1997); the gradient based channel classification system is shown in **Figure 15**.

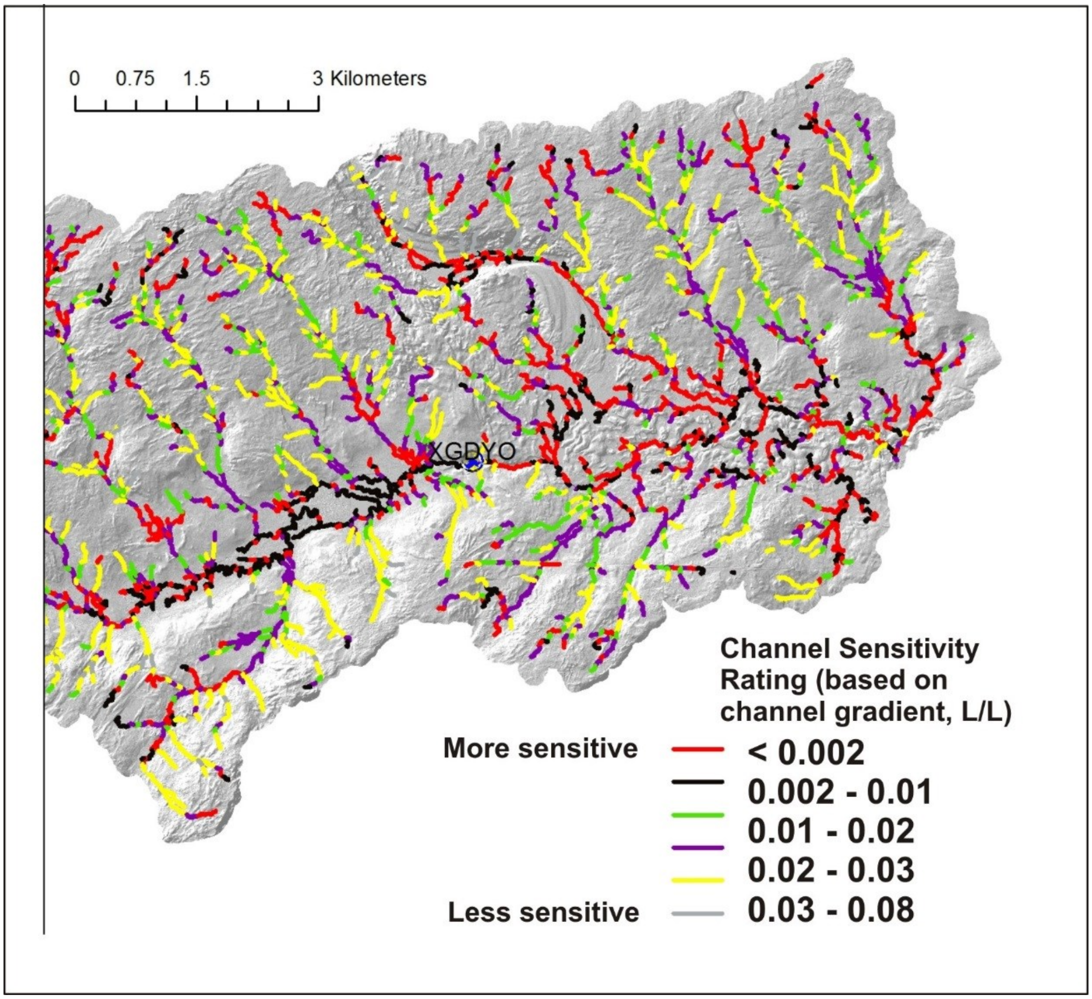


Figure 15. Channel classification based solely on channel gradient.

Based on the simple gradient-based classification system in Figure 15, many of the channels in the WM1 dataset would be considered sensitive to accelerated sediment supply (coarse or fine) and riparian processes (absence or presence) including shade and in-stream wood recruitment.

5.2 Riparian Processes and Zonation

The method used to delineate riparian processes and to delineate variable width riparian zones in Alberta is described in Benda et al. 2015 (. For additional information on riparian delineation, see here. In the Whitemud River watershed, four riparian processes are used to delineate the variable width riparian zone: (1) depth to water (WAM), (2) floodplains, (3) in-stream wood recruitment potential and (4) current shade - thermal energy to streams. The delineation framework is shown in **Figure 16**. In the method any combination of the four riparian processes are integrated within the delineated riparian zone at the watershed scale. Other riparian processes could be included.

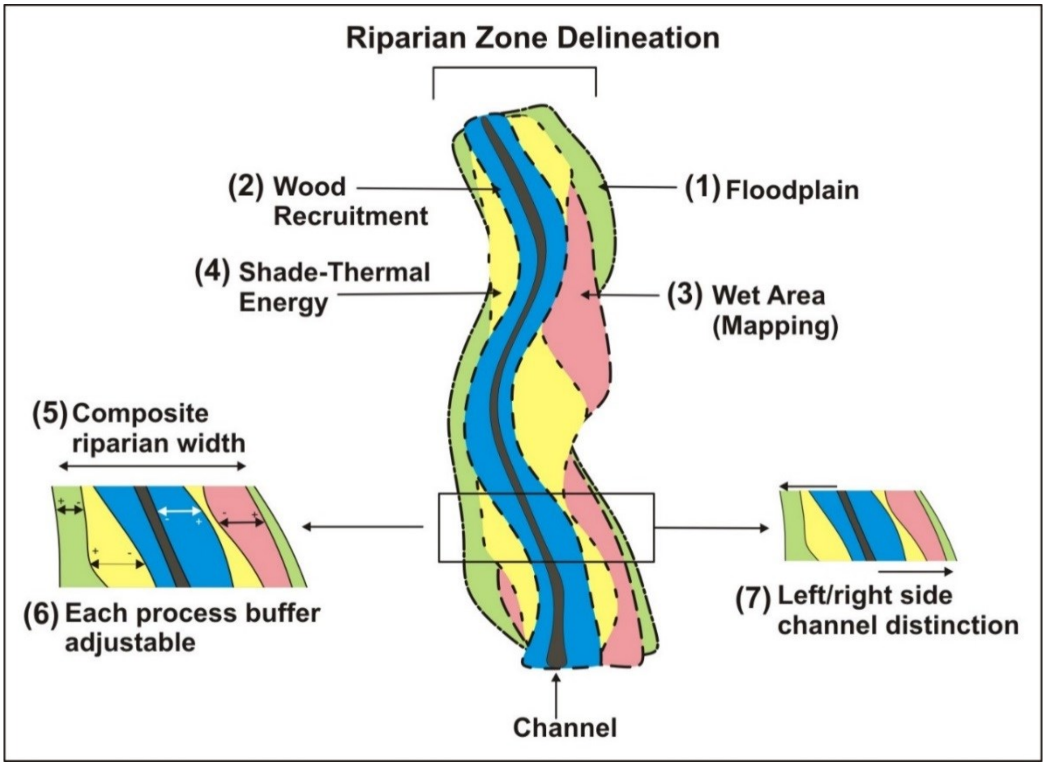


Figure 16. The riparian zone delineation method.

Alberta’s Wet Areas Mapping (WAM) Initiative is designed to facilitate sustainable development in Alberta in the context of existing regulatory programs (including Forest Ground Rules, Upstream Oil and Gas Approvals) as well as supporting other research and management planning (White et al. 2012). WAM, developed by Alberta Provincial Government (White et al. 2012) and University of New Brunswick (Murphy et al. 2009, Ogilvie et a. 2011), utilizes a 1 meter LiDAR digital elevation model (DEM) to develop a cartographic depth to water (DTW) prediction using topographic modeling of soil moisture (Murphy et al. 2009). WAM utilizes a synthetic river network (e.g., derived directly from

DEMs) with channel initiation set by an area threshold (4 ha). Stream and road/pipeline blockages to network delineation are breached to derive the flow accumulation network. The DTW index is created for all LiDAR areas in Alberta.

An analyst selects up to four riparian processes. The protection level (0 – 100%) and the lateral extent can be adjusted for each process individually. For example, thresholds to wet areas (depth to water) can be applied (for example, < 15 cm) and or a maximum lateral extent can be selected (30 m). Next, the floodplain (height above channel) is selected, such as two multiples of bank full width, three multiples etc. (often two multiples of bankfull depth) and a maximum lateral extent can be applied if desired. Next, for in-stream wood recruitment, a user can select what percentage of the instream wood volume to include in the riparian zone (0 to 100%). Finally, an analyst can determine whether the resultant riparian zone (created by the riparian processes selected) will also meet some type of thermal loading threshold (e.g., how much thermal energy is shaded compared to fully vegetated conditions).
The delineated (polygon) zones for the wet areas mapping (WAM), wood recruitment and floodplain are shown in **Figures 17, 18 and 19**. The zones are combined in **Figures 20 and 21**. The addition of zone width for thermal protection is shown in **Figure 22**.

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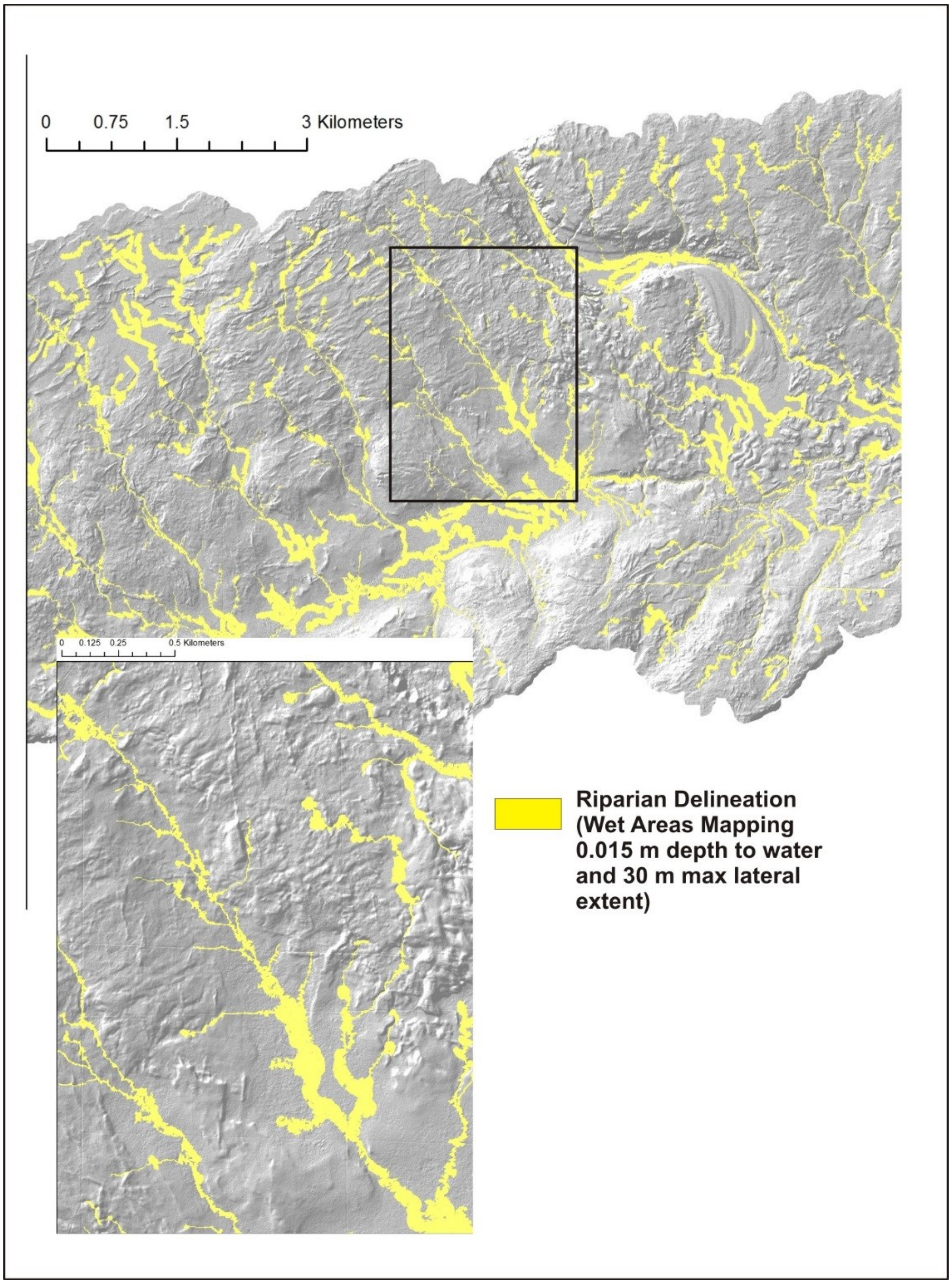


Figure 17. The delineated wet areas (WAM) mapping zone.

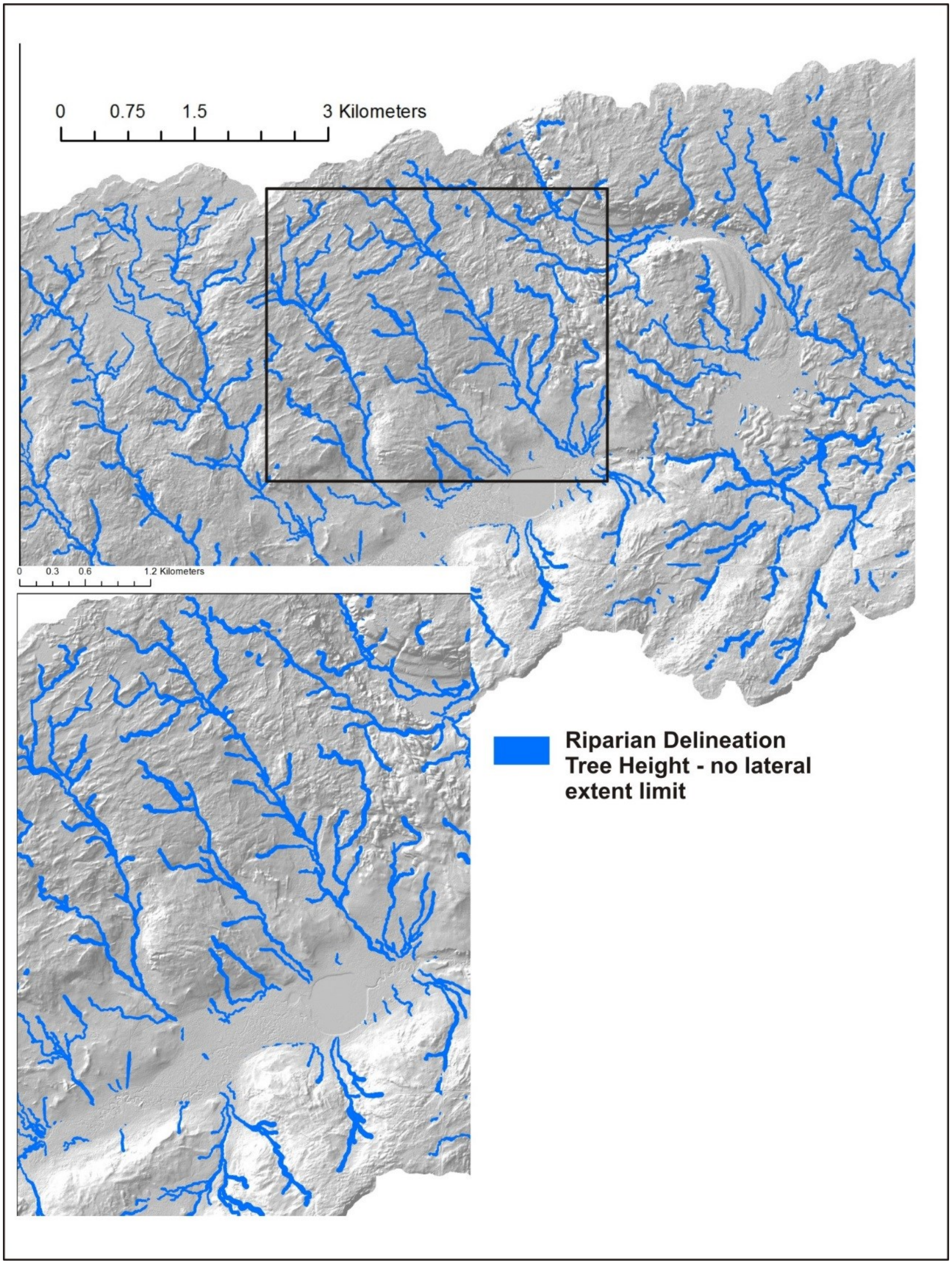


Figure 18. The delineated in-stream wood recruitment zone.

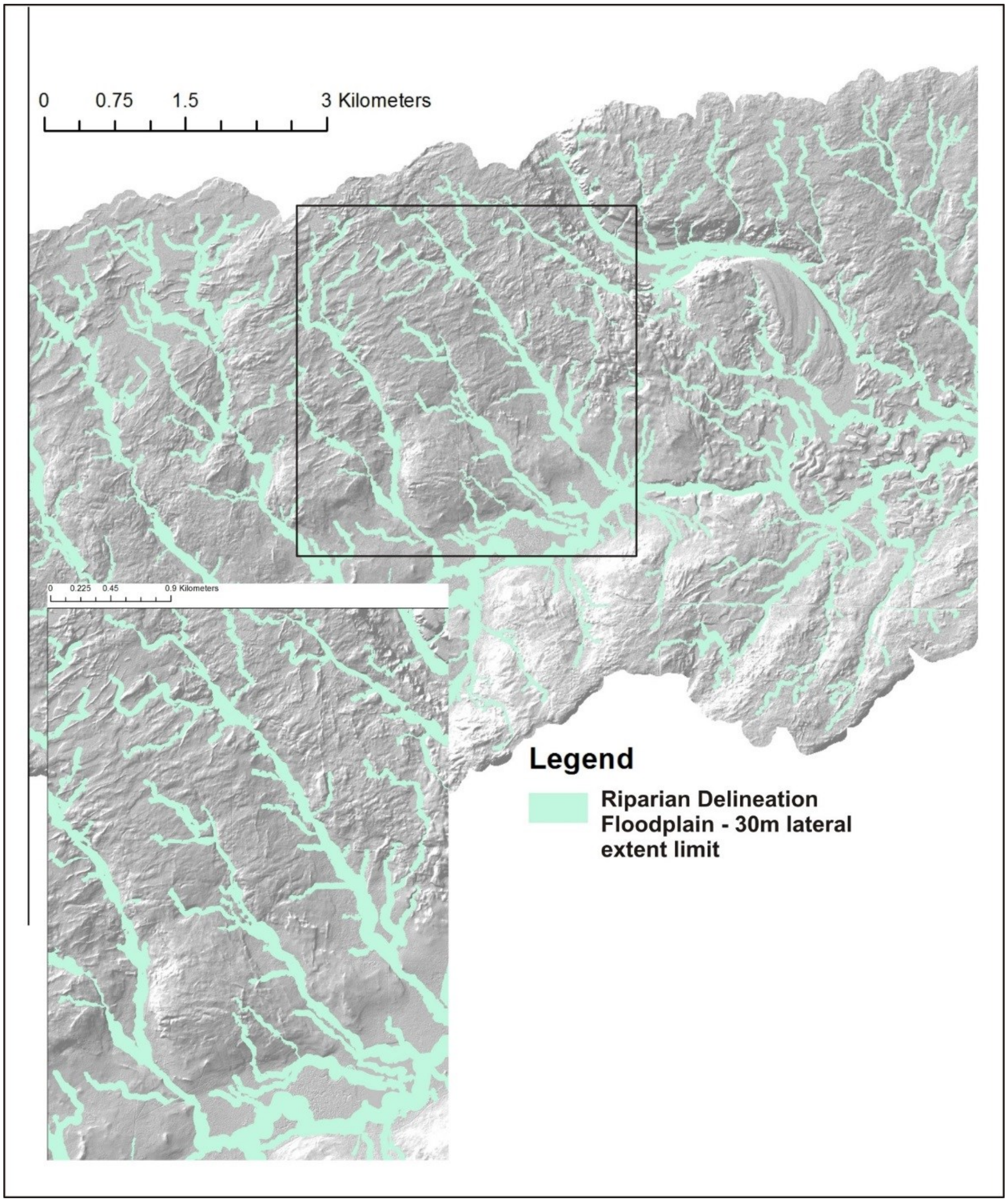


Figure 19. The delineated floodplain zones mapped at 2x bankfull depth.

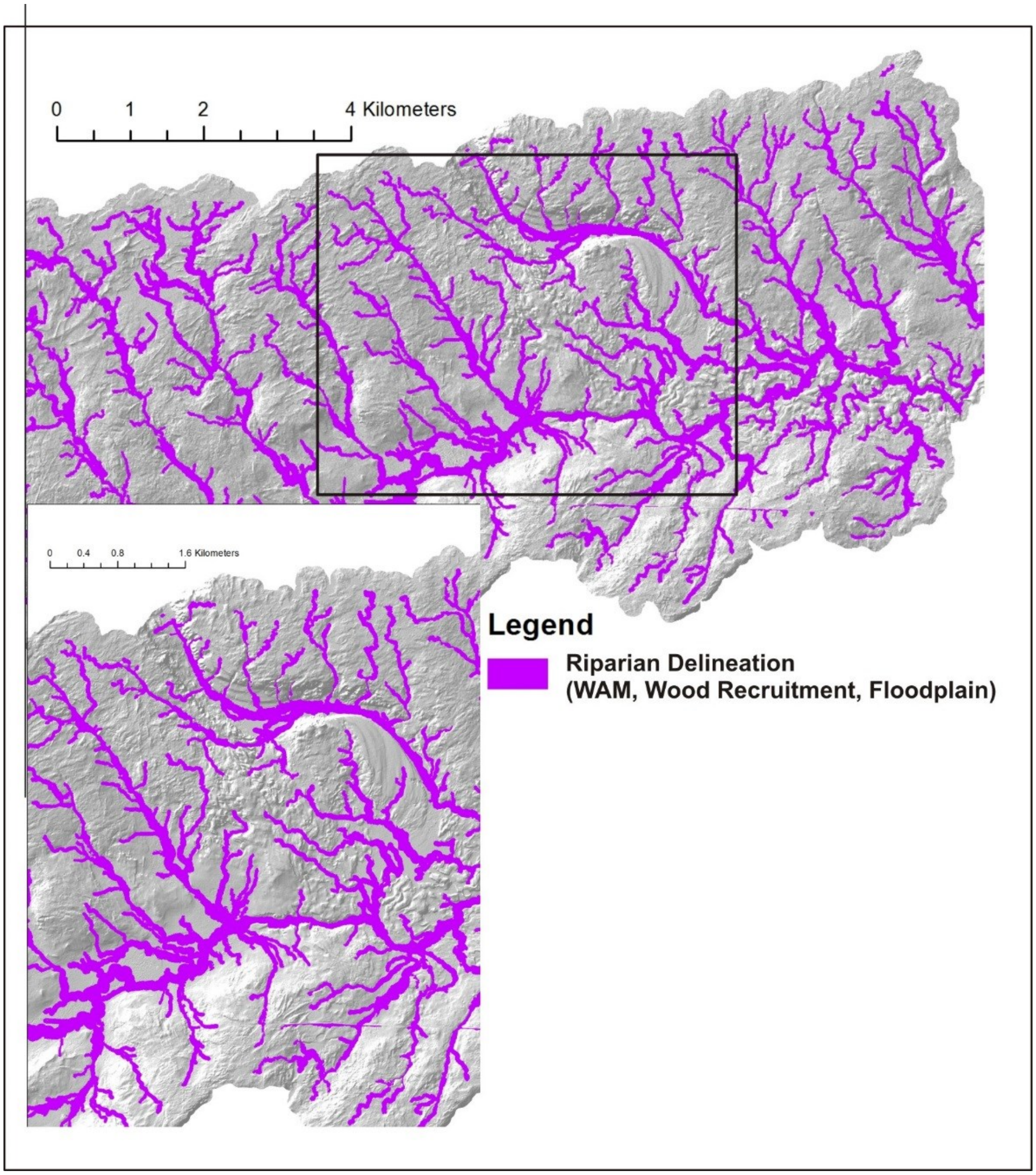


Figure 20. The variable width riparian zone in the Whitemud River watershed.

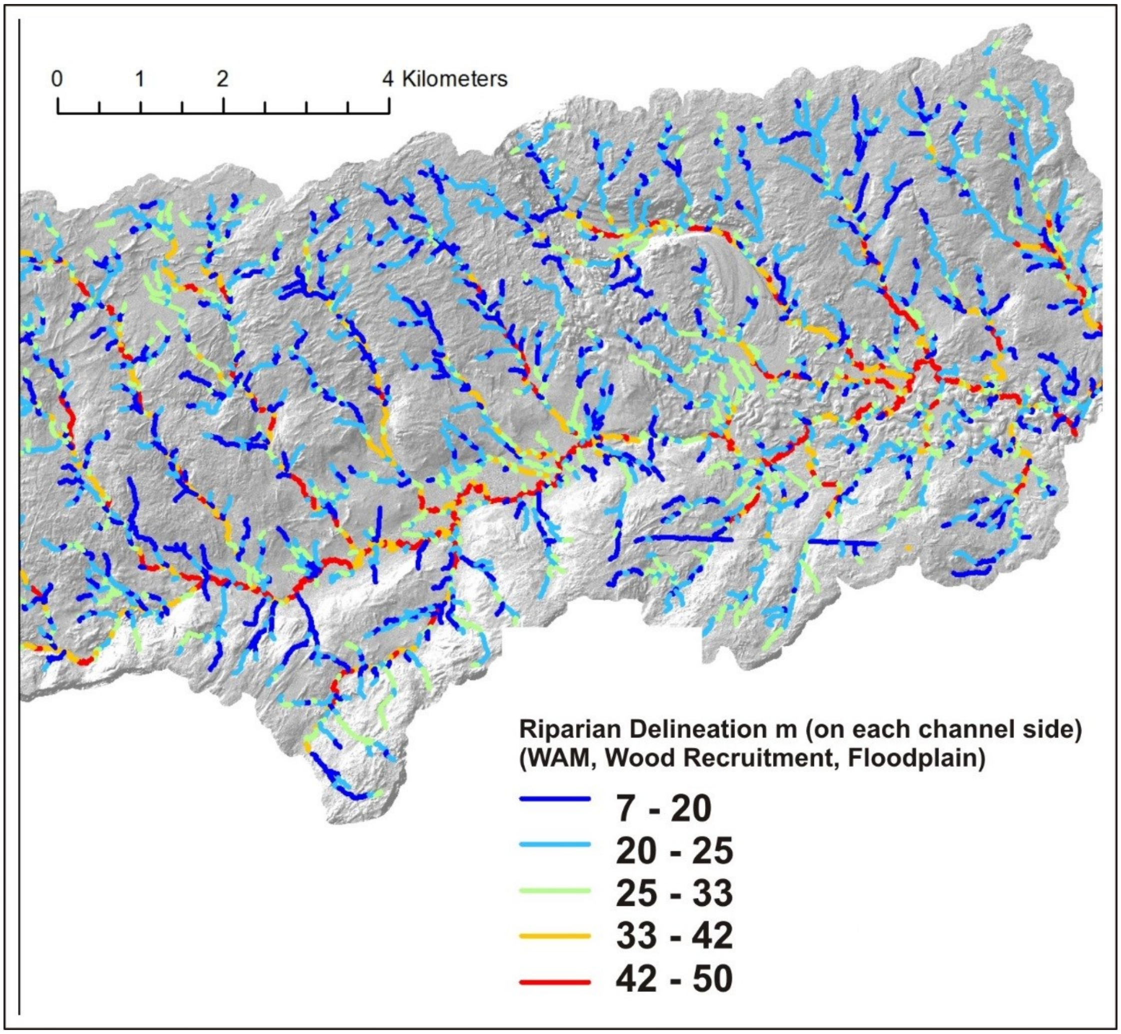


Figure 21. Variable with riparian delineation zone as a stream reach attribute.

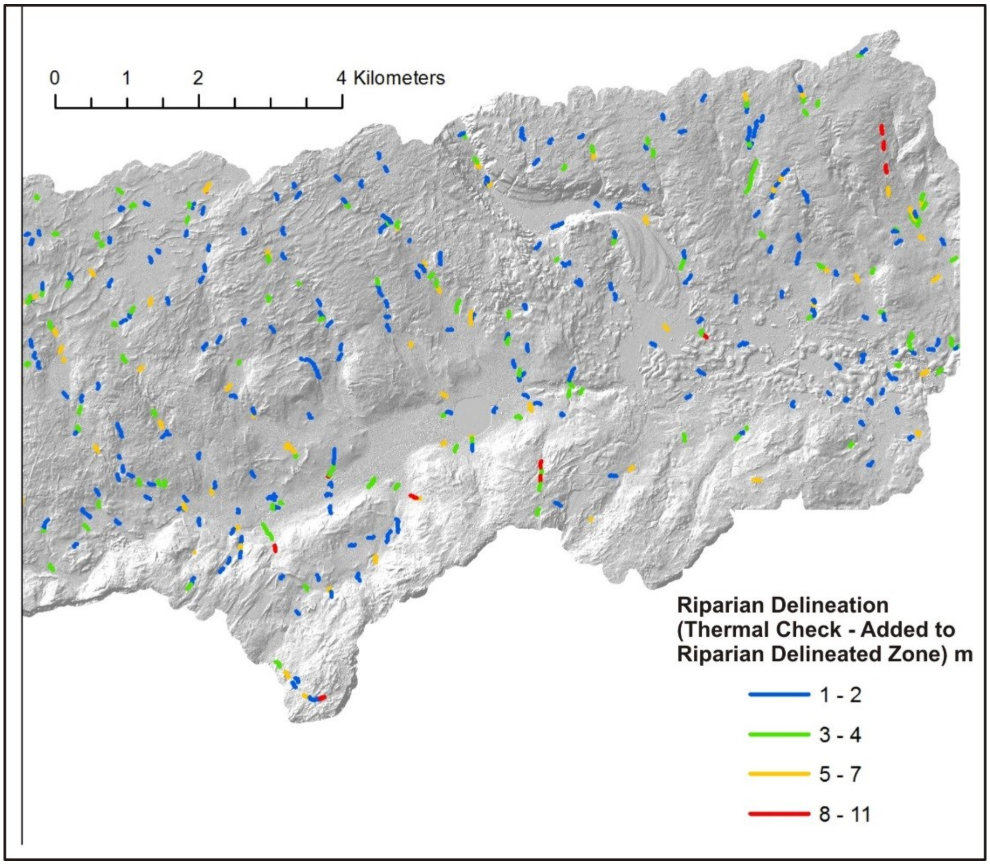


Figure 22. Riparian zone shade-thermal check analysis.

Once the riparian zone is delineated (Figures 20 and 21), a check is performed to determine whether riparian zones provide thermal protection to streams (**Figure 22**). This figure shows which stream reaches failed the test and how much zone width was added to meet the thermal protection threshold (maximum protection to within 200 watt-hours/m^2). In the context of CWE analysis, the delineated riparian zone can be used to limit impacts by directing land uses and resource extractions to outside of the riparian zones.

3.3 Road Network Analysis

Introduction

Empirical studies find that water and sediment yields from forest roads are extremely variable, with sediment production highly sensitive to details of road construction and maintenance (Luce and Black, 2001), to interactions of road and hillslope hydrology (Wemple and Jones, 2003), and to the combined time series of rainfall events and traffic (van Meerveld et al., 2014). Detailed information on these factors is typically lacking, so that predictions of sediment yield are highly uncertain (Skaugset et al., 2011).

Despite the challenges posed in accurately measuring or predicting water and sediment runoff from roads, these processes remain primary suspects in the factors degrading water and aquatic habitat quality. Hence, regulatory agencies specify standards for road construction and maintenance, and increasingly require that road networks be hydrologically disconnected from stream channels (e.g., 2016 California Forest Practice Rules, Chapters 923, 943, and 963).

Forestry and energy-related road networks in Alberta are vast. In heavily managed basins, the cumulative length of forest roads often exceeds that of fish-bearing streams. Analysis tools to identify potential problem areas and to prioritize locations for road maintenance and improvement are needed to aid in planning and to direct efforts to those locations and those modifications that will provide the most benefit at the least cost.

One of the aims of the *WIN-System* is to create a numerical template for road-network analyses that can be used to anticipate effects of roads on channel characteristics and associated aquatic habitat. A conceptual framework must address how road networks interact with processes of water and sediment movement in the context of basin topography, geology, and climate. The Road Erosion and Delivery Index (READI) in the WIN-System has two objectives in the context of CWE analyses and in resource management more generally. First, to identify existing problematic road segments, those that are predicted to generate the most sediment and deliver it to fish bearing streams (e.g., identify road segments for additional maintenance and remediation). Second, to provide information on optimized locations of additional drains (rolling dips, waterbars etc.) and also to inform the design of future roads to reduce potential for environmental impacts.

Methods

Empirical studies highlight the variability and uncertainty in measures of sediment production and delivery to streams from road networks, but they also identify a set of processes by which sediment production and delivery occur. Sediment production from roads is driven by road-segment hydrology (Surfleet et al., 2011), which can be grouped into two primary runoff-generating processes: 1) infiltration excess overland flow on road surfaces, and 2) interception of shallow-subsurface saturated flow by cut banks (Wemple and Jones, 2003). Surface water generated through these processes flows over road and cut-bank surfaces, and through ditches, collecting sediment from these surfaces as it goes, and potentially eroding rills and triggering cut-bank slumps. Sediment-bearing water is then discharged directly to streams at stream crossings, or onto the forest flow where it may continue flowing as overland flow, leaving a plume of sediment in its wake (Hairsine et al., 2002; Ketcheson and Megahan, 1996), or in certain conditions, it may incise gullies or trigger landslides and debris flows (Montgomery, 1994). For now, we focus specifically on infiltration excess overland flow and overland-flow plumes of water and sediment emanating from drain points, but recognize that these other processes must also be included for a complete characterization of road-channel interactions (Jones et al., 2000).

A variety of factors are observed to influence runoff and sediment yield from forest roads:

- Discharge rates of water and sediment are related to the surface area contributing runoff,
- sediment yield is related to the steepness of the road segment (Luce and Black, 1999),
- sediment yield varies with road surfacing material, road age, and road maintenance (Barrett et al., 2012; Luce and Black, 2001),
- sediment yield increases with increasing rainfall intensity (van Meerveld et al., 2014),
- log-truck traffic increases sediment production (Miller, 2014; van Meerveld et al., 2014),
- sediment concentrations in road runoff tend to be high at the beginning of a storm and to taper off over time (van Meerveld et al., 2014),
- the proportion of sediment delivered to streams decreases as the distance of the road from the stream increases (Croke et al., 2005; Ketcheson and Megahan, 1996).

These relationships are not found in all studies, which perhaps highlights the difficulty of measuring all the interacting variables, but because they are observed in some studies, we recognize the need for options to incorporate these relationships into a template for examining road and channel network interactions. Likewise, we recognize that because of the myriad interactions involved, accurate predictions of sediment yield may not be feasible. Hence, spatial patterns of water and sediment discharge to channels from forest roads are estimated in terms of relative amounts, rather than absolute quantities.

An analysis tool in the *WIN-System* must provide calculations of sensitivity to changes in the parameters that influence runoff, sediment production, and delivery to the channel system. This capability can show how uncertainty in input values influences predicted patterns of sediment production and delivery. It can also show where changes in road characteristics, such as surface material or drain spacing, might have the greatest effect on spatial patterns of sediment delivery to channels.

To fully characterize road-channel interactions, analysis tools in the *WIN-System* must operate over entire watersheds. To fully characterize road-ecosystem interactions, analysis tools must operate over multiple watersheds. We focus here on watershed-scale interactions. To do so, we need spatially referenced information for road and channel locations that is linked to basin topography. For this, we rely on the concept of a virtual watershed (Barquin et al., 2015; Benda et al., 2016): a digital representation that explicitly links channel networks to the landscapes they drain. Using NetMap (Benda et al., 2007), a software platform that implements a virtual watershed within a GIS and provides facilities for linking different hydrologic and geomorphic models, we can drape a vector road network onto a digital elevation model (DEM, **Figure 23**) and parse roads into discrete hydrologic segments, extending from a high point to a low point along the topographic profile traversed by the road (**Figure 24**). Road segment length and gradient are calculated, and the flow-path to the nearest stream channel is characterized. This capability provides the foundation on which to build a template for road-network analyses.

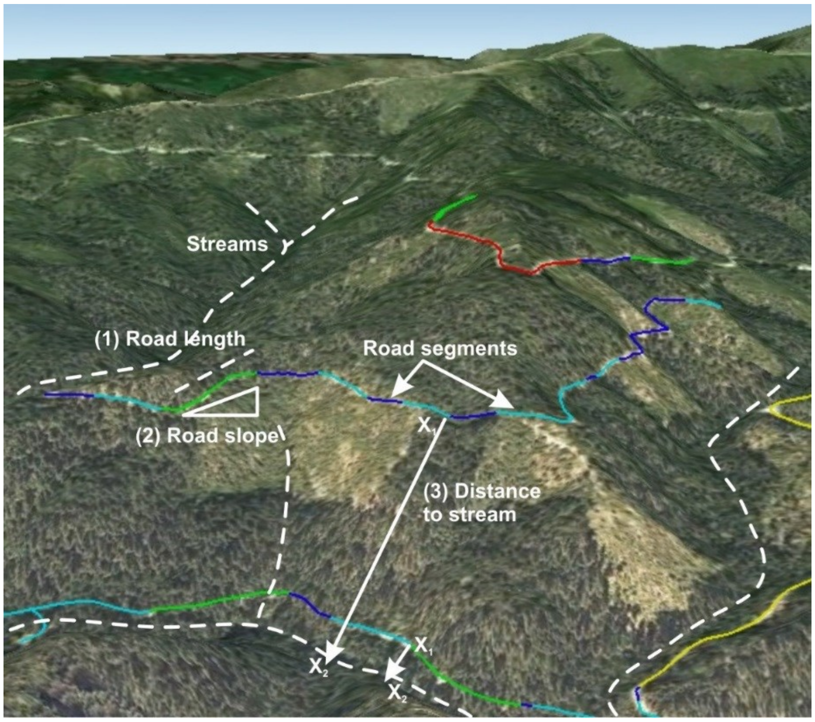


Figure 23. A vector road network is draped onto a DEM.

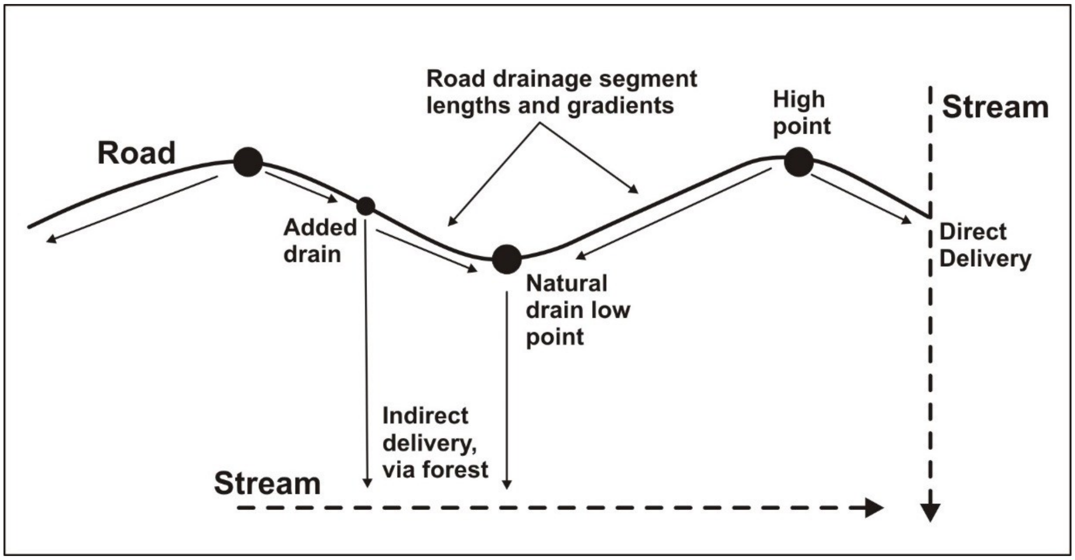


Figure 24. A road layer is broken into hydrologically discreet segments.

To develop a prototype, we focus on a subset of the processes by which roads interact with streams: we examine runoff generated by infiltration excess overland flow and delivery via drain points that discharge water directly into stream channels or generate plumes of overland flow across the forest floor that may, or may not, flow to streams. Processes that are represented can be implemented using a minimum of input parameters, but with sufficient detail to reproduce the behavior generated by these processes (**Figures 23 and 24**). For this, we adopt the following simplifications:

- Rainfall events are characterized in terms of an average intensity I over storm duration D.
- Overland flow velocities are estimated using a kinematic wave approximation.

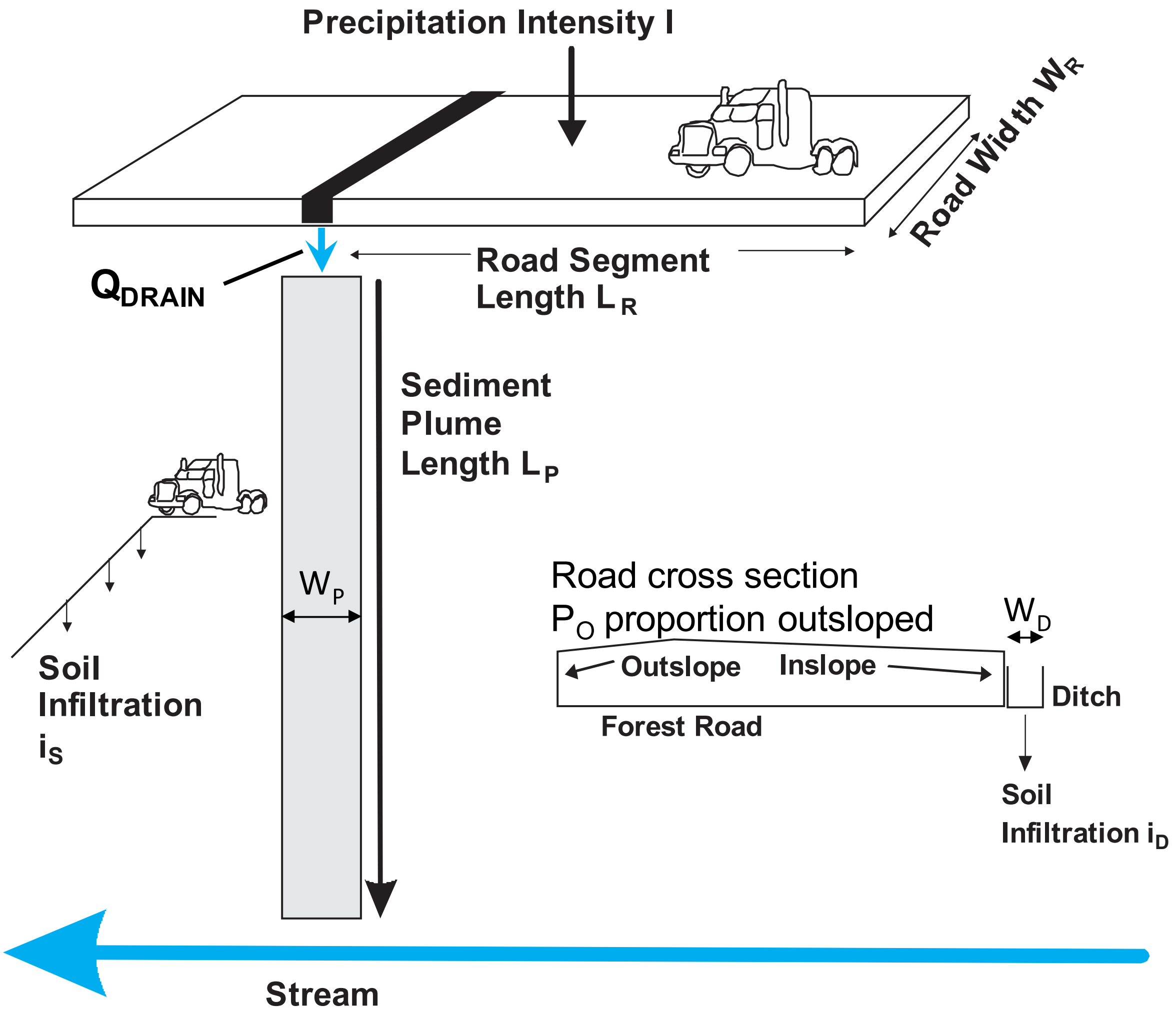


Figure 25. Representation of road segment and sediment plume geometry.

Road Runoff

Discharge Q_R from a road-surface area providing flow to a drain is estimated as

$$Q_R = MIN(v_R t, L_R) w_R (1 - P_O) I \tag{0.1}$$

Here v_R is average flow velocity over the road, t is time since beginning of rainfall, w_R is width of the road prism, P_O is the proportion of the road surface that is outsloped, so that $w_R(1\text{-}P_O)$ gives the effective width of the road prism that contributes discharge to the drain point, L_R is road-segment length, and I is rainfall intensity (**Figure 25**). We assume no infiltration into the road surface and make no accounting for depression storage, although such factors could be included in Equation (0.1).

Road geometry may specify a ditch of width w_D and infiltration rate i_D. Rainfall onto the ditch and infiltration into the base of the ditch add a discharge term

$$Q_D = MIN(v_R t, L_R) w_D (I - i_D) \tag{0.2}$$

so that discharge from a road segment and its associated ditch is the sum:

$$Q_{Drain} = Q_R + Q_D = MIN(v_R t, L_R)(w_R(1-P_O)I + w_D(I - i_D)) \tag{0.3}$$

With this simple model, discharge at the drain outlet increases linearly from initiation of the storm (t = 0) either until the time-to-concentration of the road segment ($T_{CR} = L_R/v_R$), or for the duration of the storm *D*, whichever is shorter. If storm duration exceeds time-to-concentration ($D > T_{CR}$), discharge remains constant from T_{CR} until *D*. When the storm ceases at time $t = D$, discharge decreases linearly to zero at the rate $v_R w_R It$ over time interval T_{CR} or *D*, whichever is smaller. We have applied the same average velocity for flow over the road surface and through the ditch. Channelized flow through a ditch is much faster than overland flow on the road surface, but generally the time-to-concentration for a road segment is considerably less than the storm duration, so that flow velocity has minor effect on total discharge.

NRCS Technical Release 55 (1986) provides an equation for estimating time-to-concentration (T_C) for sheet flow derived using a kinematic wave approximation for flow velocity:

$$T_C = \frac{0.002886(nL)^{0.8}}{P_2^{0.5} S^{0.4}} \tag{0.4}$$

Here *n* is Manning's roughness coefficient (Manning's *n*), *L* is flow length (m), *P* is rainfall depth (m) for the 2-year recurrence interval, 24-hour storm, and *S* is surface slope. As an example, Table 3-1 in TR-55 specifies a Manning's *n* of 0.011 for asphalt, gravel, and smooth bare-soil surfaces, and the intensity-duration curves for Mt. Shasta, CA (downloaded from the National Weather Service http://hdsc.nws.noaa.gov/hdsc/pfds/index.html), give the two-year, 24-hour storm depth as 0.105m, so a 100-m road segment with 5% slope has a time-to-concentration of approximately 0.03 hours and an average flow velocity $v = L/T_{CR}$ of about 3,333 m/hr, a leisurely walking pace. The time-to-concentration for a typical road segment is thus considerably less than the duration of a typical rainstorm, so that discharge at a drain point may be generally expressed as

$$Q_{Drain} = L_R(w_R(1-P_O)I + w_D(I - i_D)) \tag{0.5}$$

A single drain may receive flow from one or more road segments. If multiple road segments have flow to a drain, outflow from each segment is summed at the drain to produce the outflow hydrograph.

Discharge from the drain flows onto the forest floor and creates a plume of overland flow that extends downslope. Water from the plume infiltrates into the soil at a rate dictated by soil infiltration capacity and rainfall adds water to the plume from above at a rate given by rainfall intensity. Generally, the infiltration capacity of forest soils is considerably greater than even the most intense rainfall intensity, so the plume loses water with distance from the road and eventually disappears. Plume length L_P is estimated as

$$L_P = \frac{Q_{DRAIN}}{w_P(i_S - I)} \tag{0.6}$$

Here w_P is average width of the plume and i_S is soil infiltration capacity, so $L_P w_P i_S$ is the amount of water lost to infiltration along the plume and $L_P w_P I$ is the amount of water added by rainfall per unit time.

From equation (0.6) we find Q_{min}, the minimum discharge from the drain for the plume to extend length L_S, the flow distance to a stream channel.

$$Q_{\min} = L_S w_P (i_S - I), t < D \tag{0.7}$$

If discharge Qmin at the drain is reached at time t1, and the time to concentration for flow from the drain to the stream is T_{CS} (using equation (0.4)), then discharge to the stream commences at time $t_1 + T_{CS}$ with magnitude $Q_{DRAIN} - Q_{min}$. When the storm ceases at time $t = D$ (the storm duration), rainfall input to the plume ceases and the minimum discharge from the drain required to maintain flow to the stream becomes

$$Q_{\min} = L_S w_P i_S, t > D \tag{0.8}$$

Thus, once the storm stops, discharge to the stream persists only until discharge from the drain decreases to Q_{min} as specified by Equation (0.8).

Equations (0.1) to (0.8) in READI provide the means to estimate discharge from a drain point to a stream channel as a function of storm intensity and duration and of road-segment geometry. At stream crossings, all the water discharged from a drain enters the stream. At other points, the proportion of water entering the stream depends on the geometry of the overland-flow plume, the distance to the stream, and the infiltration capacity of the soil. If distance to the stream is greater than the plume length, no overland flow is discharged to the stream.

Sediment Production

A variety of factors influence sediment production from roads, including road-surface area and slope, surfacing material, traffic levels, and rainfall intensity. To accommodate these factors, we specify sediment production from a road segment per unit time as

$$P_{SED} = AS_R^n y(t, I) \tag{0.9}$$

Here *A* is road-segment surface area contributing sediment to a drain. Total sediment flux is calculated as the integral of P_{SED} over time. Here S_R^m is mean slope of the road segment, the exponent *m* is an empirical (or theoretical) constant, and $y(t,I)$ is sediment yield, which specifies the volume (or mass) of sediment produced per unit area per unit time, and which may vary with time and with rainfall intensity. Sediment yield is divided into a background rate and a separate, higher rate associated with an initial pulse of sediment production at the beginning of a storm (van Meerveld et al., 2014) that persists for a specified time T_{Pulse}. The background rate y_0 is specified as a linear function of rainfall intensity *I*:

$$y_0 = a + bI \tag{0.10}$$

Here *a* and *b* are empirical constants; their magnitude reflects the erosivity of the road surface: larger values indicate more readily eroded material. For constant erosivity, *b* is set to zero. To represent an initial pulse of sediment, y_0 is increased by a specified factor for a specified time T_{Pulse}:

$$y = cy_0, t < T_{Pulse} \tag{0.11}$$

The magnitude of coefficient *c* may be set to reflect processes that create an accumulation of erodible sediment over time, such as log-truck traffic. If *c* is set to one or T_{Pulse} to zero, there is no initial pulse.

Runoff and Sediment Delivery

For road segments that drain to a stream crossing in READI, all water and sediment enter the stream. For road segments with drain points onto the forest floor, discharge of water to the stream is assumed proportional to the ratio of potential plume length and the flow distance to the stream:

$$Q_{Stream} = (Q_{DRAIN} - Q_{\min}) * (1 - \frac{L_S}{L_P}) \tag{0.12}$$

where Q_{min} is specified by Equation (0.7) or (0.8), depending on time since beginning of the storm. The total volume of water discharged to the stream is then the integral of Equation (0.12) over time.

For road segments that drain onto the forest floor, the quantity of material deposited in sediment plumes is found to increase in a nonlinear fashion with distance downslope. Ketcheson and Megahan (1996), for example, found that the ratio of volume deposited to total volume of the plume exhibited an exponential decrease with the downslope proportion of total plume length. In examining suspended sediment concentrations, Croke et al. (2005) also found an exponential decrease as a function of the proportion of total plume length. Hence, we estimate the discharge of sediment to the stream Q_{Sed} as

$$Q_{Sed} = P_{Sed} * (c_1 e^{-c_2 (\frac{L_S}{L_P})} + c_3) \tag{0.13}$$

Here P_{Sed} is the sediment production rate specified in Equation (0.9), L_S is flow distance to the stream, L_P is the potential length of the plume specified in Equation (0.6), e is the base of the natural algorithm, and c_1, c_2, and c_3 are empirically determined coefficients. Total sediment delivery is calculated as the integral of equation (0.13) over time.

This conceptual model for generation of runoff by infiltration excess overland flow and delivery of water and sediment to streams via an overland-flow plume, implemented using Equations (0.1) through (0.13), provides a means to estimate water and sediment delivery to a stream channel for a specified road segment for a storm of specified intensity and duration. This model includes only a subset of the processes recognized to generate sediment production and delivery – it lacks interception of subsurface flow by cut banks, or delivery via gullying or landsliding, for example – so it may not include the primary mechanisms in some landscapes. It is, however, the first step in building a comprehensive tool for road network analysis. It can be implemented within a virtual-landscape framework, and applied over all segments contained in a road network to show spatial patterns of connectivity to the stream-channel system. Primary parameters required for this model – road segment length, road segment slope, and flow distance from drain points to stream channels – are obtained by draping a road network over a DEM. Other road attributes (road-prism width, proportion out-sloped, ditch width) can be obtained from records of road type, or from surveys of the road network, or set constant to represent average conditions. Parameters for sediment yield can be adjusted to account for differences in road surfacing and traffic levels. The model can be applied over a range of design storms to show how road-stream connectivity might change with storm characteristics.

Importantly, this framework in READI provides insights. If parameter values for sediment yield or road geometry are not well characterized, constant values can be applied and sensitivity of model results to changes in these values used to gage the need for more data collection. As we describe below, this framework can identify locations where construction of additional drains, or where application of gravel surfacing can be optimally applied to reduce connectivity to streams. It can show how reductions of soil infiltration rates due to wildfire might affect connectivity.

Optimization Module:

To evaluate and use a model like that described here, it is important to understand how output values change in response to changes in input values. For this case, it is important both to identify the degree to which uncertainty in input values affect predictions and to see where changes in input variables have the largest effect. Here we will focus on the second aspect of sensitivity to identify locations where changes in sediment yield and road-segment length (via addition of new drain structures) will produce the largest reductions in the quantity of water and sediment discharged to the stream system.

To examine sensitivity of delivered sediment to changes in sediment production, the sediment delivery from each road segment is calculated twice: first with sediment yield calculated using the coefficient values (a, b, and c in Equations (1.10) and (1.11)) specified for each portion of the road network in the attribute table of the GIS road-network vector file, and then with coefficient a increased by 10%. The difference in delivered sediment is then divided by the change in coefficient value to give the change in delivered sediment per unit change in the background yield. High values indicate road segments where a change in yield, by resurfacing for example, will create the greatest changes in modeled sediment delivery. A change in yield only affects sediment production, but our interest is in the quantity of sediment delivered to streams. By calculating sensitivity of sediment delivery to changes in sediment production, segments with no delivery are ignored and those with high delivery – particularly those draining directly to streams – are highlighted.

We also want to identify those locations where additional drain structures will do the most to reduce delivery of water and sediment to the stream system. Imagine a road segment draining directly to a stream crossing. To reduce delivery from this segment, a new drain may be placed on the segment at some distance from the stream. However, some discharge from the new drain may still reach the stream, depending on the length of the overland-flow plume. Our goal is to find the location where the combined discharge to the stream from both the stream crossing and the new drain is a minimum. In fact, we want to find where over the entire road network, or some specified portion of the network, one additional drain will create the largest reduction in total water or sediment delivery. Then, once that new drain is in place, we want to find the next location where a new drain will create the largest reduction in delivery, and so on.

This model provides an estimate of total water and sediment delivery to streams from each drain point in the road network for a specified storm (or sequence of storms). A new drain can be added to any road segment in the model, and the amount of water and sediment making it to the stream from both the original drain and the new drain can be calculated and the sum compared to the amounts delivered from the original drain. To find the optimal drain placement locations, we go to each road segment in the road network and find the location where a new drain minimizes sediment or water delivery from that segment. The relationship between drain placement and water or sediment delivery can be quite complex: depending on road layout, downslope topography, and stream locations, the graph of total sediment or water delivery versus location along the segment for the new drain may have multiple local minimums. Hence, we use a brute-force approach and march meter-by-meter along each segment, placing a new drain and calculating the combined delivery from the combined new and original drains to find the lowest minimum along the segment. This procedure is done for all segments, and the reduction in delivered water or sediment is stored in a priority queue.

We then march through the queue, starting with the new-drain location that provides the largest reduction. We take this drain from the queue and add it to the road network. This splits a road segment into two, so we then determine the optimal new drain placement for each of these segments, calculate the difference in delivered water or sediment, and place these values into the queue. This ensures that the optimal location is always at the top of the queue, even if it happens to fall within one of the newly created segments.

This procedure is repeated until the specified number of new drains are added, or until continued addition of new drains no longer reduces the total amount of water or sediment delivered. This provides a list of new drain points, each with an associated reduction in total delivery of water or sediment, ranked in order from that with the largest reduction to the least.

Example Application/Results

The READI analysis used natural drains and optimized drains; GPS locations of drains were not available and it is recommended that the analysis be re-run in the Whitemud River watershed when GPS drain locations are available. In addition, data on sediment plume lengths were also not available. Thus, READI was run in the Whitemud watershed using plume length data available from another area (northern California) as an illustration. The distribution of plume length data is shown in **Figure 26** where the mean plume length is 14 m.

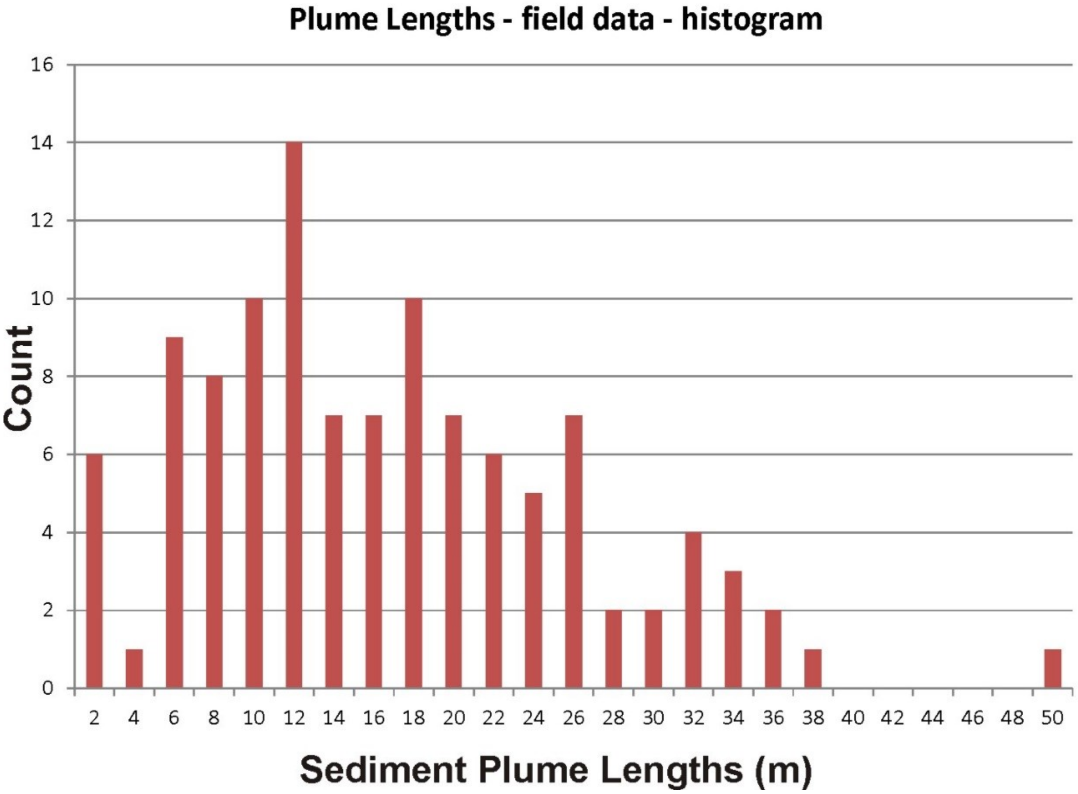


Figure 26. Sediment plume data from northern California.

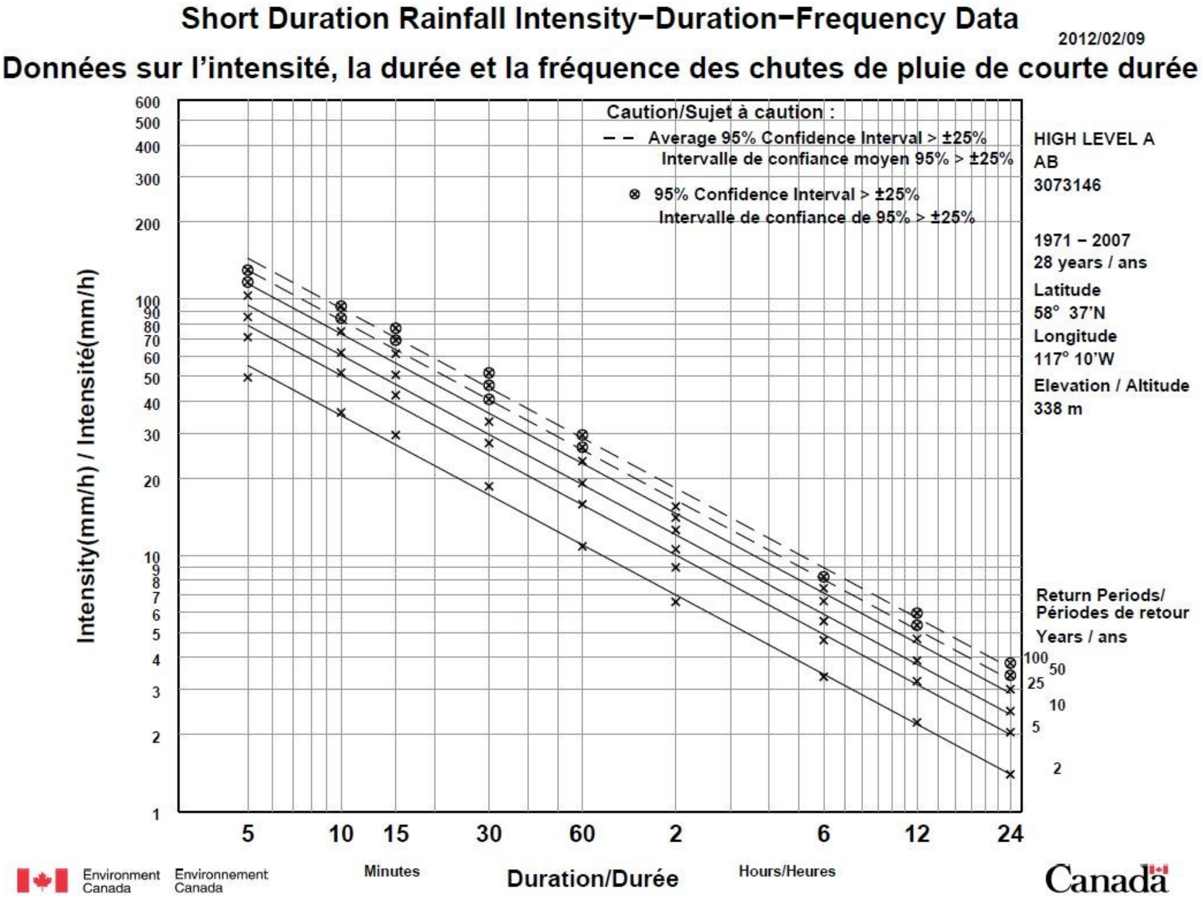


Figure 27. Storm intensity-duration-frequency data used in the Whitemud.

READI model parameters included: 1) minimum road segment length of 300 m, 2) minimum segment relief of 1 m, 3) maximum drain spacing of 300 m, 4) design storm duration 1 hour, 5) design storm intensity 0.02 m/hr (10 year event, **Figure 27**), 6) soil infiltration rate of 0.105 m/hr, 7) ditch infiltration rate of 0.073 m/hr, 8) outslope proportion 0.25, and 9) plume width of 1.5 m (rectangular plume).

The roads and current road drains are shown for a portion of the Whitemud basin in **Figure 28**. Predicted sediment production and sediment delivery (using a dimensionless index) are displayed in **Figures 29 and 30**. Additional road drains (299) located to optimize hydrologic connectivity between roads and streams and hence to reduce sediment delivery are shown in **Figure 31**. The resulting sediment delivery to streams and road-stream connectivity were reduced by 86% (**Figure 32, Table 7**).

Table 7. Summary of READI outputs in the Whitemud River watershed, dataset WM1.

Parameter	Current Condition	After Adding Optimized Drains	Percent Change
Sediment Production (dimensionless)	497,000	497,000	0%
Sediment Delivery (dimensionless)	148,000	21,000	-86%
Fraction of Production Delivered to Streams	29.8%	4.3%	-84%
Percent Road Length Hydrologically Connected	30.5%	4.3%	-86%
Average Sediment Transport Length (plume length)	31 m	15 m	-52%

Another form of mitigation associated with a CWE analysis that can be applied using the *WIN-System* is an evaluation of which road segments in a watershed would respond the most (reduce erosion potential) to surface maintenance (**Figure 33). Figure 34** shows the same prediction but after the addition of optimized drains (e.g., Figure 28). In a WIN-System CWE analysis, predicted road sediment delivery can be mapped to stream channels (**Figure 35**), thus allowing analysis of overlaps of land use stressors with valuable and sensitive aquatic habitats (see Habitat-Stressor Overlap Tool).

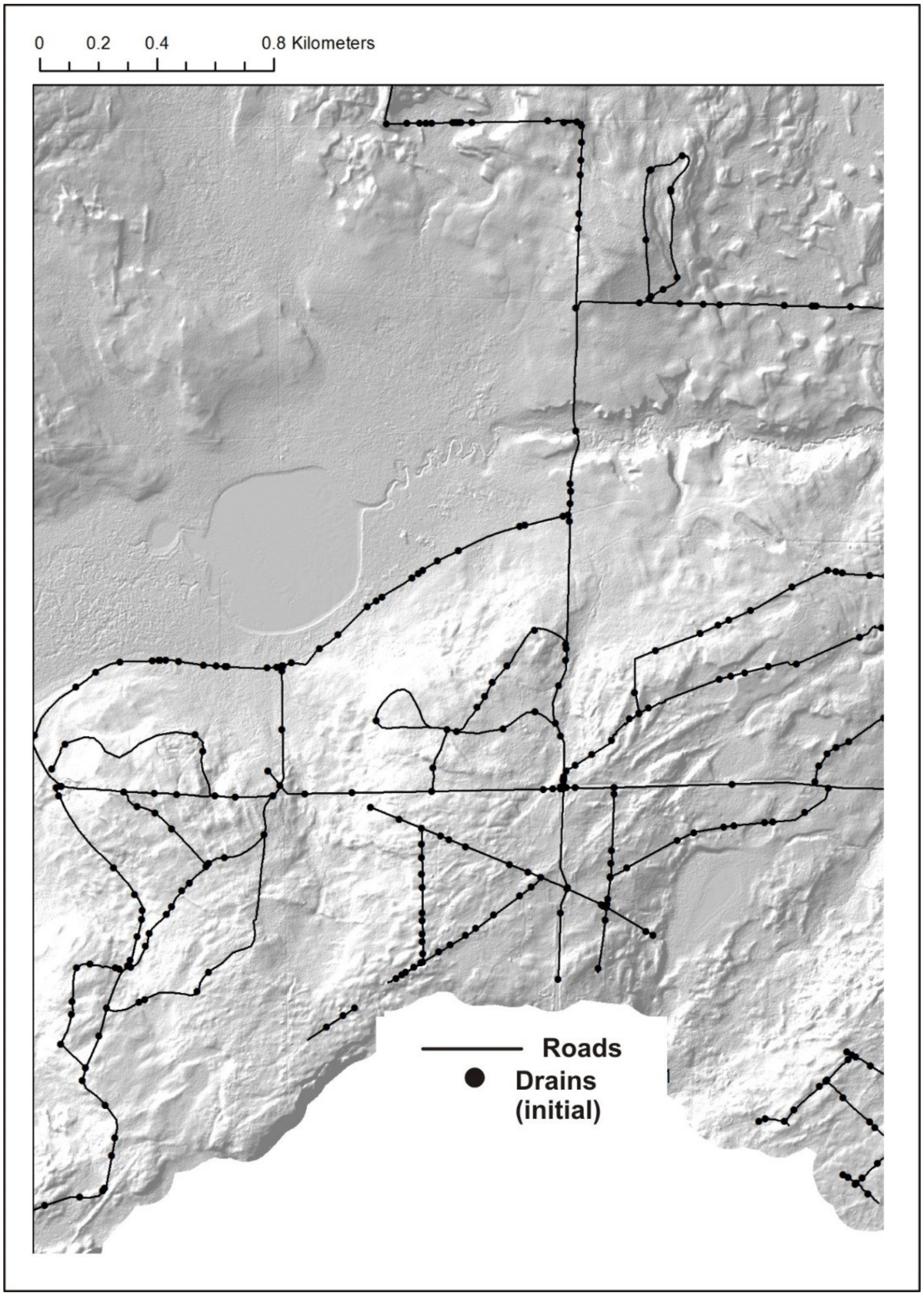


Figure 28. Locations of natural drains (e.g., Figure 24).

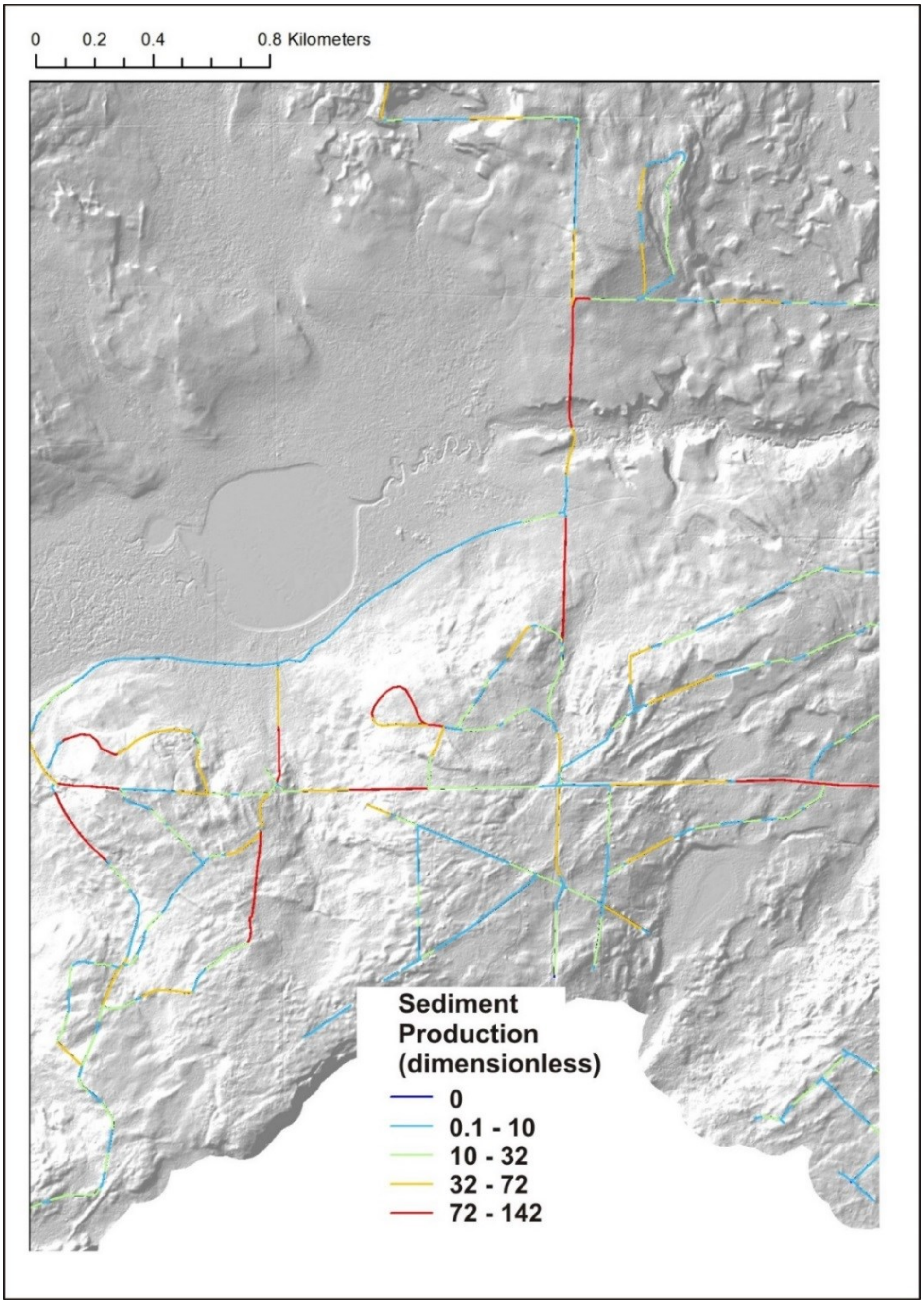


Figure 29. Predicted sediment production (y_o set to 1).

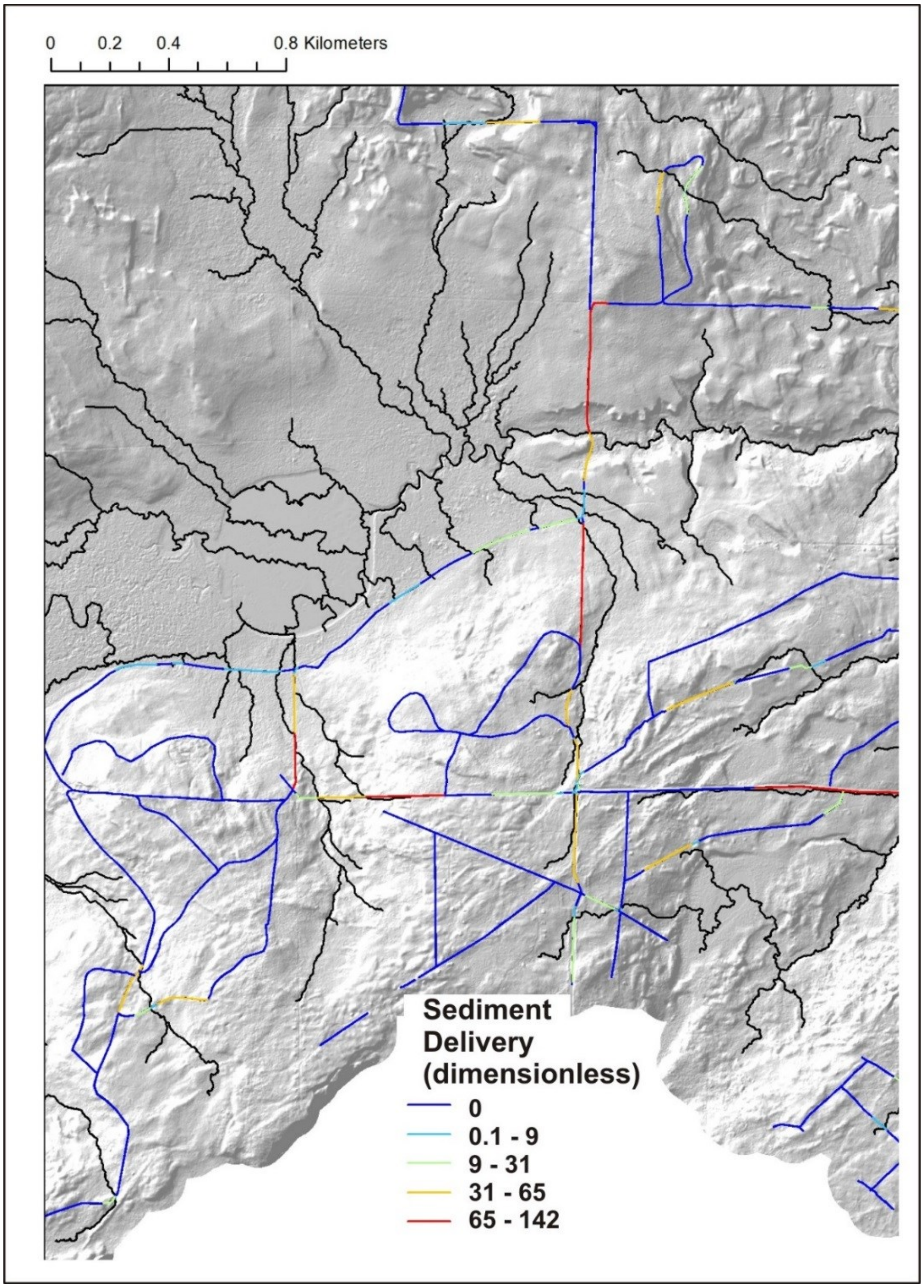


Figure 30. Predicted sediment delivery (yo set to 1).

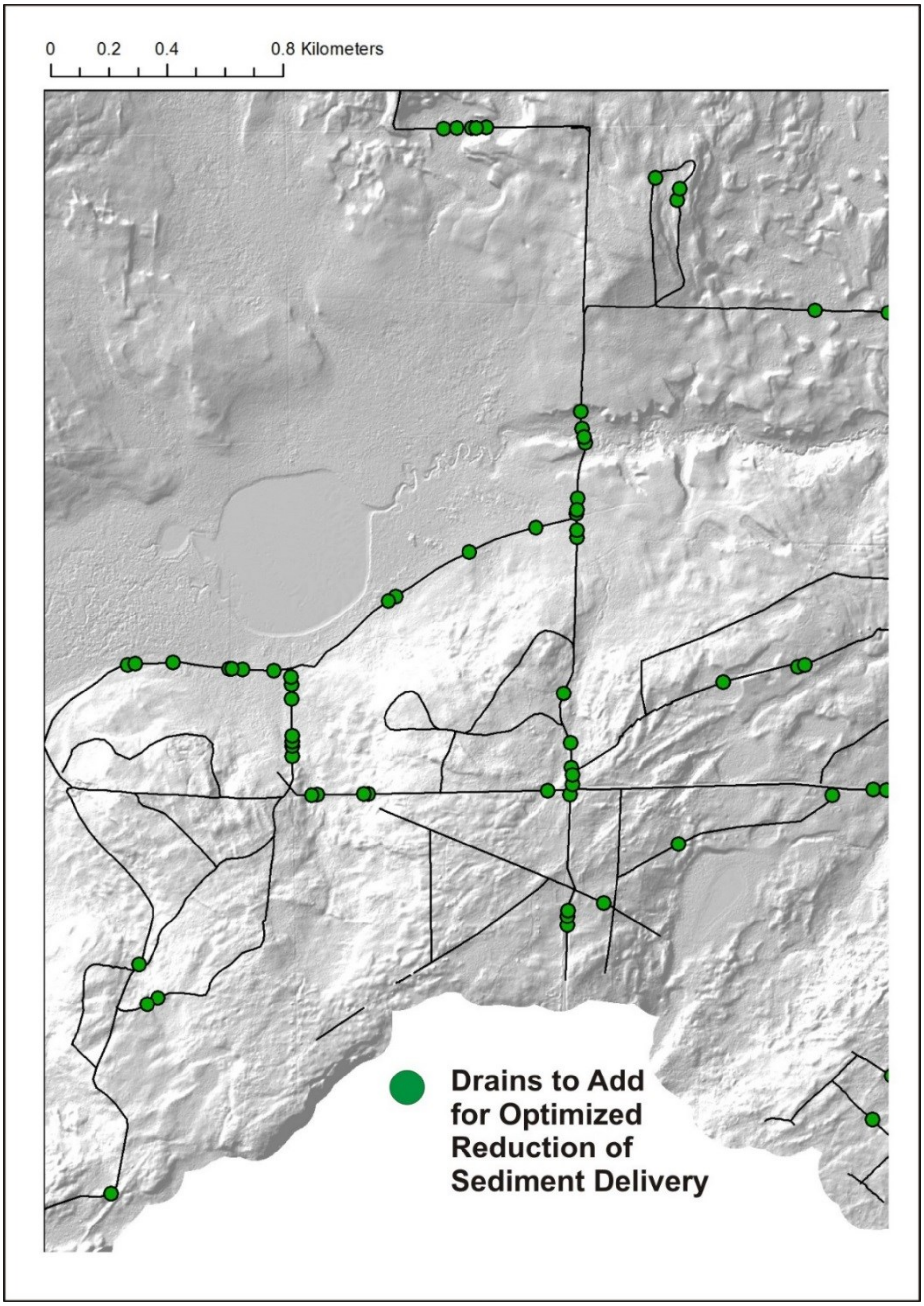


Figure 31. Optimized road drain locations (added to natural drains, Figure 28).

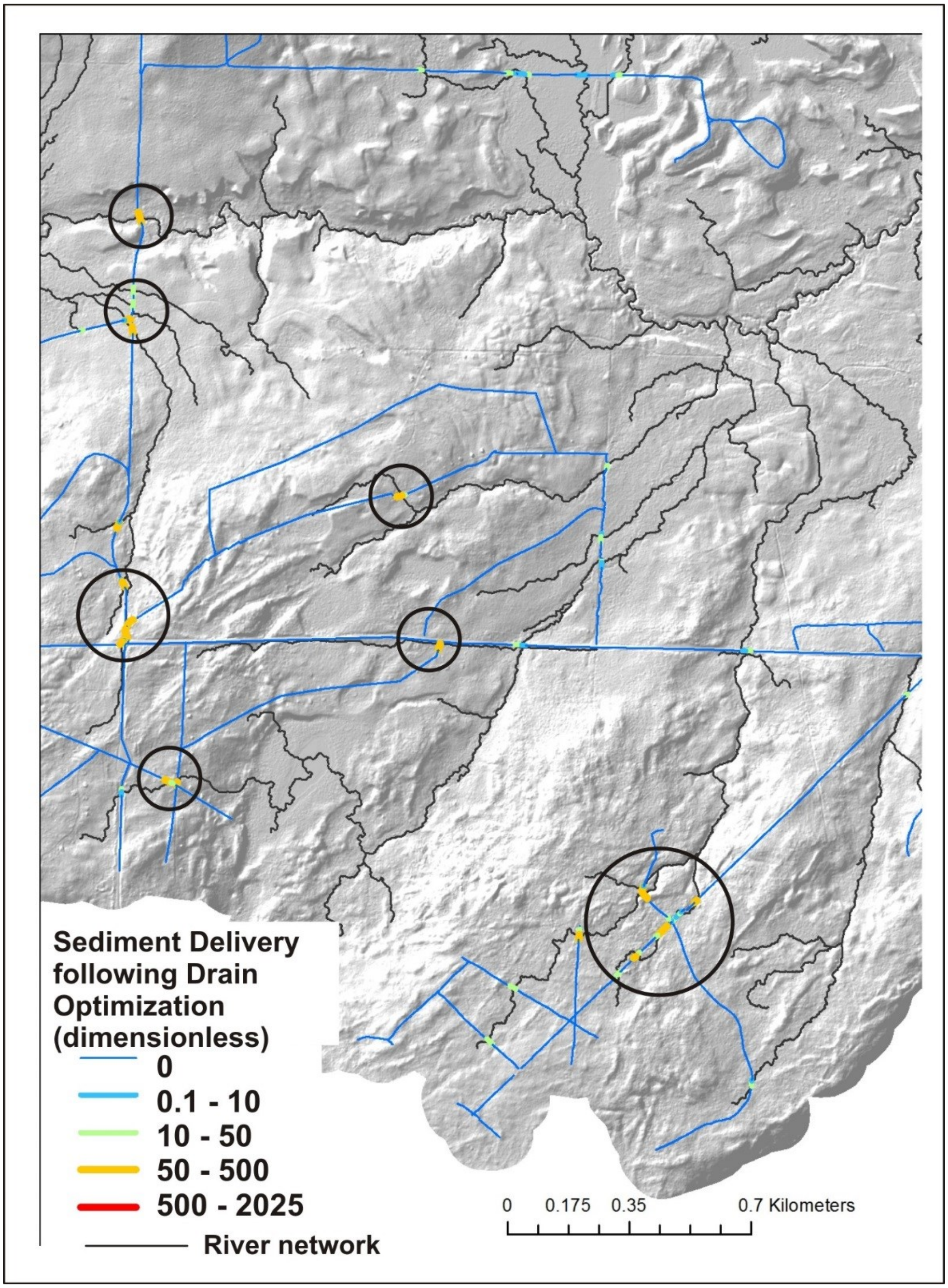


Figure 32. Sediment delivery following drain optimization.

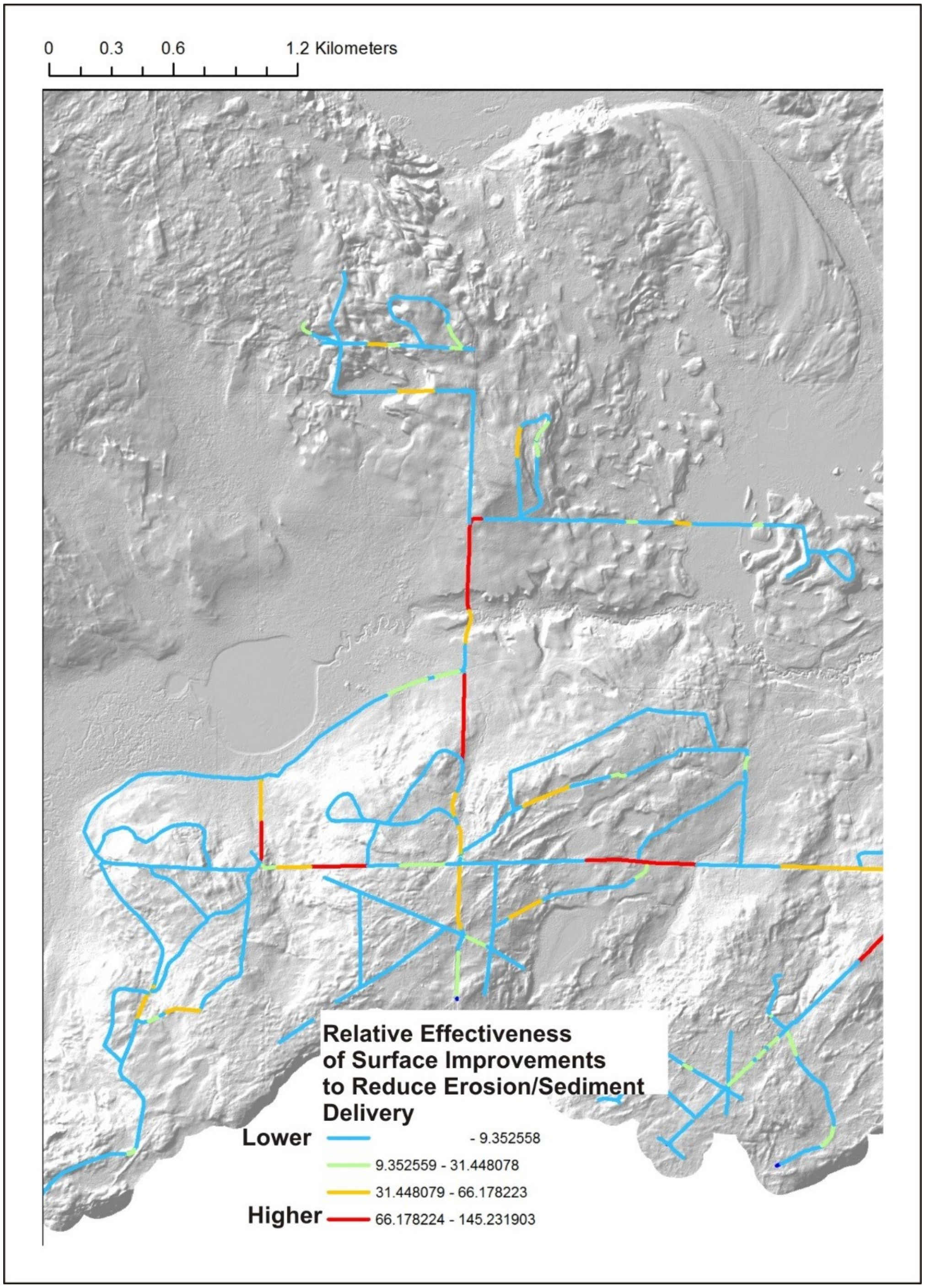


Figure 33. Relative effectiveness of road surface improvements in reducing erosion.

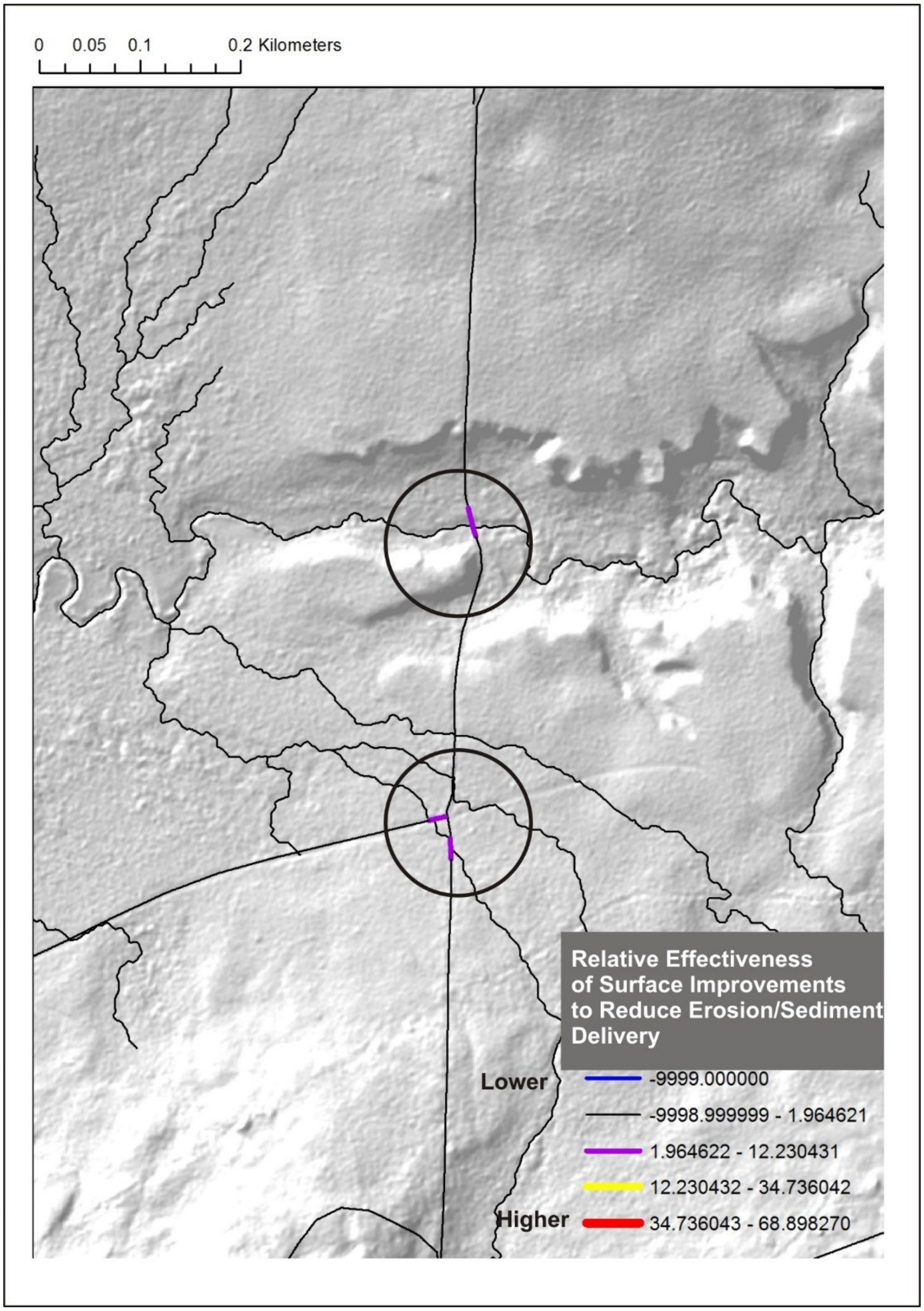


Figure 34. Relative effectiveness of surface improvements following drain optimization.

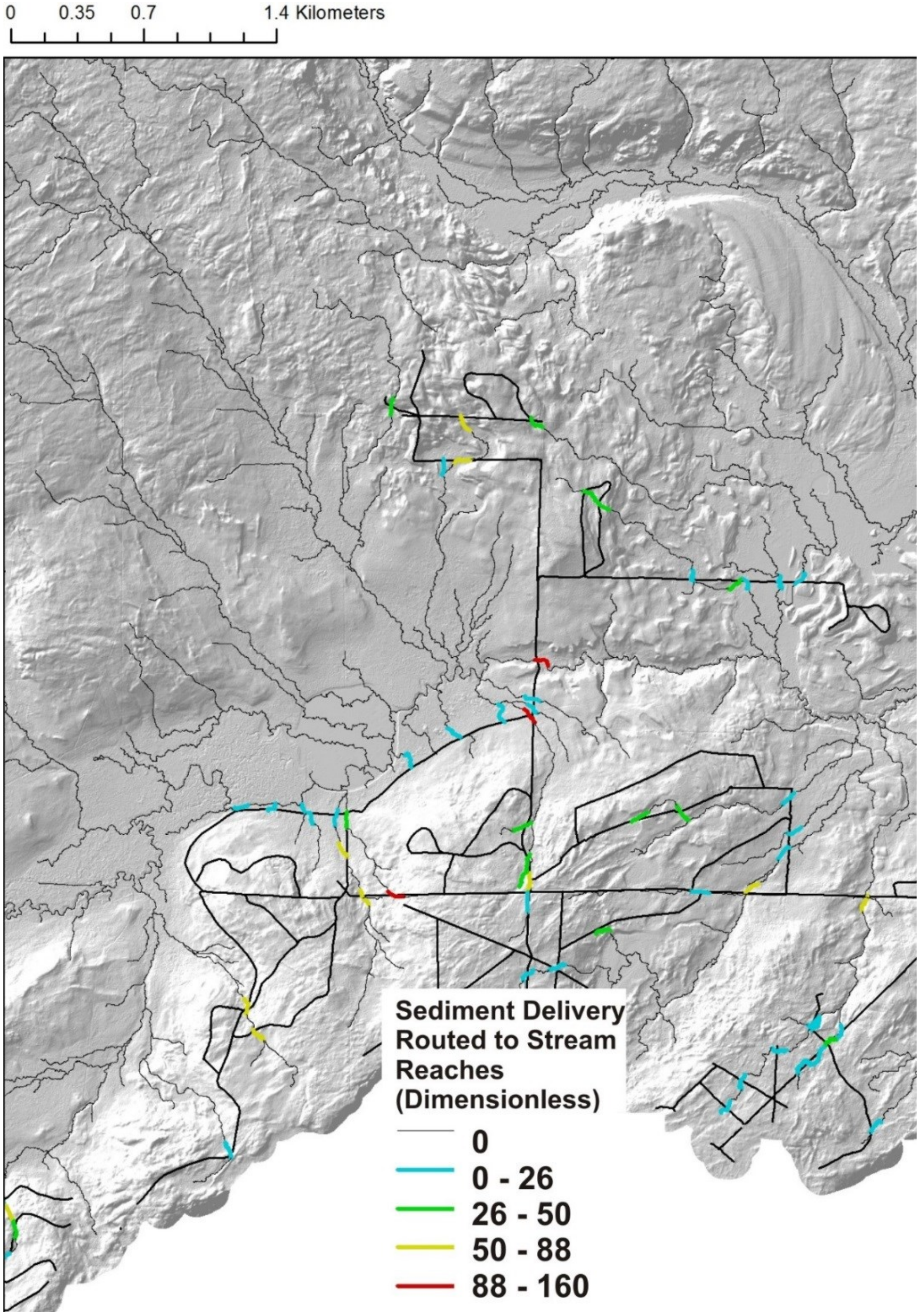


Figure 35. Predicted sediment delivery using non-optimized drains reported to reaches.

3.4 Erosion Processes

Surface Erosion Potential

The *WIN-System* was used to assess three types of erosion potential in the Whitemud River watershed: surface erosion, gullying and shallow landslide. The WEPP-Disturbed model (Elliot et al. 2010) was applied to identify sensitivity of the watershed to surface erosion due to removal of vegetation and ground disturbance by vehicles. The WEPP model requires information on soils (a silt loam soil was selected in the absence of site specific information on soil types in the watershed), vegetation (a minimal shrub vegetation was assumed for the entire watershed), topography (hillslope steepness) and proximity to stream channels (for sediment delivery). To learn more about the U.S. Forest Service WEPP model, go here. The analysis reveals that the majority of the watershed has low to moderate surface erosion with only the steeper hillsides adjacent to the larger channels exposed to higher surface erosion potential (**Figure 36**).

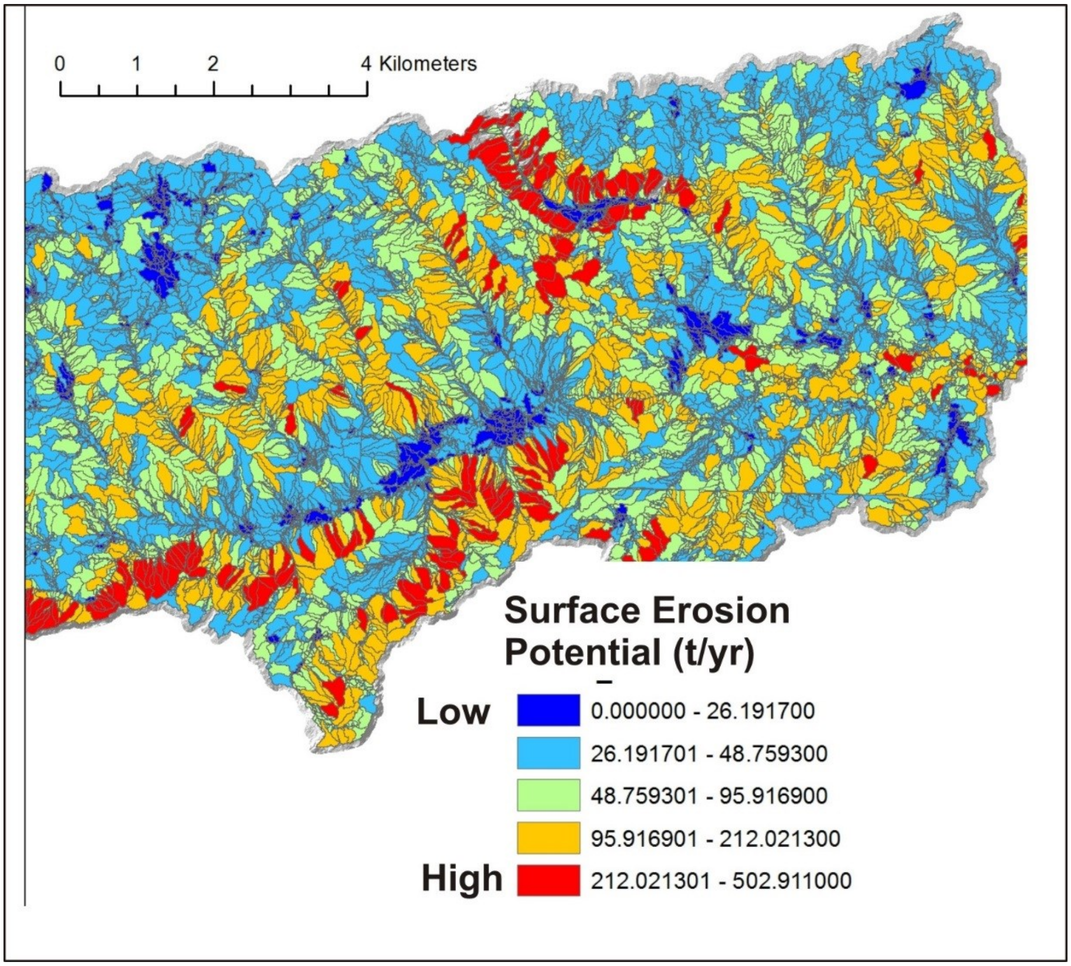


Figure 36. Predicted surface erosion potential under low vegetation conditions using WEPP.

Gully Erosion Potential

Recent work on the controlling influences of gully development has identified enlargement of pipes through subsurface flow as a critically important soil erosion process which can be responsible for exceptionally high soil losses (Faulkner, 2006). In terms of topographic influence Thorne et al. (1984) identified that “the formation of an ephemeral gully depends on the generation of concentrated surface runoff of sufficient magnitude and duration to initiate and maintain erosion, leading to channelisation”. From this, the first three of the above factors listed by Zevenbergen (1989): discharge, slope and planform curvature, are key topographic controls in the formation process.

The importance of these three factors can be theoretically considered using stream power, a parameter commonly used to represent flow intensity and predict sediment carrying capacity (Bagnold, 1966; Yang, 1977). The concentration of surface runoff described by Thorne et al. (1984) can be physically represented by specific stream power, which is a function of discharge, slope and width. Drainage area is often used in geomorphic analysis as a surrogate for discharge and, consequently, drainage area multiplied by slope gives a parameter acting as a proxy for total stream power. This line of argument justifies the inclusion of both slope and drainage area (as an acceptable surrogate for discharge) in a technique responsible for predicting the formation of ephemeral gullies.

The third topographic factor, planform curvature, or convergence, contributes to ephemeral gully formation in multiple ways. Firstly, without convergence runoff volume and discharge are linearly proportional to slope length, while with convergence these values are related to slope length to a power greater than unity (Zevenbergen 1989). Secondly, at any point along a swale in the downstream direction the degree of planform curvature determines local flow geometry, including the degree of flow concentration. This means that the level of convergence in the land surface is important in controlling the initial flow path geometry, and therefore, the initial channel location. In other terms, whilst the product of slope and discharge may adequately represent total stream power, planform curvature is necessary to represent the degree of concentration of this stream power and so enables it to become a representation of specific stream power, the key component of Bagnold’s sediment transport theory.

Zevenbergen and Thorne (1987) developed a methodology for calculating slope, aspect, planform curvature and upstream drainage area for each point within an elevation grid matrix. Thorne et al (1986) used these parameters to calculate a Compound Topographic Index (CTI) for each grid cell within that matrix, which is used to identify potential locations for ephemeral gullies based on land topography. The CTI is defined by:

$$\mathrm{CTI} = A \cdot S \cdot \mathrm{PLANC} \qquad (0.14)$$

where: A = upstream drainage area (L^2) and provides a surrogate for runoff discharge since the two are generally strongly positively correlated; S = local slope (L/L), which together with upstream area provides an indication of the stream power per unit downstream distance of the runoff; and PLANC = planform curvature (1/L), a measure of the landscape convergence (negative for spurs and positive for swales) indicating the degree of concentration of the runoff and so allowing the CTI (L) to represent specific streampower (streampower per unit bed area). As a result, the CTI represents the major parameters controlling the pattern and intensity of concentrated surface runoff in the field.

The CTI index was applied to the Whitemud River watershed. Based on the CTI model, The vast majority of the watershed has no to very low gully erosion potential. A few localized areas (on bluffs adjacent to larger river valleys) have higher gully erosion potential (**Figure 37**). For information on predicting gully erosion in the NetMap system, go here.

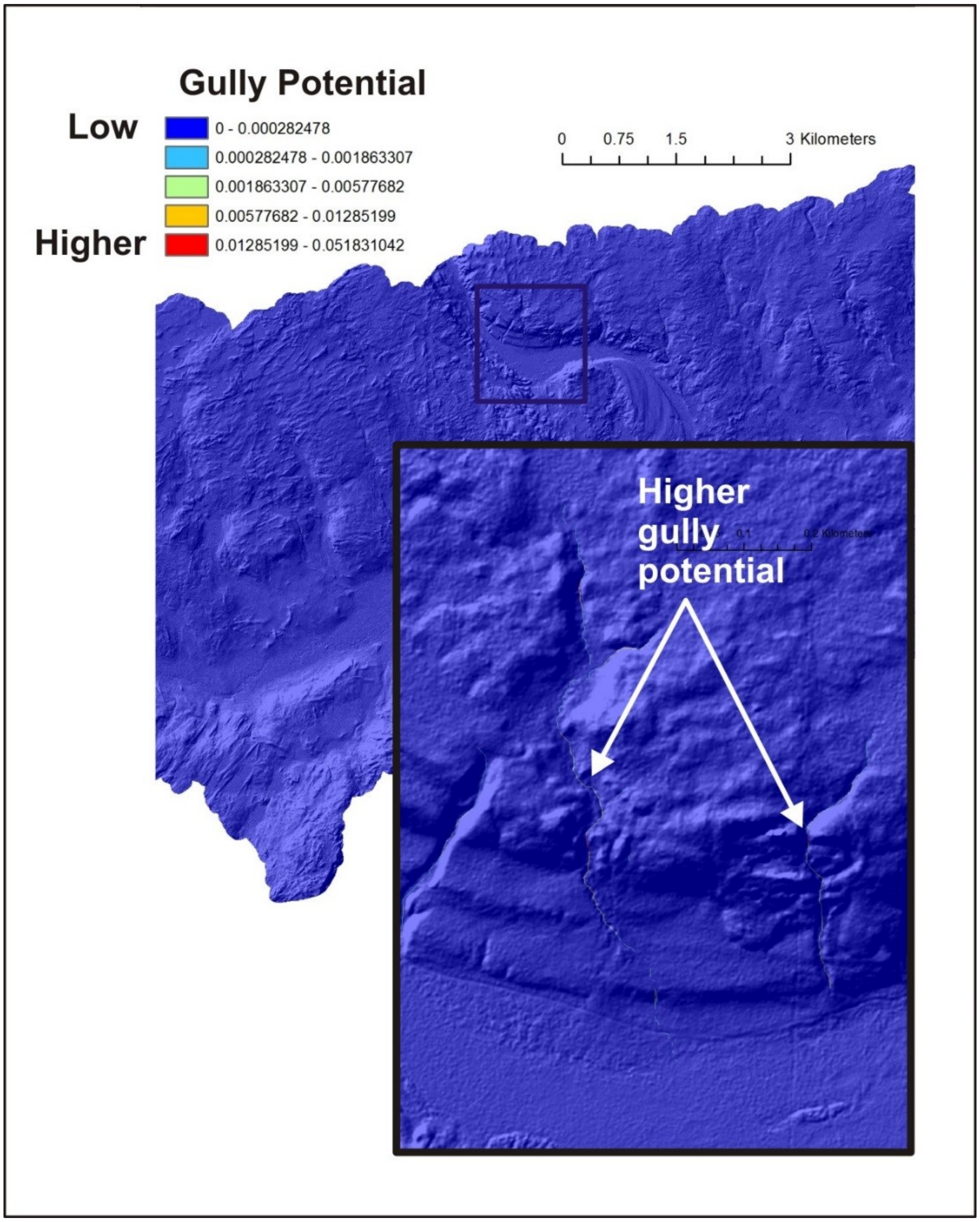


Figure 37. Predicted gully erosion potential.

Shallow Landslide Potential

The potential for gully erosion and shallow landsliding are considered together since the topography associated with each is similar (steep and convergent landforms). 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). 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:

$$GEP = S*aL/b \tag{0.15}$$

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). To learn more about shallow landslide potential, go here.

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.

NetMap’s topographic index for shallow landslide potential reveals very low risk throughout much of the MW1 dataset in the Whitemud River watershed (**Figure 85**).

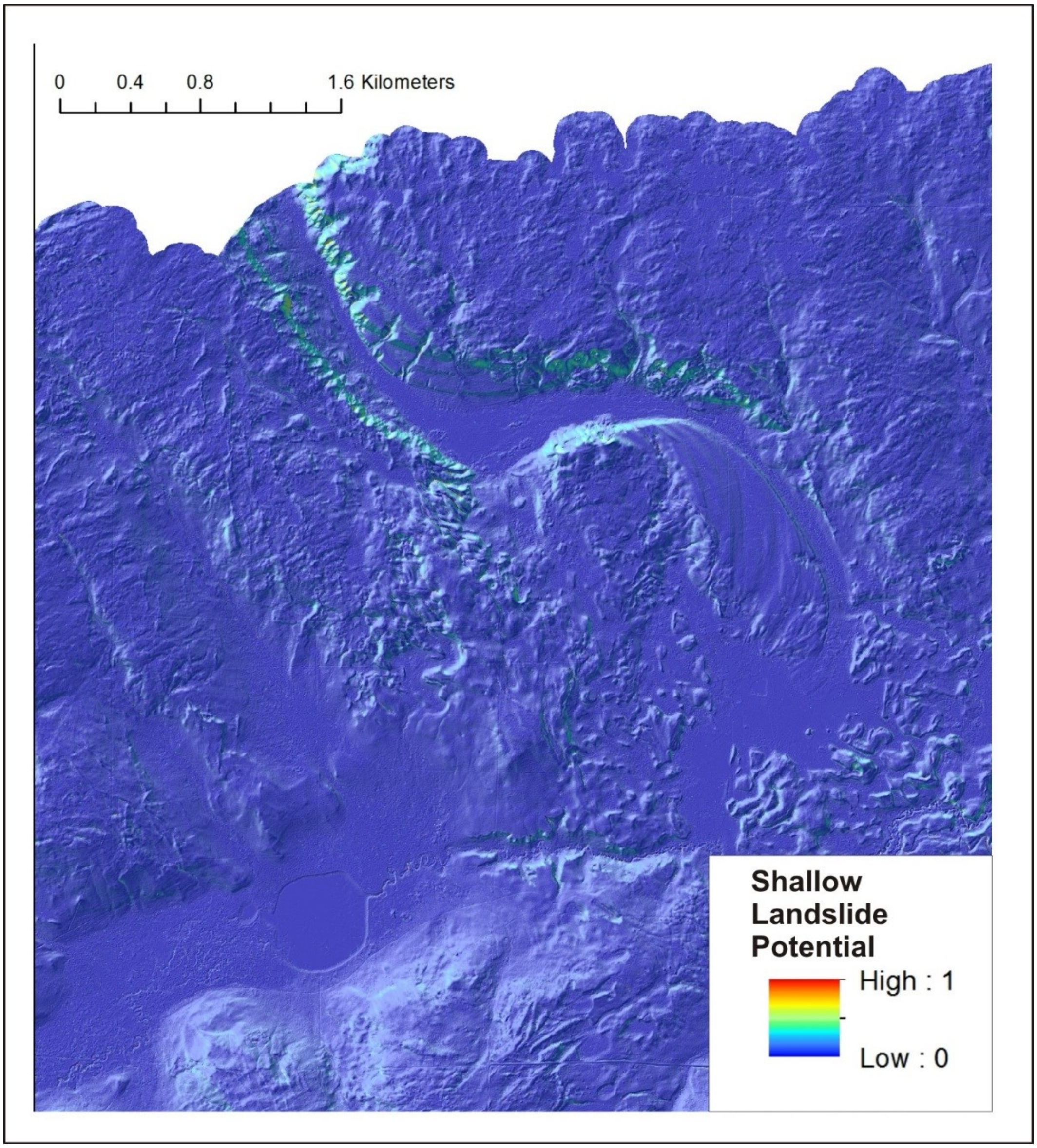


Figure 38. Shallow landslide potential.

3.5 Forestry cut blocks

Timber harvest is taking place within the Whitemud River watershed, with age of cut blocks extending over multiple decades. To illustrate the potential effects of vegetation removal and ground disturbance on surface erosion potential, the U.S. Forest Service WEPP model was applied to a shapefile of cut blocks in the WM1 sub-watershed (**Figure 39**). Input parameters to the WEPP model for the cut blocks included soil management file (silt loam), vegetation management file (harvest) and a climate was selected from CLIGEN from southcentral Alaska that was similar to the continental Alberta climate (similar climate to what was applied in the Simonette forest road analysis in 2015).

The WEPP model predicts a highly variable potential for surface erosion due to removal of vegetation during timber harvest with only a subset of cut blocks having a moderate to high erosion potential sensitivity (**Figures 40 and 41**).

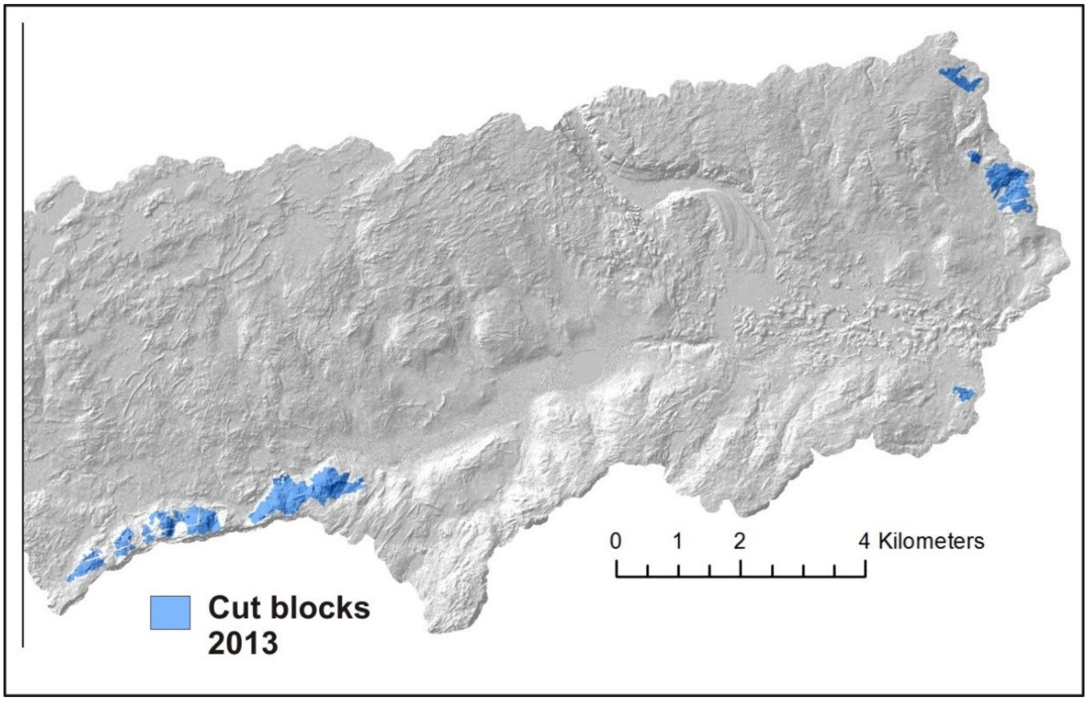


Figure 39. Locations of forestry cut blocks (circa 2013).

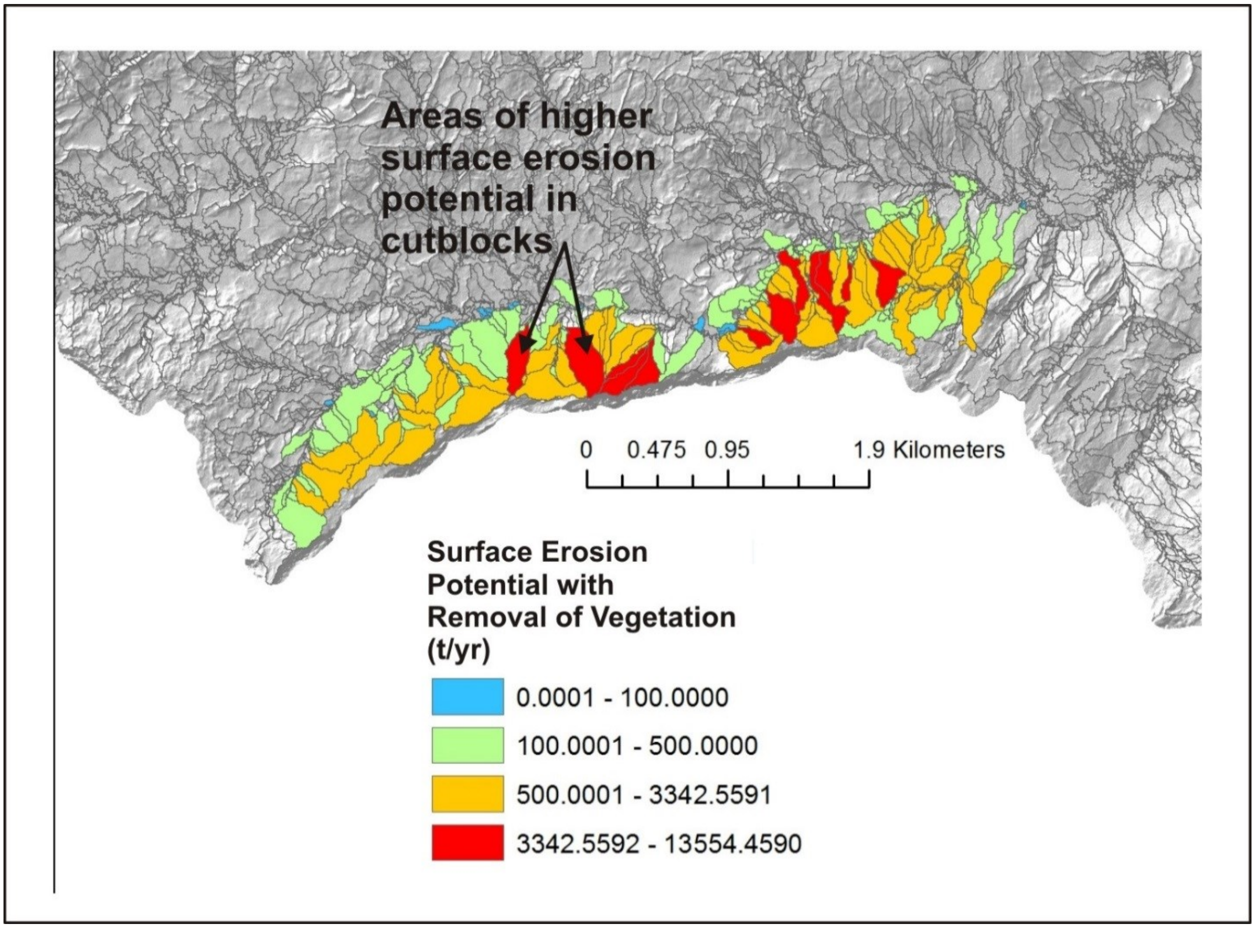


Figure 40. Predicted surface erosion potential for cut blocks using the WEPP model.

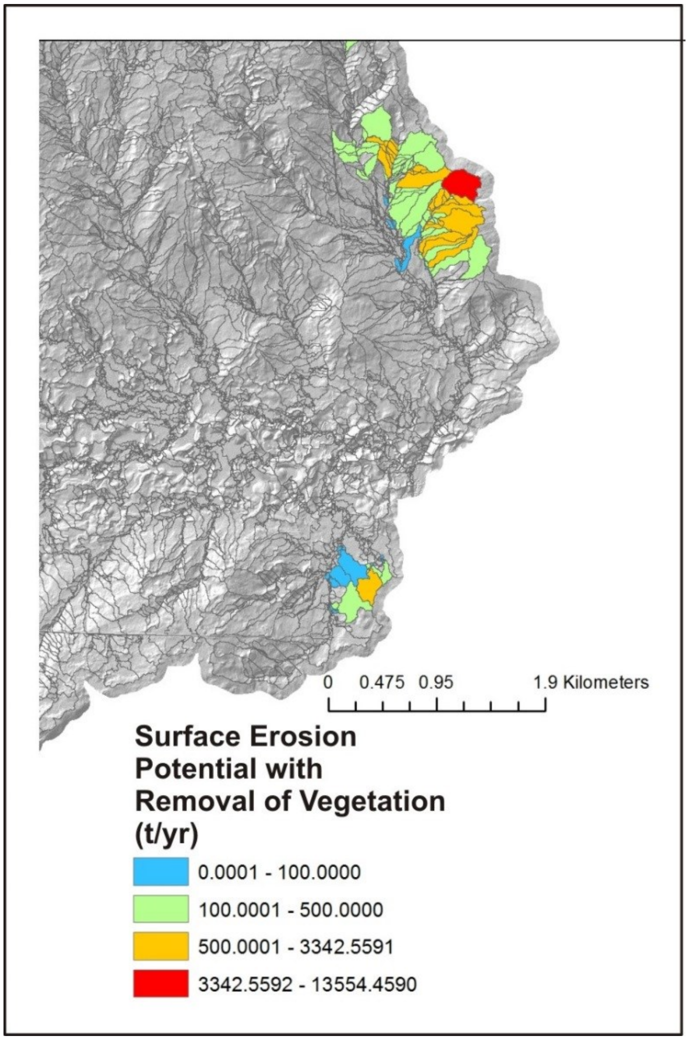


Figure 41. Predicted surface erosion potential in recent cut blocks using the WEPP model.

3.6 Bark Beetle Killed Trees and Shade – Thermal Impacts

Bark beetles are causing widespread forest mortality in western Canada, including in Alberta, although mortality in the Whitemud River is spotty. Relatively small patches of tree mortality associated with bark beetles are located throughout the Whitemud River watershed (**Figure 42**). Beetle kill mortality ranges from 25% to 50% of the stands, according the GIS layer. In the context of the *WIN-System* CWE analysis, we calculated thermal energy into the stream using shade, conditioned by Alberta data on vegetation height and basal area. To learn how thermal energy is calculated based on vegetation height and basal area, go here.

In stream reaches within 50 m of beetle killed forests, the vegetation basal area was reduced by the percent tree mortality (25% or 50%, see Figure 42). This was used within the *WIN-System*'s thermal energy tool to predict the change in radiation loading to stream reaches. Some affected stream reaches would be more exposed to thermal increases than others (Figure 43); these areas could be targeted for restoration.

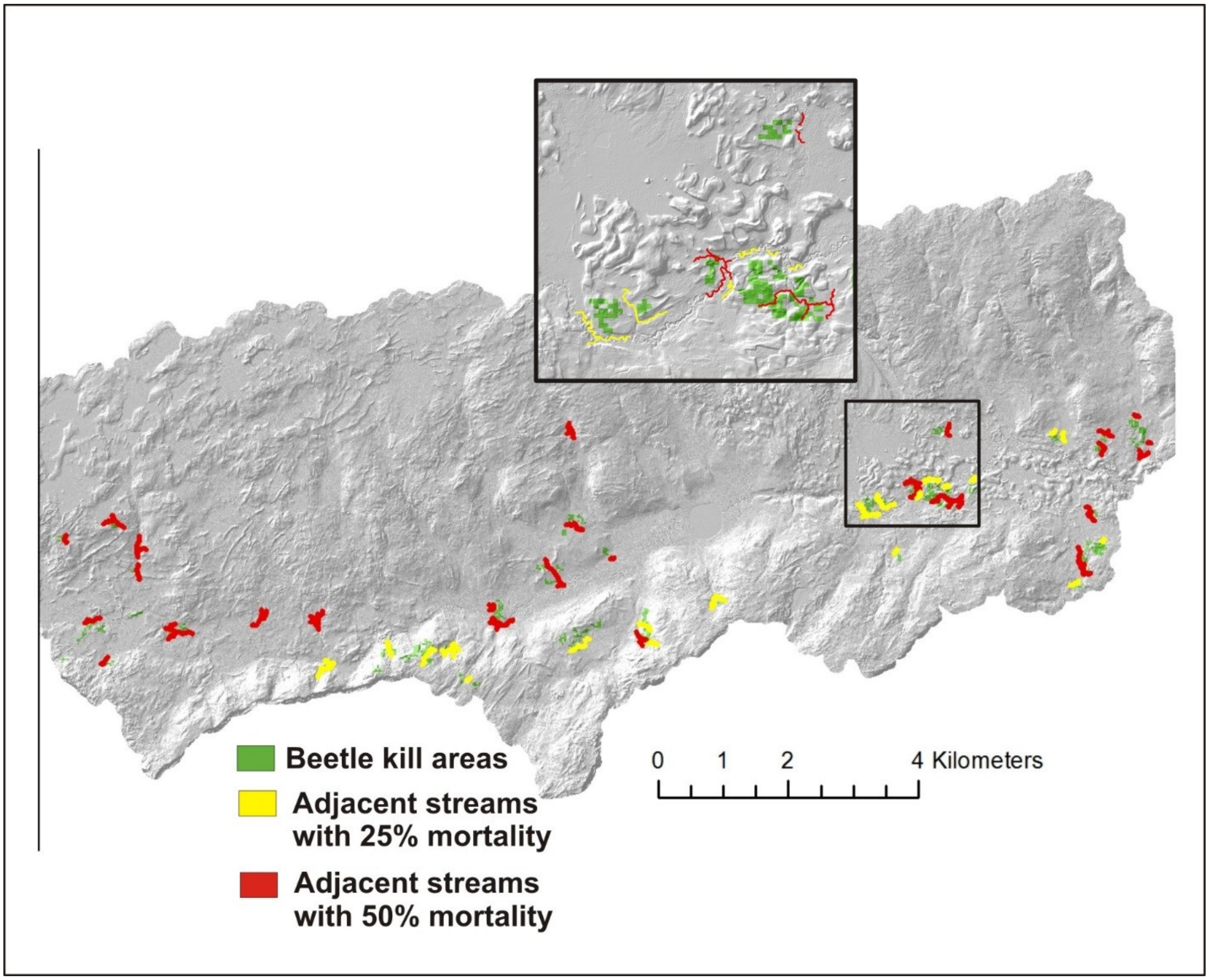


Figure 42. Beetle kill areas in the WM1 dataset with 25% to 50% mortality.

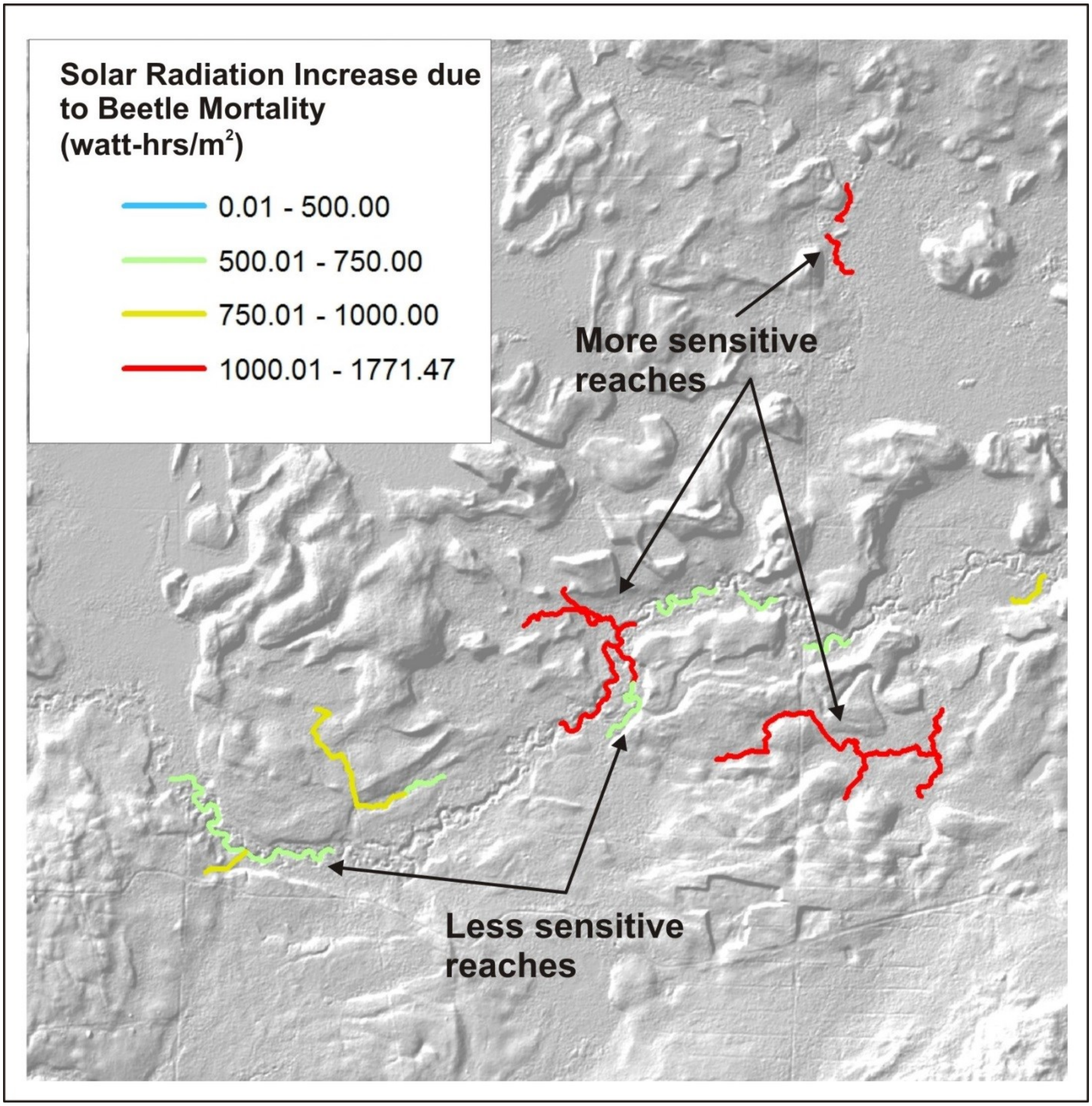


Figure 43. Predicted increases in stream thermal loading due to beetle reductions in shade.

3.7 Wildfire

Information on wildfire history in the Whitemud River watershed extends back to the 1940s. In our demonstration analysis of the *WIN-System*, we were only concerned with more recent wildfires (e.g., those more recent than 2005 in which soil disturbance may still be effecting soil erosion potential). Across the entire Whitemud River watershed, we cross referenced GIS meta data on burn severity (high and low) with burn severity indices in the WEPP-Disturbed model; to learn how WEPP-Disturbed predicts post fire surface erosion, go here. In the WM1 dataset, there were no fires more recent that the 1940s. To learn more about how the *WIN-System* could be used in pre-wildfire and post-wildfire, go here and here.

During this study, predictions of fire probability and severity were not available to incorporate into the analysis. However, such data might become available in the near future. Hence, we add two sections below that summarize how

Post-Wildfire Analysis and Planning

The capabilities of a NetMap related analysis of a post fire area in eastern Oregon for the U.S. Forest Service could be applied to post fire areas within Alberta, including in the context of the *WIN-System*. Below is a series of illustrative figures that summarizes the types of analyses that could be conducted in post wildfire areas in Alberta.

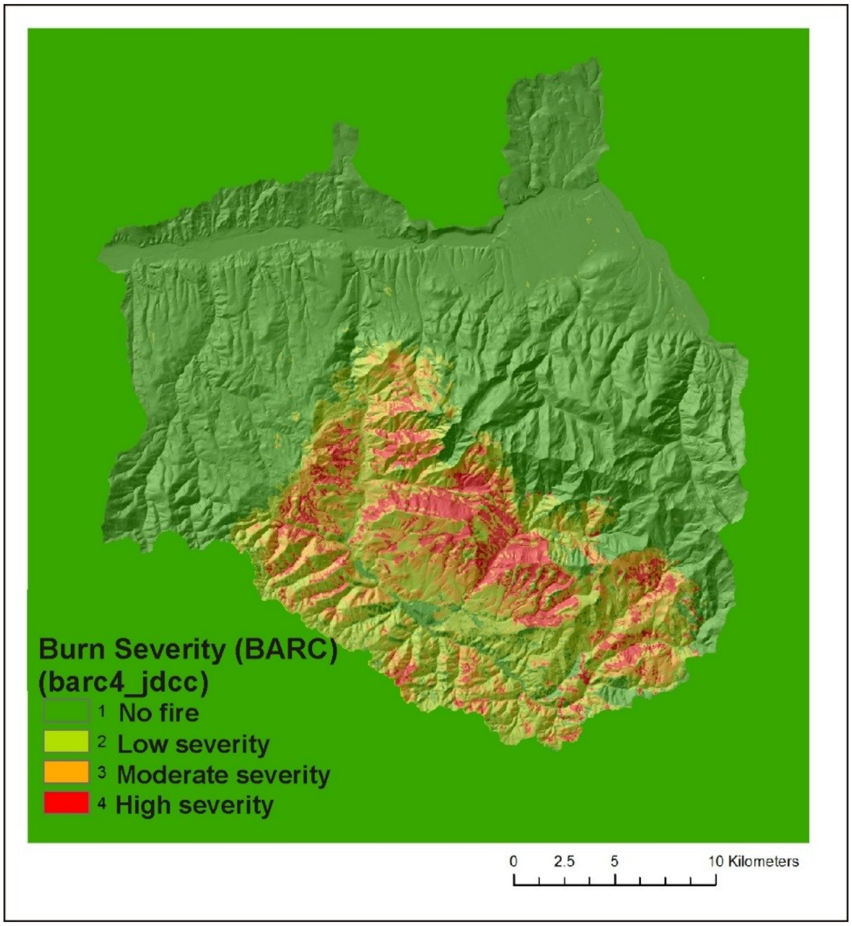


Figure 44. A burn severity map is required.

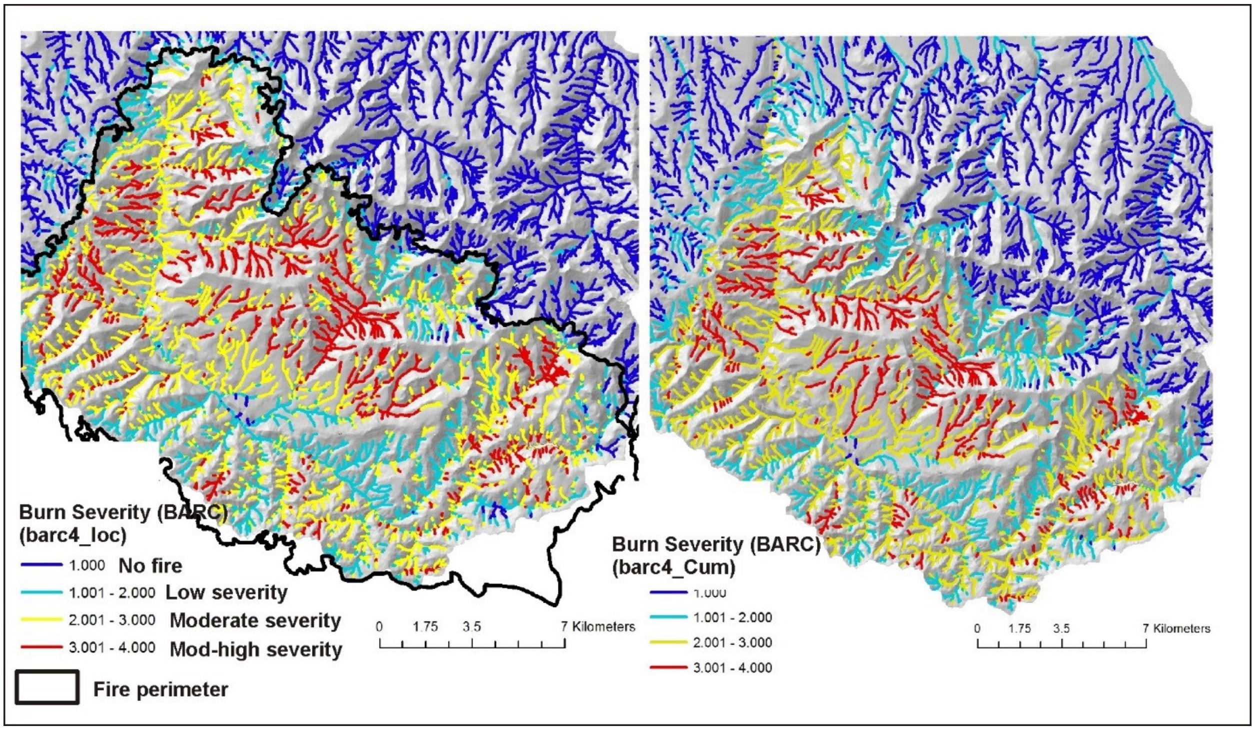


Figure 45. Burn severity can be represented in the WIN-System's synthetic river network.

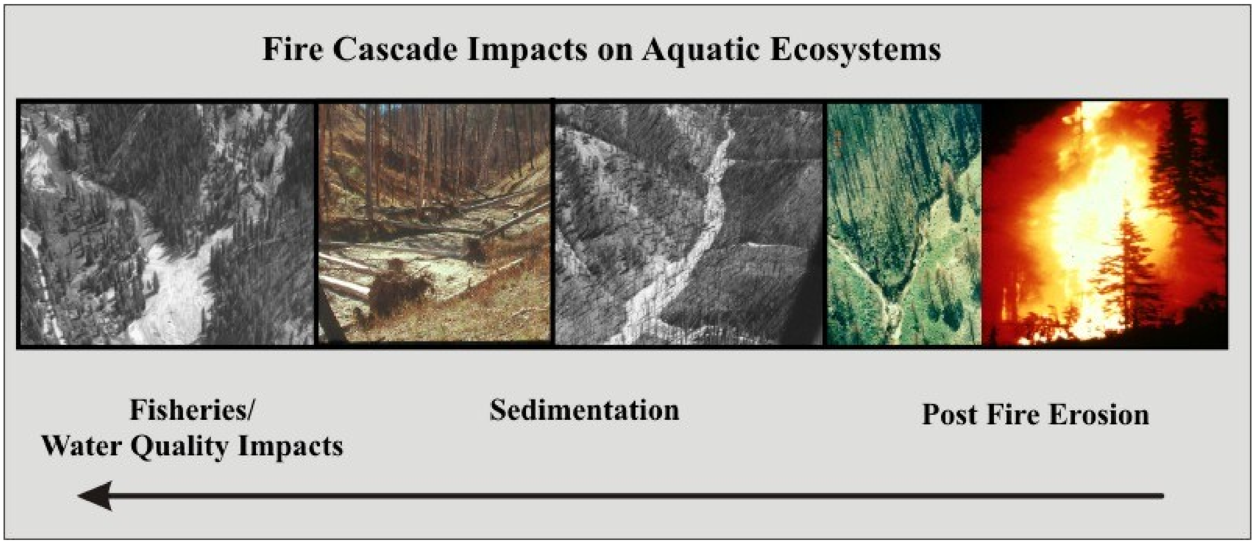


Figure 46. Fire can lead to a cascading set of impacts downstream, via erosion and flooding.

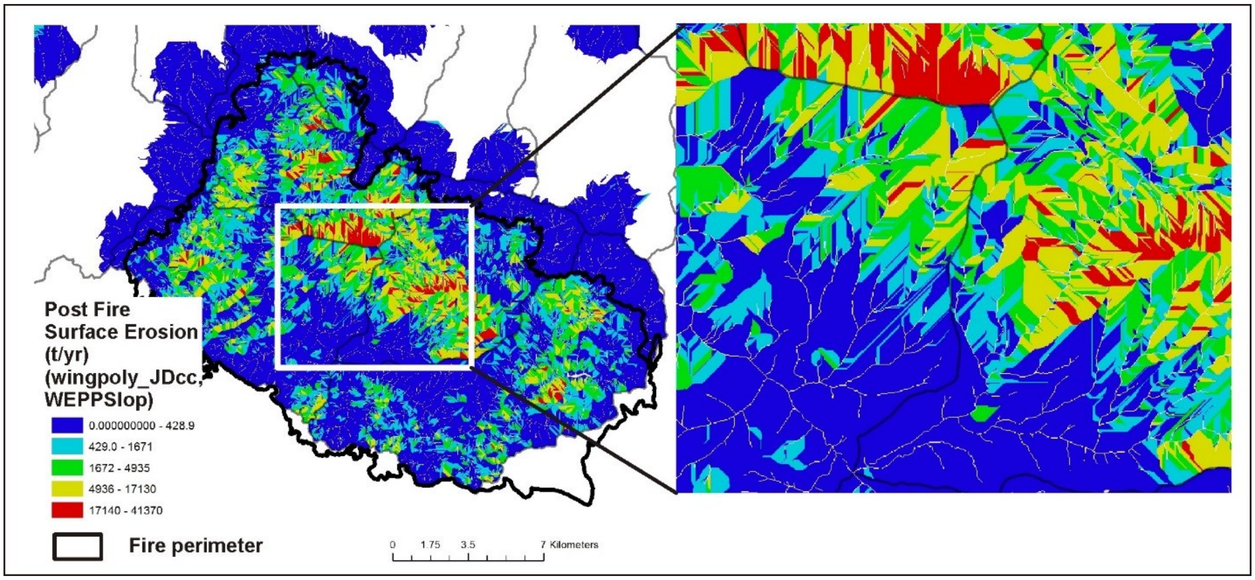


Figure 47. Post fire soil disturbance can lead to accelerated erosion.

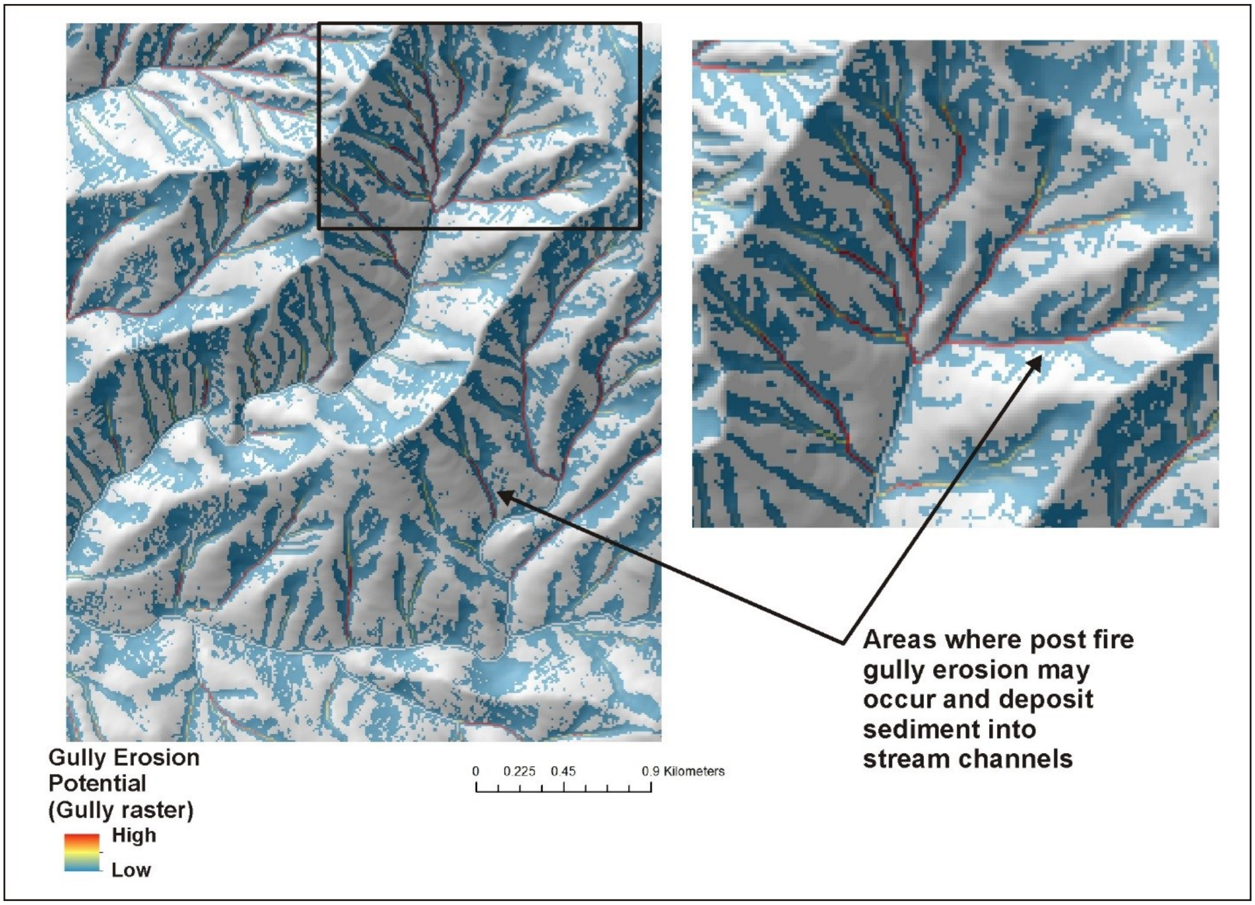
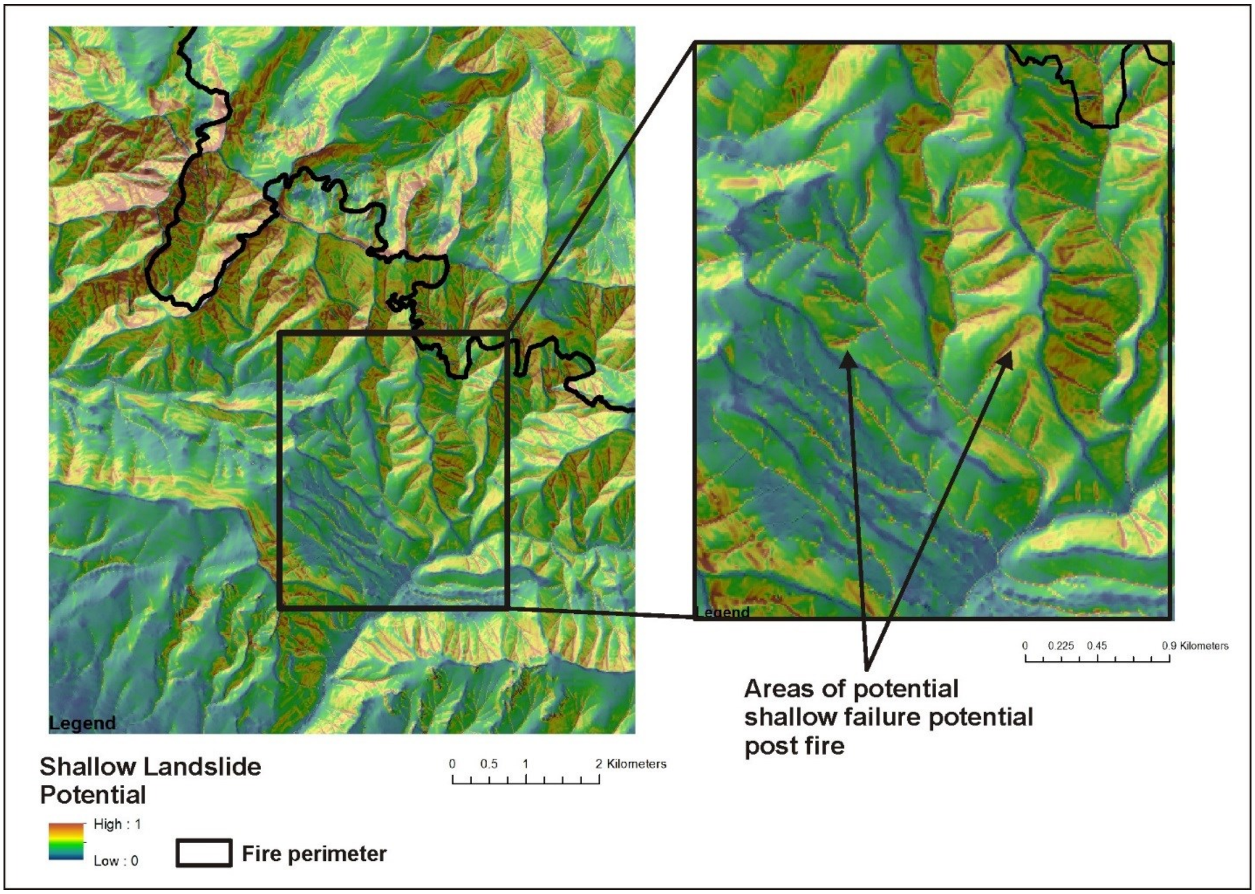
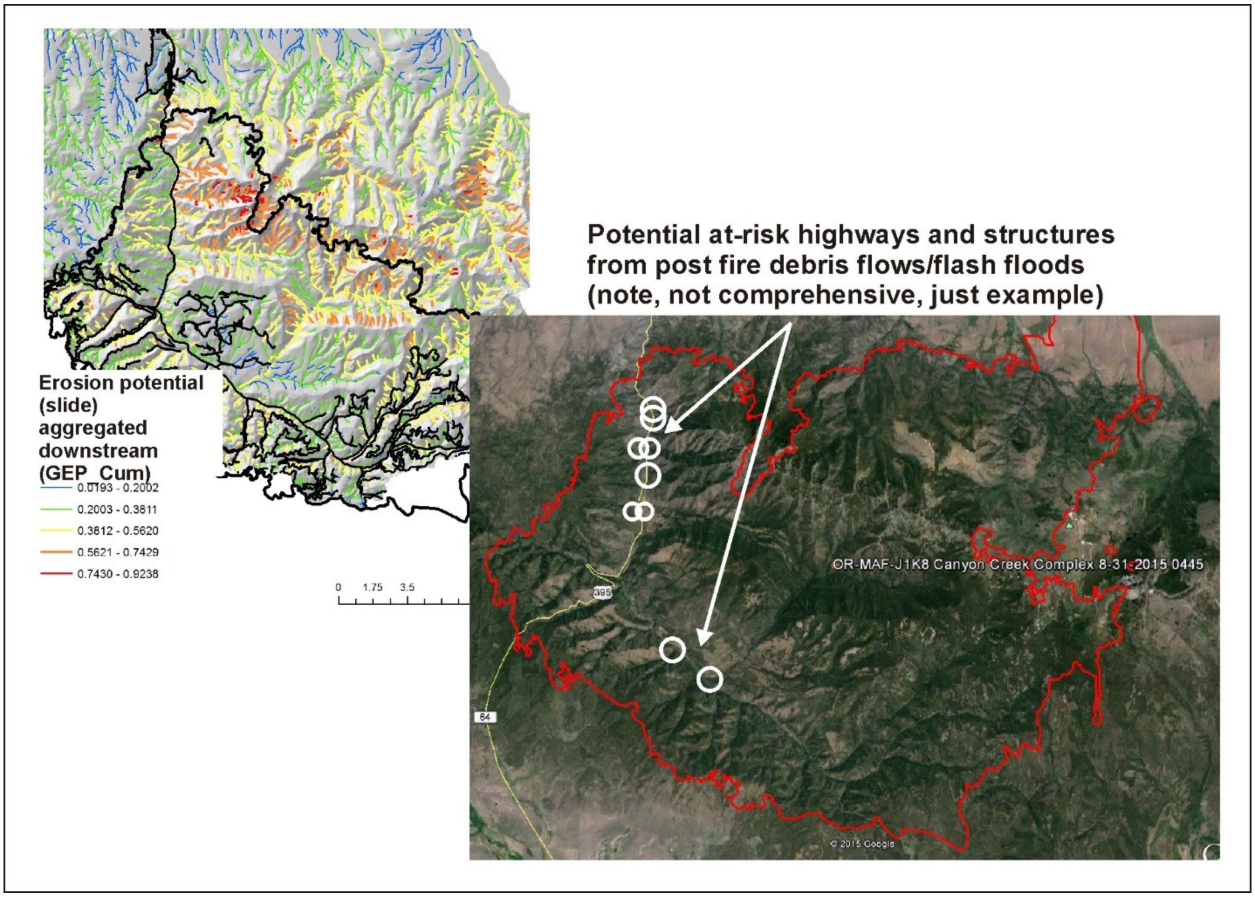


Figure 48. Fire can lead to accelerated gully erosion which can be predicted.



Areas of potential shallow failure potential post fire

Figure 49. Fire can lead to accelerated shallow landsliding.



Potential at-risk highways and structures from post fire debris flows/flash floods (note, not comprehensive, just example)

Figure 50. At risk highways and structures can be identified during a post fire analysis.

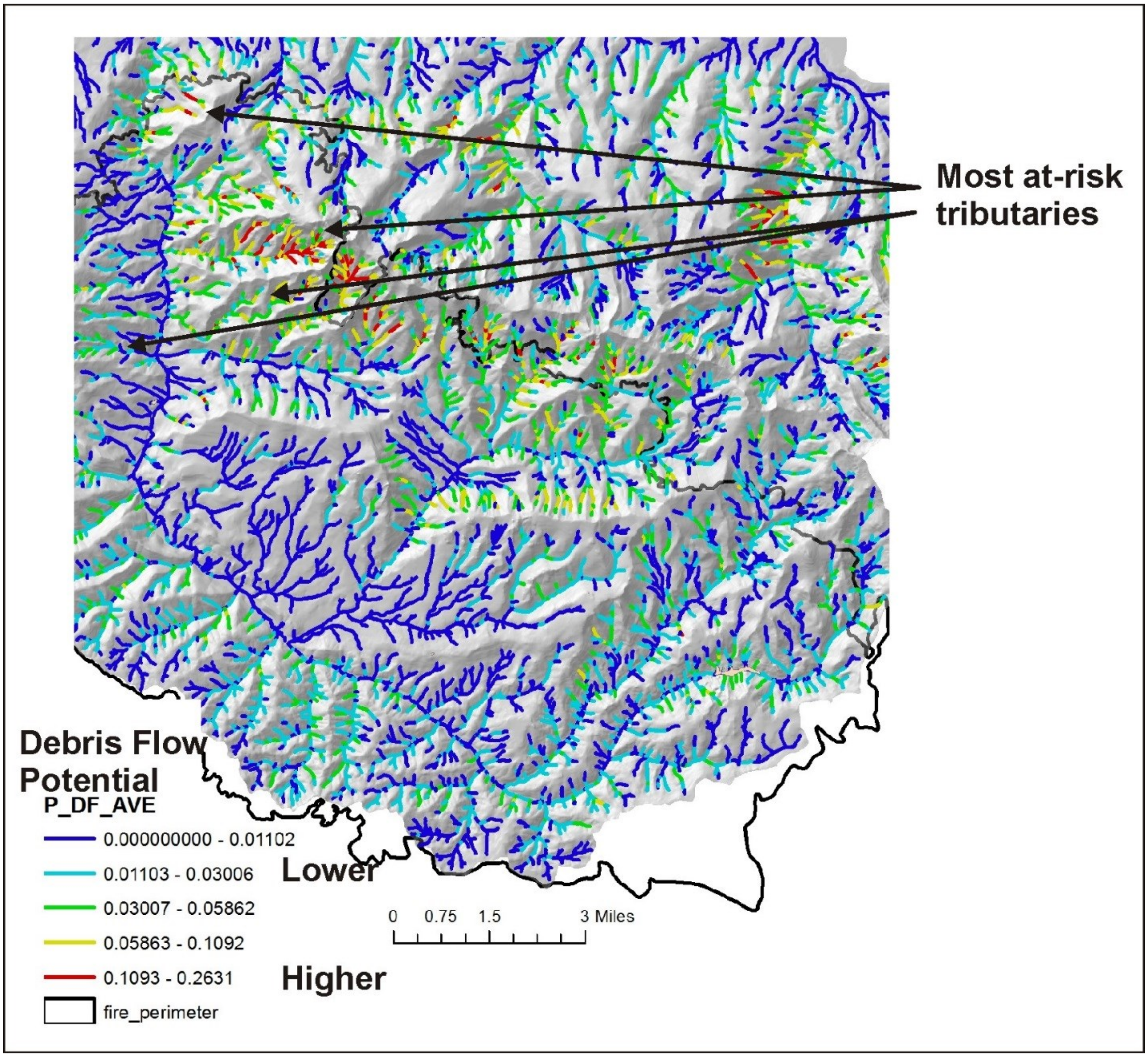


Figure 51. Post fire debris flow risk can also be identified.

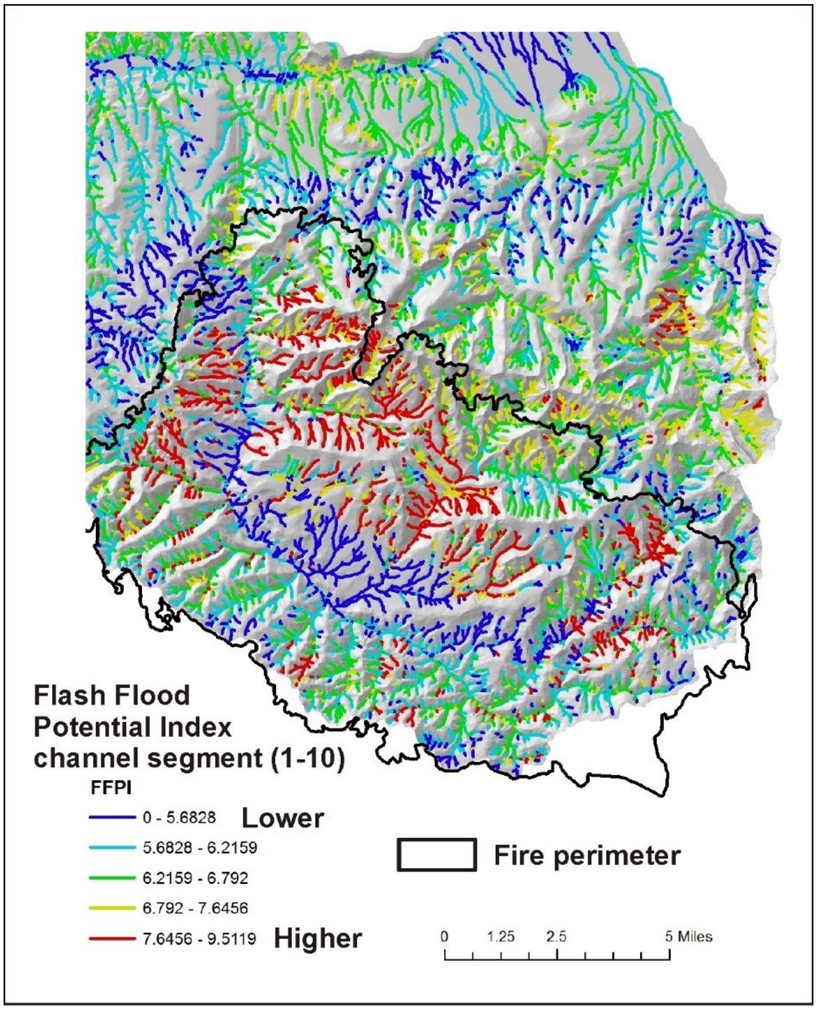


Figure 52. A WIN-System analysis of post wildfire areas can include flash floods.

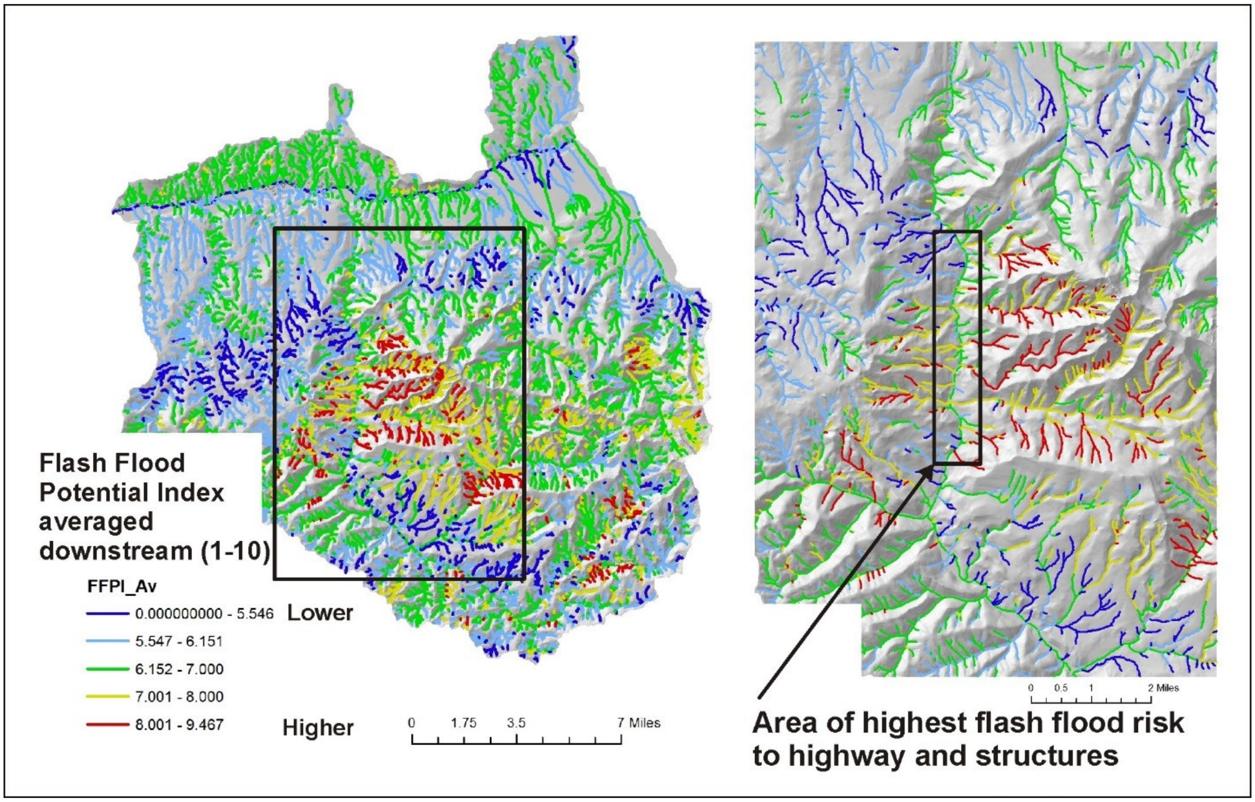


Figure 53. Flash floods present risks to homes and highways, post fire.

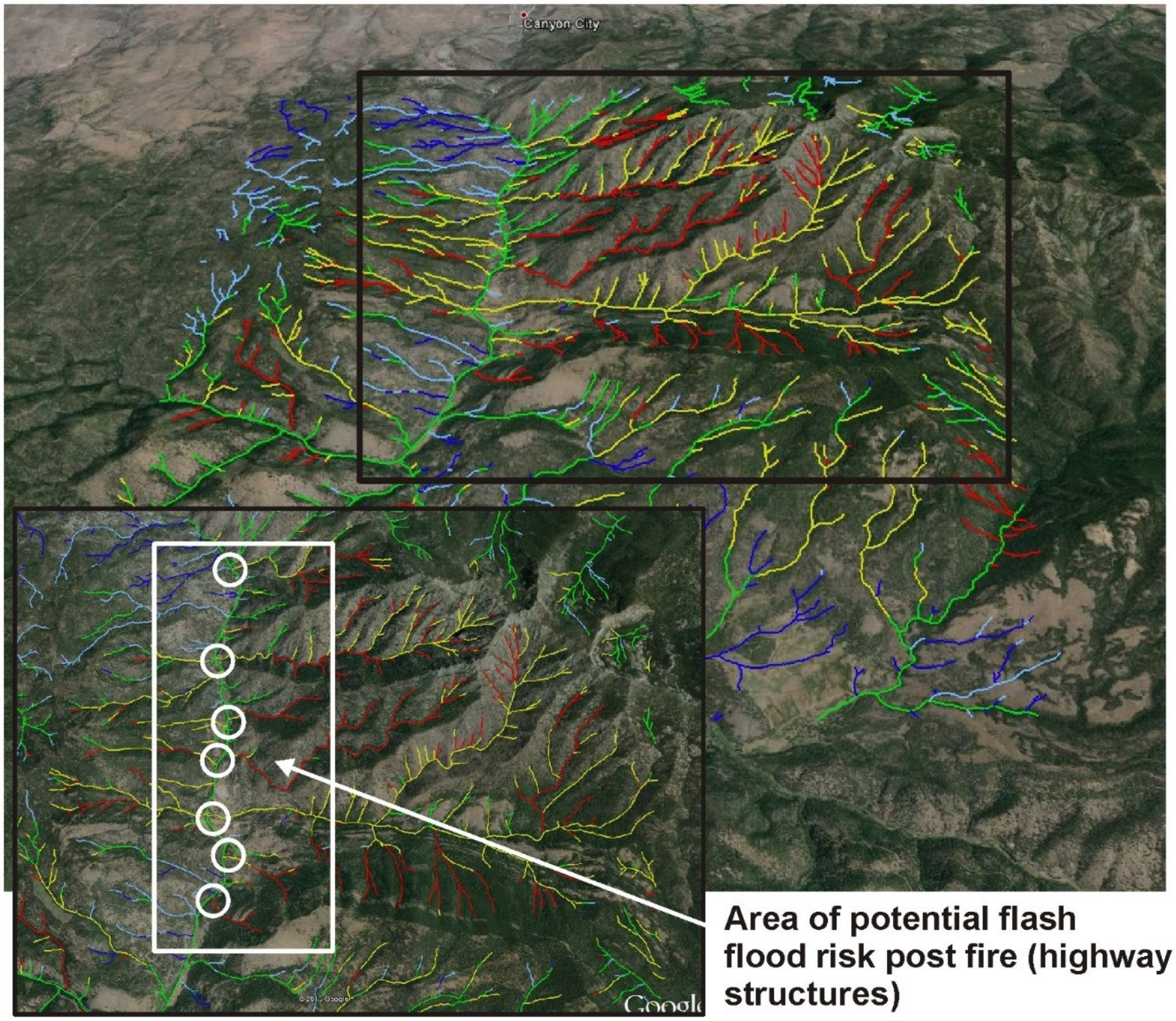


Figure 54. Use of Google Earth helps visual the potential risks and to communicate with the public.

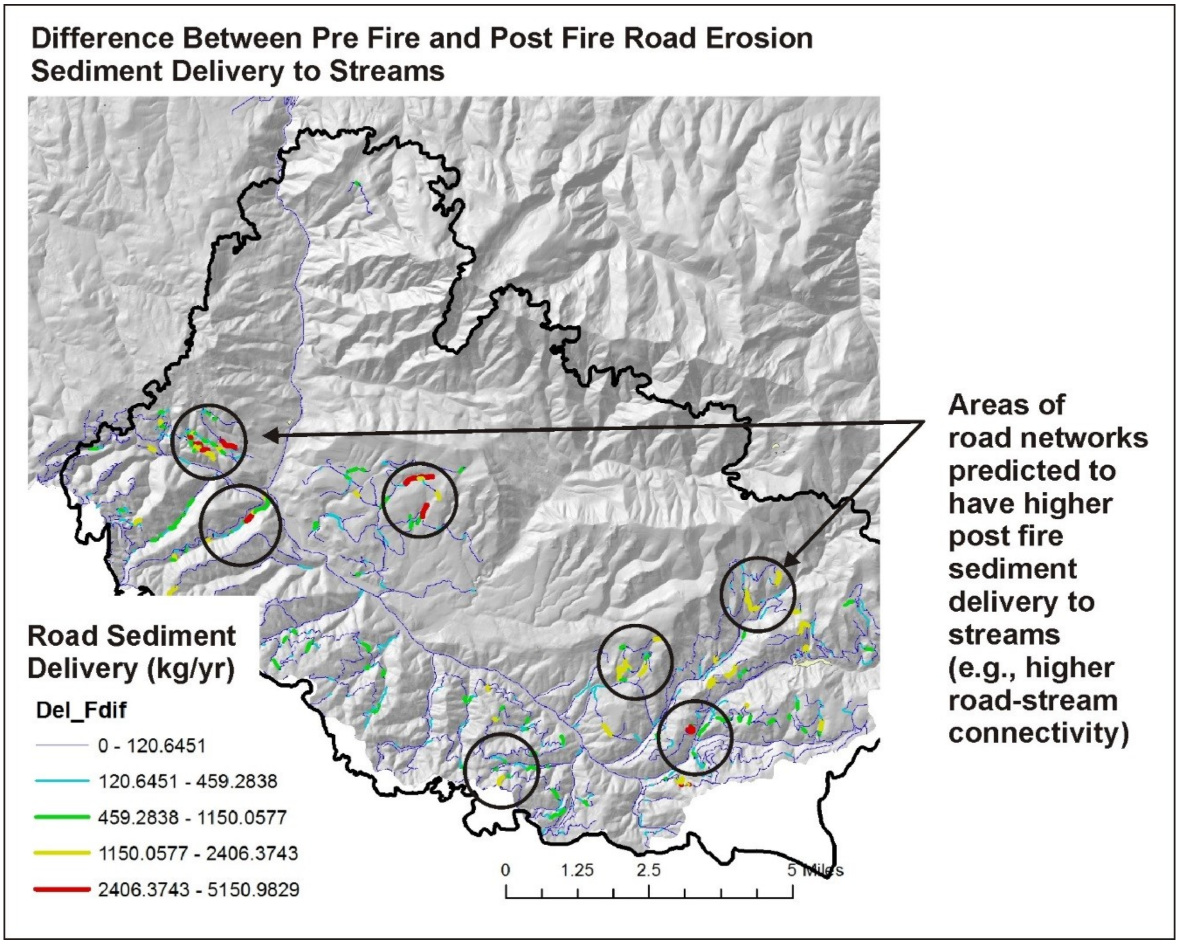


Figure 55. Forest roads can have a higher hydrologic connectivity, predicted by the READI model.

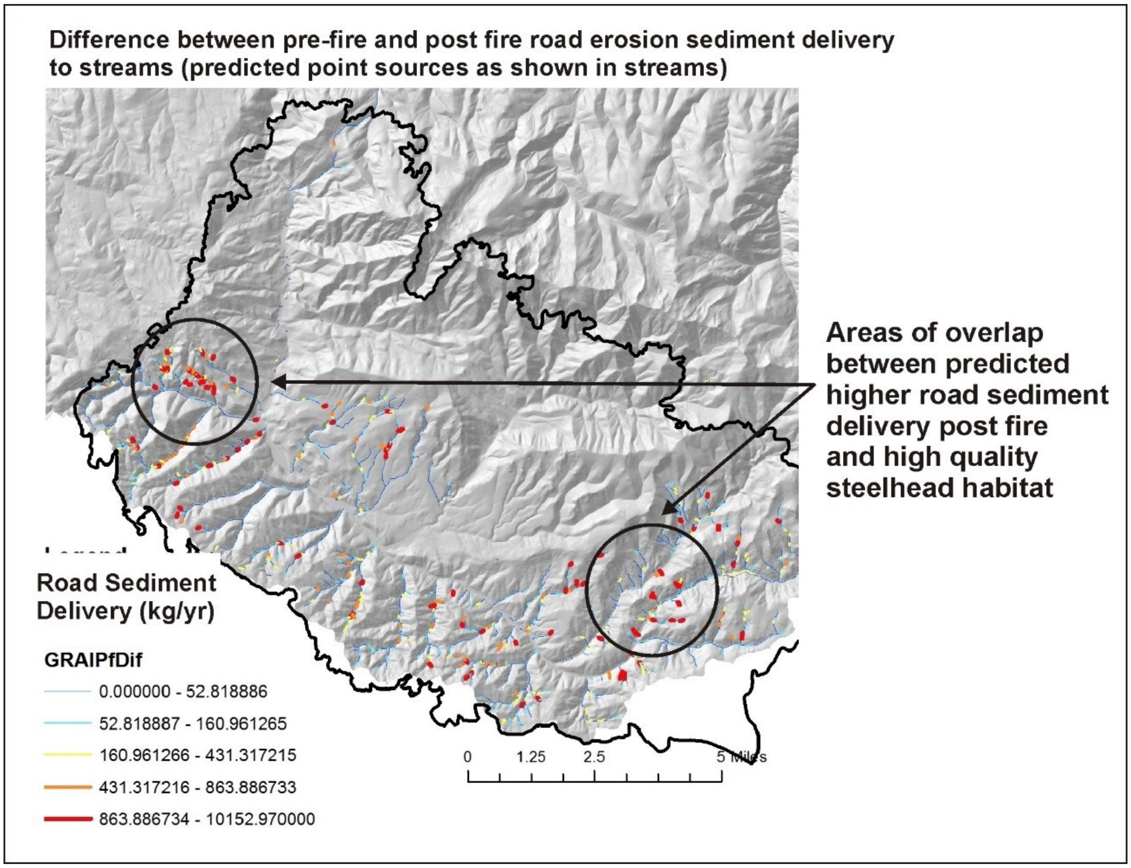


Figure 56. Areas of higher erosion potential can be overlaid on fish habitats.

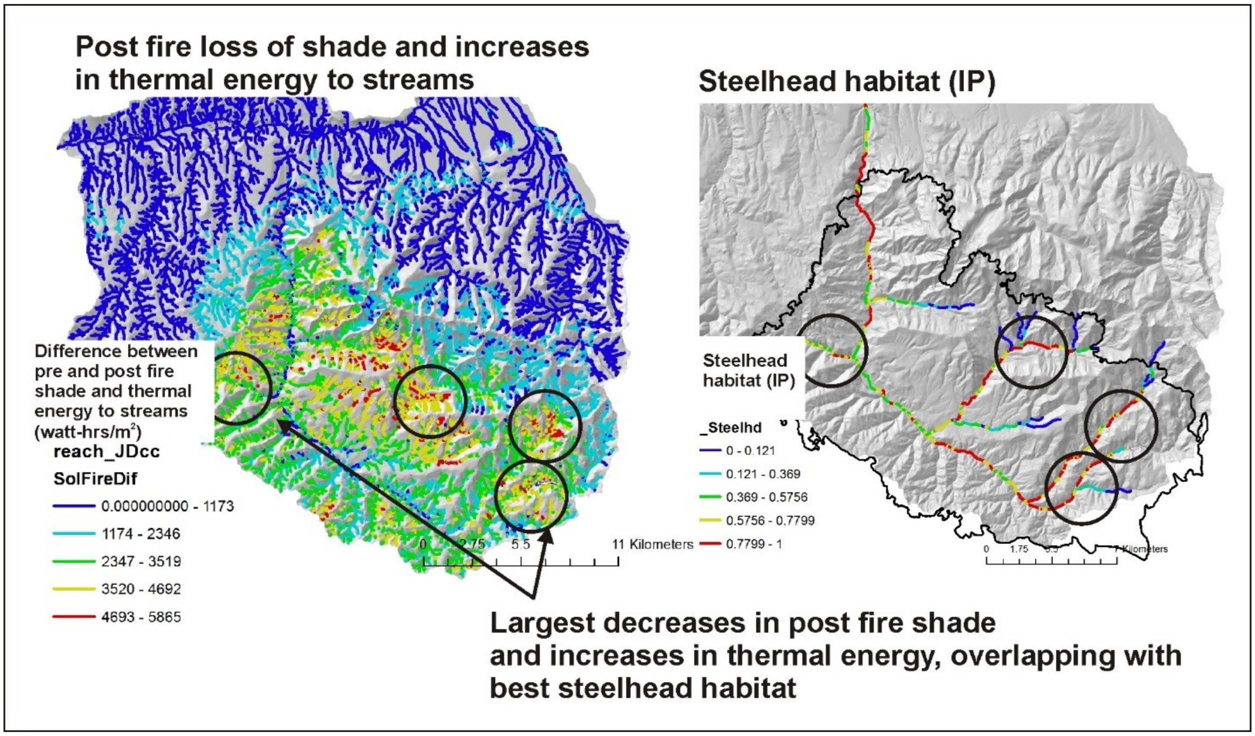


Figure 57. Fires reduce shade and increase stream temperatures; overlay risks on fish habitats.

For additional information on this type of analysis, go here.

Pre-Wildfire Analysis and Planning

To learn more about how the *WIN-System* could be used in pre-wildfire go here.

4.0 Evaluating Cumulative Effects in Alberta using *Win-System*

Users of the *WIN-System* can readily apply three analysis approaches to cumulative watershed effects (Figure 1):

1. Overlapping: Search for one or more natural or land use stressors intersecting valuable and sensitive terrestrial or aquatic habitats at multiple scales in a watershed.
2. Accumulating: Evaluate downstream accumulation of any watershed attribute or land use aggregated along channel networks, revealing patterns at any spatial scale defined by the channel network.

3. Distribution Shifting: Analyze shifts in spatial distributions of terrestrial watershed attributes such as forest ages, road networks, wildfires, beetle-killed trees and other raster and polygon data.

More specifically, the *WIN-System* contains multiple analytical capabilities to address CWEs, and more generally resource management, in Alberta. *WIN-System* unique capabilities include:

1. Information on landforms, physical and biological processes, and land-use activities are linked directly to the specific parts of the channel network that they can influence. This is accomplished by the strategic use of flow direction and accumulation rasters, and discreet stream segment scale local contributing areas referred to as "drainage wings" and subbasin polygons.
2. Terrestrial information linked by flow paths to stream channels can be aggregated up and downstream, revealing spatial patterns of any watershed landform, streamform, process, disturbance or land-use activity at any spatial scale defined by the channel network. Data outputs include rasters, points, arcs, or polygons.
3. Watershed information (aquatic and terrestrial) is captured in frequency distributions and can be ranked at the scale of channel segments (approximately 100 m length scale), drainage wings, and subbasin polygons. Sorting and ranking can be used to examine aggregate patterns of any watershed feature or landform at the scale of entire management areas.
4. Within the *WIN-System*, frequency or cumulative distributions of any watershed attribute (landforms, processes, land uses) are used within the habitat-stressor overlap tool to search for locations (in the river network) where selected combinations of watershed and land use attributes overlap. The tool currently supports five levels of overlapping attributes. One can find, for example, where the highest 5% of road surface erosion intersects the highest 10% of fish habitat quality, or where the highest 10% of forest mortality due to beetles overlaps the highest 10% of thermally sensitive stream reaches, and where does that combination overlap with the highest 10% of fish habitat potential.
5. Habitat-stressor analyses can also be applied at the scale of subbasins, using another *WIN-System* tool. An example of how this would potentially work in Alberta can be viewed using TerrainWorks online TerrainViewer tool.

6. Intersections between watershed processes and land uses can also be viewed longitudinally along variable lengths of the channel network using the profiling tool. Any number of watershed and land use attributes can be selected and overlaid revealing along channel patterns of land uses and watershed processes.
7. Cumulative effects often have a temporal component, including the history and time series of land use changes and natural disturbances in a watershed. The numerical structure of the *WIN-System* can support routing and mixing of materials downstream (such as flow, nutrients, sediment, wood, pollutants), with a stochastic time element. See numerical simulations that used this data structure in the form of simulation videos .
8. New analysis capabilities can be added to the *WIN-System* by TerrainWorks or by Alberta Province and others.

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