Road Cumulative Effects Analysis in the Simonette River Watershed, Alberta

For University of Alberta and Canfor

Dr. Lee Benda, Kevin Andras and Daniel Miller
TerrainWorks (NetMap) www.terrainworks.com; Mt Shasta, California USA

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Executive Summary:

A cumulative watershed effects analysis of unpaved roads in the Simonette River watershed in north central Alberta was conducted for the University of Alberta and Canfor. Two advanced technologies, Alberta's Wet Areas Mapping (WAM) and NetMap's virtual watershed coupled to tools, were integrated and used in the analysis. To accomplish the integration, the WAM D8-flow direction and flow accumulation grids, and its synthetic stream layer, were integrated with NetMap's node-based stream delineation technology to create a river network wide, seamless, attributed and routed synthetic stream layer, and virtual watershed, using Alberta's one meter LiDAR DEM. 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. The streamlines geo-referenced to the DEM to support the road analysis, specifically road erosion and sediment delivery to streams.

The Road Erosion and Delivery Index (READI) within NetMap was used to predict forest road sediment production and delivery to streams as a dimensionless index because local controls on erosion potential are unknown and sediment yield data were not available. However, READI can be calibrated using local data on sediment production to predict sediment yields (kg yr^{-1}) at the scale of individual road segments or for populations of road segments at the basin scale. The delivery index utilizes a design storm duration and intensity to predict road runoff and sediment delivery (plumes). Lengths of sediment plumes with a given geometry are controlled by differences between road runoff (rainfall intensity over road segment area) and loss of runoff into the forest floor via infiltration; the predicted length of sediment plumes can be calibrated using local data on sediment plumes, if available. The model includes runoff (with sediment) directly to streams at road-stream intersections and indirectly to streams via sediment plumes across the forest floor.

READI was also used to identify optimal locations for adding new drains (water bars, rolling dips etc.) to hydrologically disconnect roads from streams. In addition, the model also predicts where road segments would benefit most (e.g., reduce sediment delivery to streams) by improving road surface conditions designed to lower erosion rates (e.g., rock surfacing, seeding cutbanks etc.). In addition, READI can be used to help design new roads; once the approximate location of a new road is defined, READI can be used to determine the most effective locations for culverts and other drainage structures.

NetMap tools contain two other road erosion models. The U.S. Forest Service Water Erosion Prediction Project (WEPP) model combines a physics based approach with a stochastic storm generator to predict a time series of sediment yields (Elliot et al. 1999). WEPP requires information on road surface type (native, gravel, paved), soil type (three different loams), cutslope angle, and traffic levels. Average predicted sediment delivery to streams was reported for all streams that delivered sediment. Because of WEPP's design, it cannot be calibrated for local conditions including sediment delivery via plumes. The clients can apply this model in the Simonette River watershed but it requires selecting appropriate parameter values. A second model, GRAIP-Lite, was designed specifically for U.S. Forest Service road networks and has agency specific attributes including road surface type and maintenance level.

1.0 Introduction

Forest roads can be an important component of cumulative watershed effects in Alberta. Erosion on and along unpaved roads, often in forested settings, continues to be a source of sediment to streams and rivers and has the potential to impact water quality and aquatic biota across North America (Goode et al. 2012). Road sediment delivery to streams may be the dominant source of land use related sediment pollution in forested landscapes (Ketcheson and Megahan 1996). Road erosion and sediment delivery are a continuing concern considering that road density (km km^{-2}) may approach and even exceed stream network density in certain landscapes, particularly in those with intensive forest management or oil and gas development (Luce and Wemple 2001, Buto et al. 2010, TerrainWorks 2016).

The recognition of roads as a continuing source of sediment pollution (but also nutrient pollution, Gucinski et al. 2001) has led some areas in North America to impose tougher regulations designed to hydrologically disconnect forest roads from streams, including in Washington State (WFPB 2001) and in California (CSBF 2014). BMPs designed to reduce road erosion and sediment delivery imposed by resource management agencies include paving, converting native surfaces to gravel surfaces, adding drainage structures, and other erosion control methods such as vegetation seeding and construction of sediment catch basins (Dube´ et al. 2004, U.S.F.S. 2012).

An increasing area of concern in North America is how high road densities in forested settings can exacerbate altered runoff following wildfires caused by hydrophobic soils and lowered infiltration capacities (MacDonald and Hoffman 2004). Decreased infiltration can lead to higher hydrologic connectivity between roads and streams by increasing runoff from roads. Increased surface runoff following fires can also be concentrated by roads and their ditches leading to heightened gully erosion. Thus, roads are often targeted for certain types of remediation following fires, including abandonment, removal of drainage structures (culverts), upgrades of road–stream crossing structures (culverts and bridges), and placement of additional drainages to lessen road concentration of runoff (McIver et al. 2000).

Road surface erosion and sediment delivery models are designed to provide resource managers and planners with information on the potential magnitude of the problem and where to focus remediation efforts. For example, the U.S. Forest Service Water Erosion Prediction Project (WEPP) model combines a physics based approach originally developed for croplands (Flanagan and Nearing 1995), but extended to unpaved forest roads with a stochastic storm generator to predict a time series of sediment yields

(Elliot et al. 1999). WEPP requires information on road surface type (native, gravel, paved), soil type (three different loams), cutslope angle, and traffic levels. WEPP is designed primarily for application on a project level scale rather than at the scale of entire watersheds or landscapes and it cannot be calibrated using local field data on sediment production or sediment delivery. The model 'GRAIP-Lite' offers a GIS version of predicted road sediment production and delivery (Nelson et al. 2014) that is derived from a field intensive version of the analysis that requires road segment scale surveys of road geometry, drains, erosion characteristics and the collection of sediment yields (Black et al. 2012). GRAIP-Lite was developed specifically for roads in the U.S National Forest system and it requires agency specific road attributes involving surfacing and maintenance level. Washington State's 'SEDMODL' (Dube´ et al. 2004) uses empirically derived estimates of sediment yield and couples that to a single threshold of road distance to stream to predict sediment delivery. Thus, SEDMODL is geographically specific, targeting Washington State's state and private forest lands. For a more comprehensive review of road erosion and sediment delivery models, see Fu et al. (2010).

In the Simonette River watershed the Road Erosion and Delivery Index (READI) model was applied that included abilities for: (1) generating a dimensionless index of road sediment production and delivery where local controls on erosion potential are unknown or where sediment yield predictions are not required or reliable; (2) calibrating the index using local data on sediment production (if available) at the scale of individual road segments or watersheds to predict sediment yields (kg yr^{-1}) and increase prediction accuracy; (3) utilizing geo-referenced locations of natural and engineered drainage structures to increase prediction accuracy; (4) linking sediment delivery to road segment area and design storm intensity and duration to provide the basis for calculating road to stream connectivity and road to stream disconnections that are sensitive to storm recurrence intervals; (5) utilizing local data on sediment delivery characteristics, specifically sediment plume lengths below roads, to increase prediction accuracy; (6) predicting where additional road drains can be strategically placed to further disconnect road segments from streams, and where road maintenance and upgrades can reduce sediment delivery; (7) predicting, in post wildfire environments, where decreased infiltration can lead to increased road to stream connectivity, thus informing post fire mitigation; and (8) making predictions for populations of road segments, including aggregating at the watershed scale, to prioritize remediation in watersheds and landscapes or by land ownership or management jurisdictions.

2.0 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 (TerrainWorks 2016). 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, and virtual watershed, in conjunction with Alberta's one meter LiDAR DEM. This required using 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 1**). This hybrid dataset is referred to as the WAM Integrated NetMap system or WIN-System and it has been proposed as the numerical platform to assess cumulative watershed effects (CWE) in Alberta and provide decision support to resource planners, managers and researchers (TerrainWorks 2016).

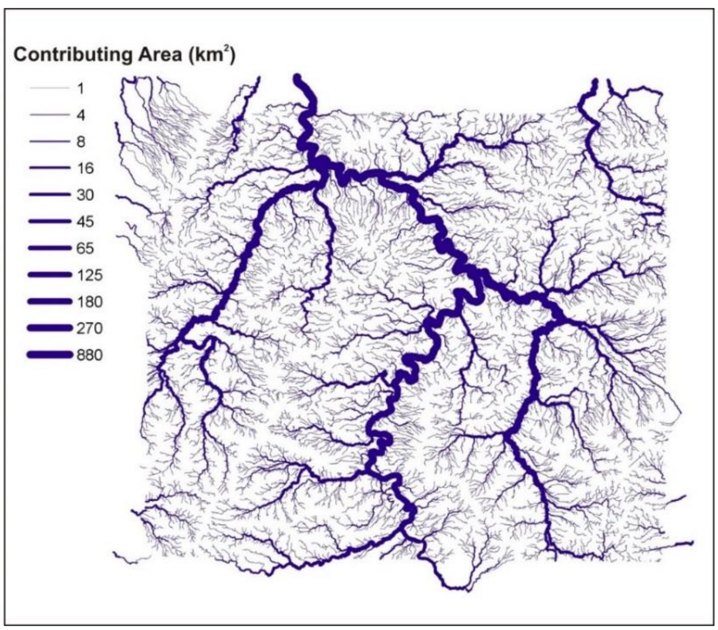

Figure 1. A complete and routed synthetic river network is built using WAM and NetMap.

The Simonette synthetic river network is comprised of a node based data structure, delineated at the scale of the 1 m LiDAR (**Figure 2**). From the nodes, individual channel reaches are created at a length scale that ranges between 100 and 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.

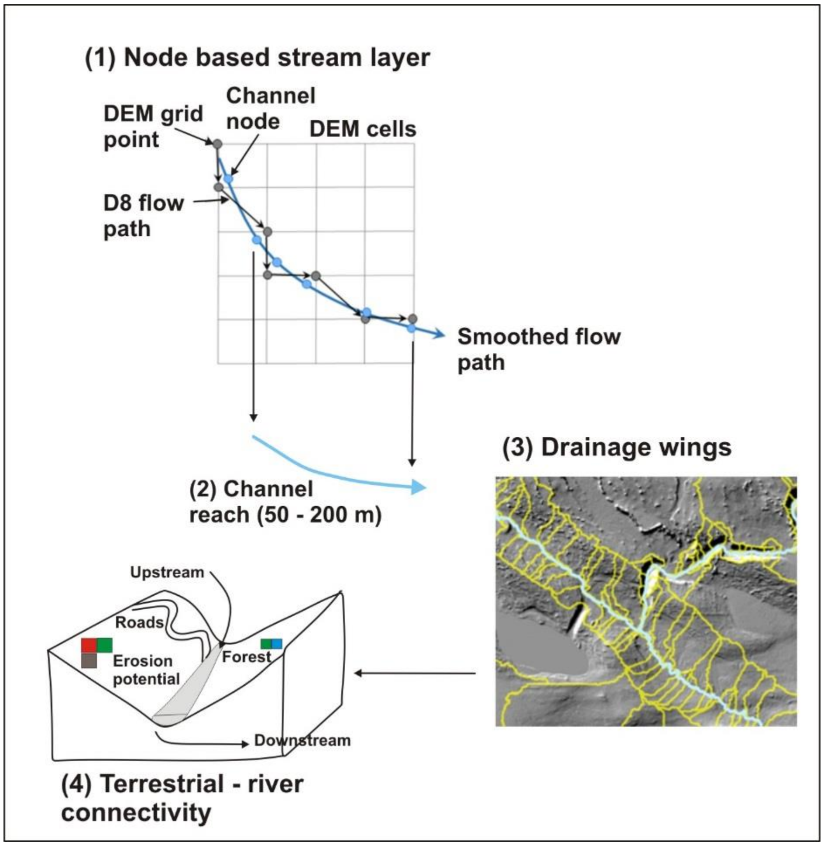

Figure 2. NetMap's node based synthetic river network and associated drainage wings.

3.0 Study Area

The study area is the Simonette River basin (5,220 km^2), a tributary of the Peace River in north-central Alberta (**Figure 3**).

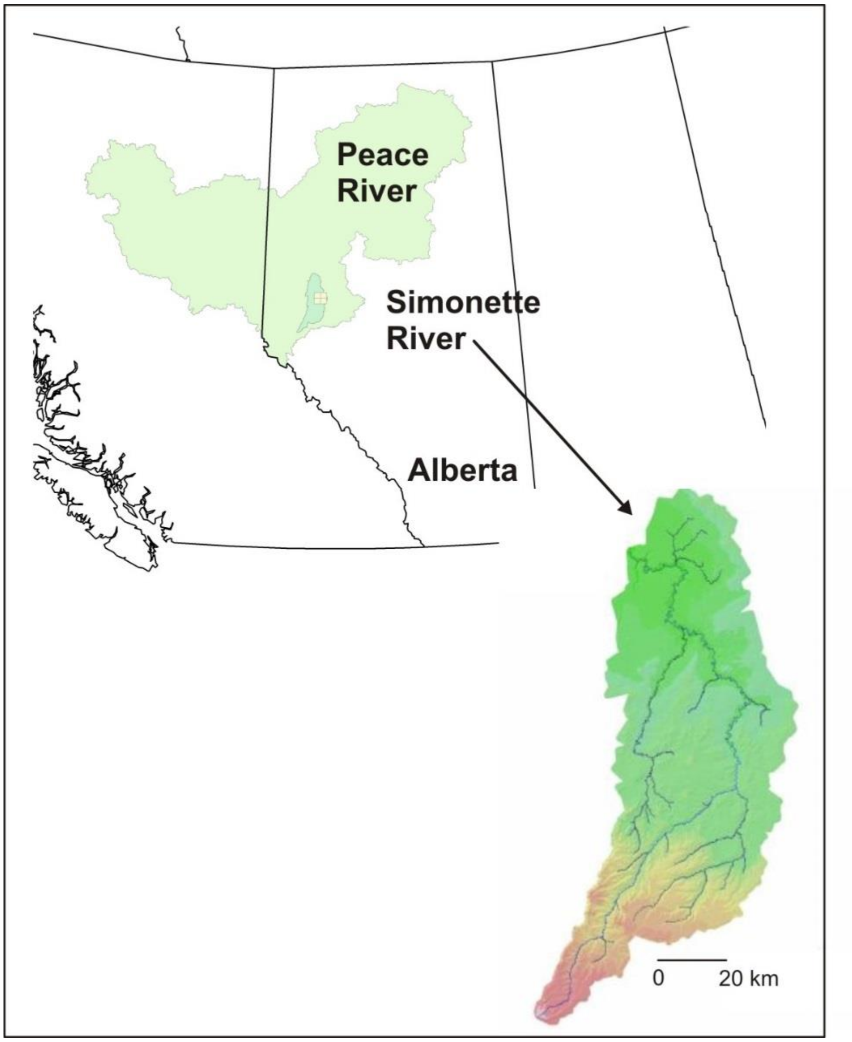

Figure 3. The Simonette River watershed project area.

The Simonette River pilot study area is located primarily within the Lower and Middle Boreal Cordilleran ecoregions that includes the transition between the deciduous to conifer cordilleran boreal vegetation. Common tree species include lodgepole pine (*Pinus contorta*) on well drained soils with trembling aspen (*Populus tremuloides*), balsam poplar (*Populus balsamifera*), paper birch (*Betula papyrifera*), white spruce (*Picea glauca*), black spruce (*Picea mariana*), and balsam fir (*Abies balsamea*) occurring on more well drained sites. Black spruce, white spruce and lodgepole pine often occur in more poorly drained landforms.

The surface geology and geomorphology in the study area has been heavily influenced by Laurentide and Cordilleran ice sheets, including their recession approximately 10,000 years ago (Steedman et al.

2003). Surficial materials are dominated by deposits of tills and glacial outwash sediments. The Simonette River originates in the foothills of the Rocky Mountains of west central Alberta and flows out across the gentle topography of the boreal lowlands. Consequently, the lower river networks are interdigitated with numerous lakes, bogs, wetlands and wet areas, with ground water tables often close to the surface because of low permeability glacial sediments.

Annual precipitation over most of the Simonette River basin is about 460 cm with most occurring as summer rainfall. Highest flows in the Simonette River basin occur in early summer in association with summer snowmelt. Lowest flows occur in the fall-winter periods.

There are approximately 22 species of fish in the Simonette-Lower Boreal ecosystem (Scrimgeour et al. 2013. Cyprinid minnows are the dominant species (eight species), followed by salmonids (four species) and suckers (three species). Salmonids include Trout-perch (*Percopsis omiscomaycus*), Arctic grayling (*Thymallus arcticu*s), Bull Trout (*Salvelinus confluentus*) and Rainbow trout (*Oncorhynchus mykiss*).

4.0 Methods and Results

Ten WIN-System datasets, or virtual watersheds, were assembled for the CWE analysis in the Simonette River watershed to evaluate the potential impacts of unpaved forest roads (**Figure 4**).

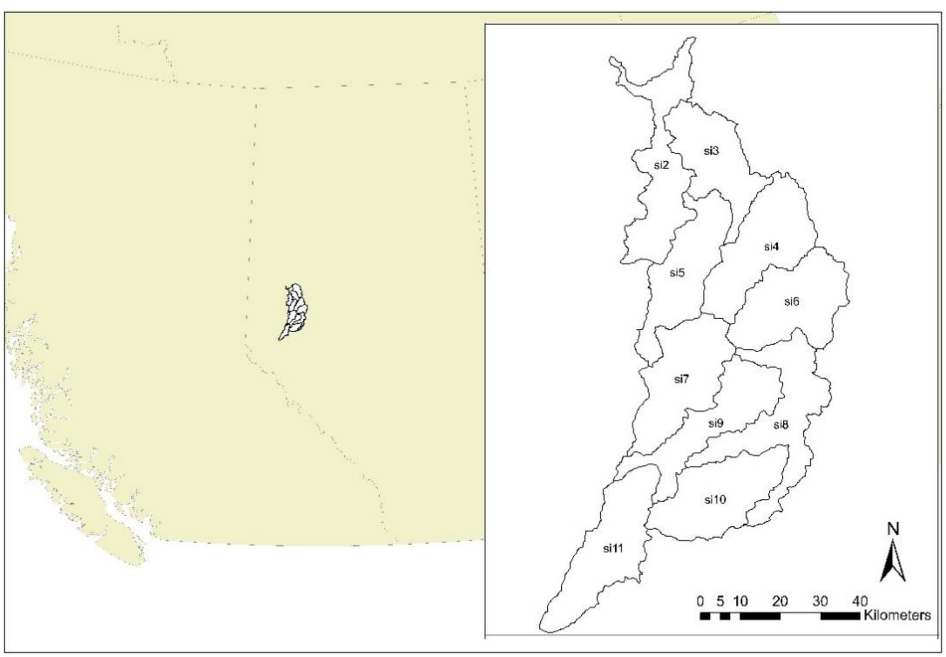

Figure 4. Ten NetMap datasets were built in the Simonette River watershed.

4.1 Channel Network and Floodplains

The synthetic channel network in the Simonette River watershed used hydraulic geometry relationships (regressions) from the Alberta Rocky Mountain Foothills (Hinton area) (Table 1) but WIN-System contains tools for recalculating bankfull channel depth, width and flow using new regressions.

Table 1. Hydraulic geometry relationships used in the Simonette River Watershed road CWE analysis. Regressions are derived from Alberta Rocky Mountain Foothills (Hinton area).

Hydraulic Geometry and Flow	Expression	Coefficients
Bankfull flow (m^3s^{-1})	= a* (drainage area^b)* (Precip^c)	a=0.0216, b=0.933, c=0
Bankfull width (m)	= a* (drainage area^b)* (Precip^c)	=0.966, b=0.5353, c=0
Bankfull depth (m)	= a* (drainage area^b)* (Precip^c)	a=0.4427, b=0.2866, 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 Simonette River watershed, mean annual precipitation gridded data were obtained from PRISM.

Mean Annual Flow

Mean annual flow is predicted based on the flow regression in Table 1. Analysts can use other statistical relationships to inform this parameter in the WIN-System using this tool.

Floodplain Width/Channel Confinement

Floodplains are an important landscape feature in the Simonette River watershed and one of the road analyses that can be considered (roads within or near floodplains) requires that floodplains be delineated in the WIN-System virtual watershed. There are two types of valley mapping in the Simonette River watershed: (1) valley floor elevations pertaining to terraces, off-channels, ox-bow lakes, and alluvial fans in absolute elevation and (2) floodplains, at varying heights above the channel (**Figure 5**).

To characterize valley-floor surfaces in the WIN-System, 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 (Figure 5). 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.

For floodplain mapping, 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. In general, valley surfaces located approximately two multiples of bankfull depth above the channel are considered the active floodplain and could be flooded approximately once every two years on average (Rosgen 1996). However, floods can inundate areas above the active floodplain at intervals of decades or longer. Thus, the multiple floodplain levels created in the WIN-System can be used to consider flooding potential beyond the lowest, most active floodplain and also to map the potential for channel migration. For additional information on NetMap valley floor mapping tools, see here and here. To learn more about how NetMap's floodplain mapping tool can be applied, see: http://www.hydrol-earth-syst-sci.net/15/2995/2011/ .

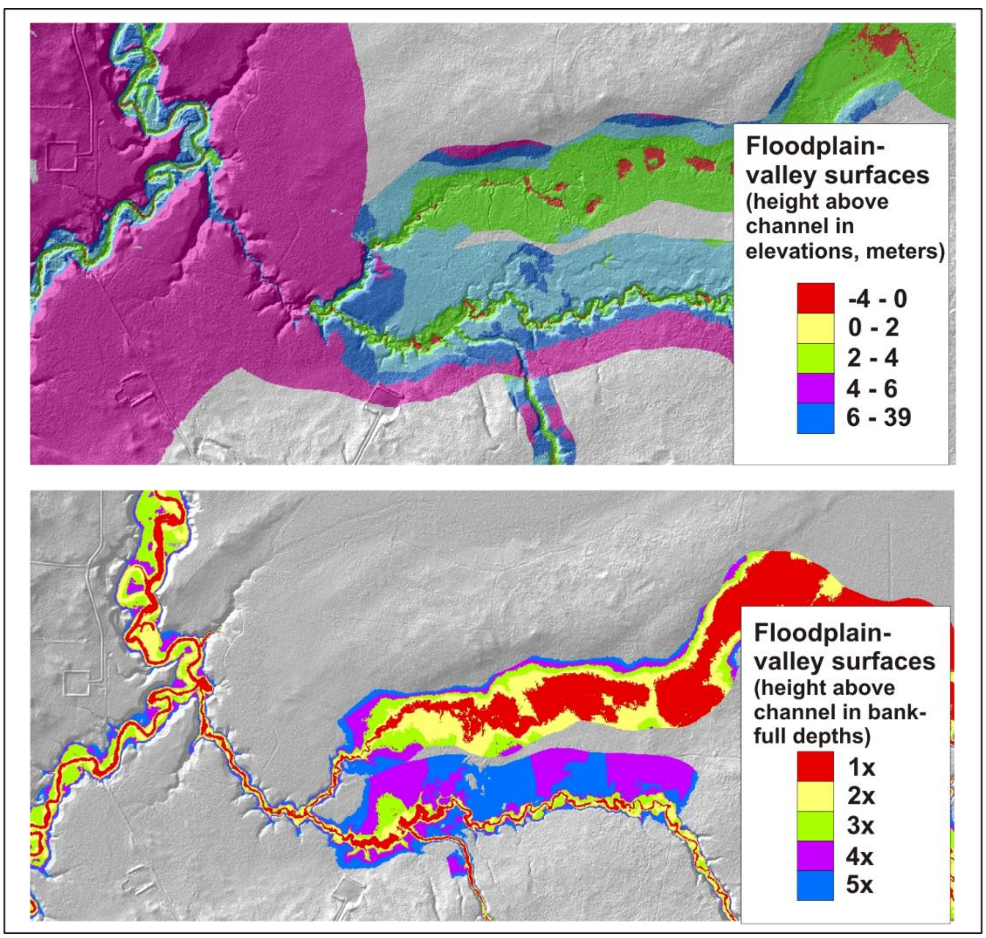

Figure 5. Two different types of valley floor and floodplain mapping in the Simonette River basin.

4.2 Road Analyses

Empirical studies find that water and sediment yields from forest roads are extremely variable, with sediment production highly sensitive to types of road construction and levels of 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 (Buto et al. 2010). Hence, regulatory agencies specify standards for road construction and maintenance, and increasingly require that road networks be hydrologically disconnected from stream channels.

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 road analysis in the Simonette River watershed 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. Application of the Road Erosion and Delivery Index (READI) model in the Simonette River watershed has three objectives in the context of CWE analysis 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 identify optimal locations where additional drains (rolling dips, waterbars etc.) and additional road surface remediation would have the greatest effect in reducing erosion and sediment delivery to streams. Third, to identify the optimal locations of drainage structures and surfacing in the design of new roads that would eliminate or reduce road surface erosion and sediment delivery to streams.

4.2.1 Road Erosion and Delivery Index (READI)

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). Based on this information, NetMap's road analysis tool, the Road Erosion and Delivery Index (READI) model, focuses 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 (Surfleet et al. 2011),
- 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, they are incorporated into

READI for examining road and channel network interactions. Likewise, 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 can be estimated in terms of relative amounts (e.g., dimensionless index), rather than absolute quantities. However, a user can specify an average empirically based sediment yield to inform READI and to make erosion and sediment delivery predictions in terms of mass per unit time (kg yr^{-1}).

READI in the *WIN-System* provides 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. READI 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, READI can operate over entire watersheds (or only a selected subset of road segments). In the WIN-System's virtual watershed, a vector road layer is draped onto a digital elevation model (DEM, **Figure 6**) and roads are divided into discrete hydrologic segments, extending from a high point to a low point along the topographic profile traversed by the road (**Figure 7**). Road segment length and gradient are calculated, and the flow-path to the nearest stream channel is characterized in the virtual watershed. This capability provides the foundation on which to build a template for road-network analyses.

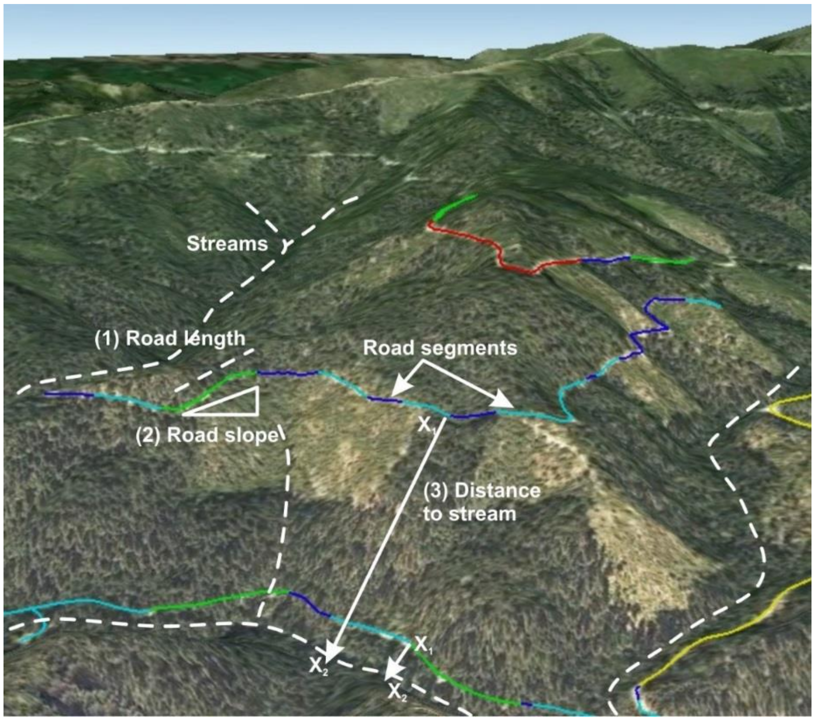

Figure 6. A vector road network is draped onto a DEM.

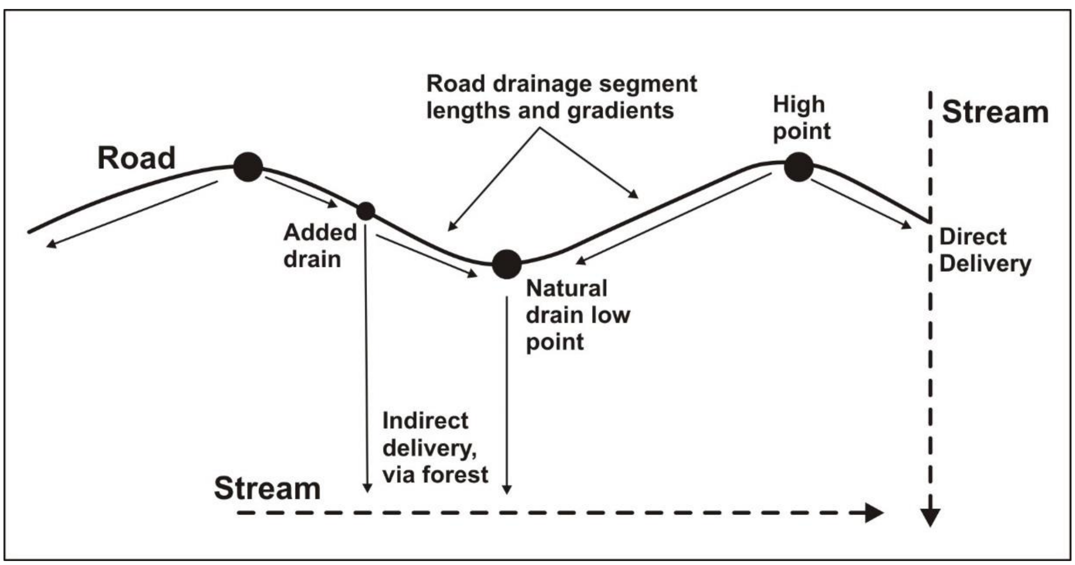

Figure 7. A road layer is broken into hydrologically discreet segments.

READI addresses a subset of the processes by which roads interact with streams including 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 in READI can be implemented using a minimum of input parameters, but with sufficient detail to reproduce the behavior generated by these processes. 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.

Road Runoff in READI

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

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

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 $w_R(1-P_O)$ 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 8**). Infiltration into the road surface and depression storage are assumed not to occur, although these factors could be included in Equation (0.1).

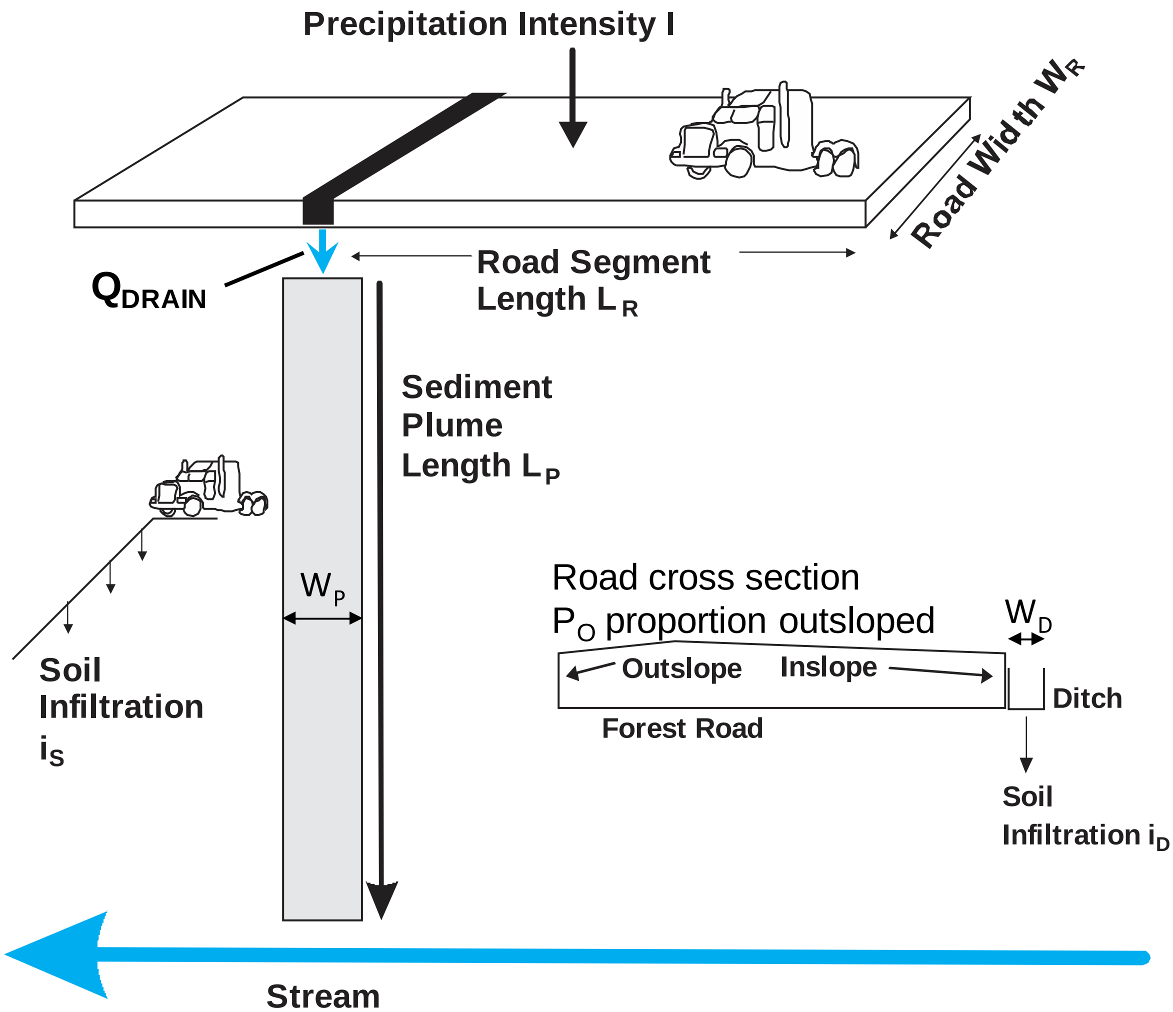

Figure 8. Representation of road segment and sediment plume geometry.

Road geometry can include a ditch of width w_D and infiltration rate i_D. Rainfall onto the ditch and infiltration into the base of the ditch adds 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 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. The average velocity for flow over the road surface and through the ditch is assumed to be equal. 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), associated with, for example, a 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 $L_Pw_Pi_S$ is the amount of water lost to infiltration along the plume and L_Pw_PI is the amount of water added by rainfall per unit time.

From equation (0.6) Q_{min} is he 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 in READI

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 in the model, 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:

$$y_0 = a + bI \qquad (0.10)$$

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}:

$$y = cy_0, t < T_{Pulse} \qquad (0.11)$$

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 in READI

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:

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

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:

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

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. READI 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. READI can be implemented within the Simonette's virtual watershed 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 READI – 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 (Figure 6). 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, the READI framework provides insights. If parameter values for sediment yield or road geometry are not well characterized, constant values can be applied (or dimensionless) 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

READI contains two components used to improve road erosion and sediment delivery conditions in watersheds. The first is used to identify 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. READI's 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. The model will determine, 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, the next new drain will create the largest reduction in delivery, and so on.

This model component 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, the model analyzes each road segment in the road network and searches for locations where new drains will minimize 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, the model assesses 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.

READI moves 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 the model determines the optimal new drain placement for each of these segments, calculates the difference in delivered water or sediment, and places 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.

The second component is designed 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.

Example Application/Results

In the analysis in the Simonette watershed, READI used natural drains and optimized drains; GPS locations of drains were not available and thus it is recommended that the analysis be re-run in the Simonette River watershed when GPS drain locations are available. In addition, data on sediment plume lengths were not available. Thus, READI was run in the Simonette watershed using plume length data available from another area (northern California) as an illustration. The distribution of plume length data is shown in **Figure 9** where the mean plume length is 14 m.

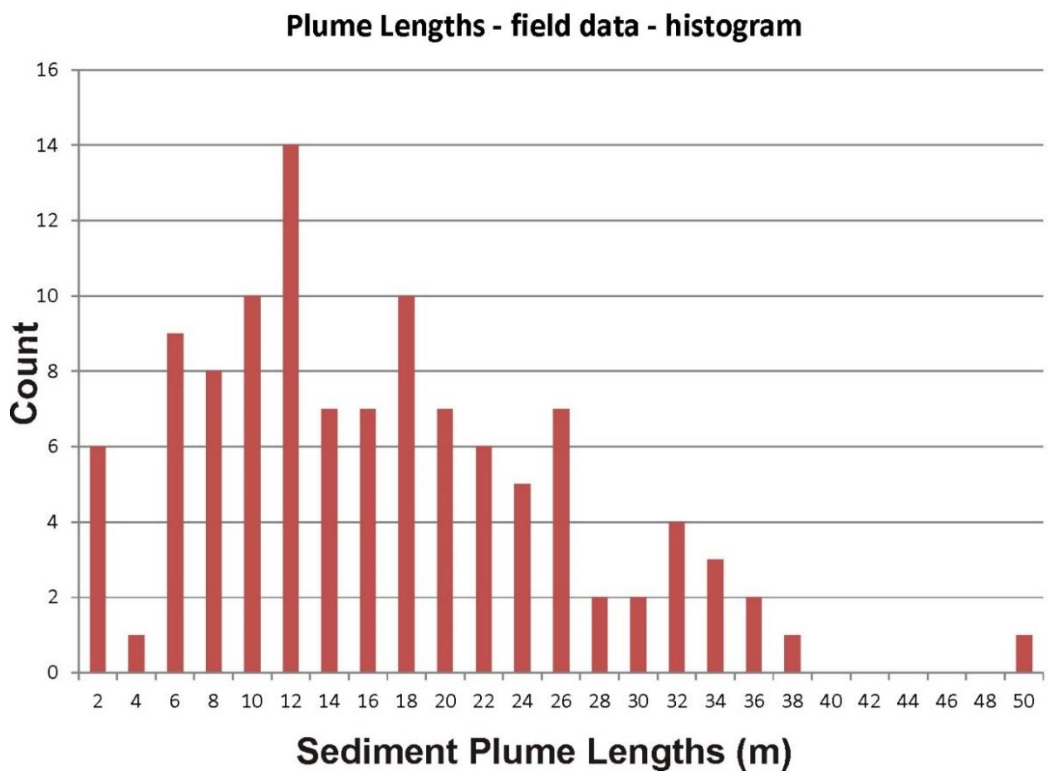

Figure 9. Sediment plume data from northern California.

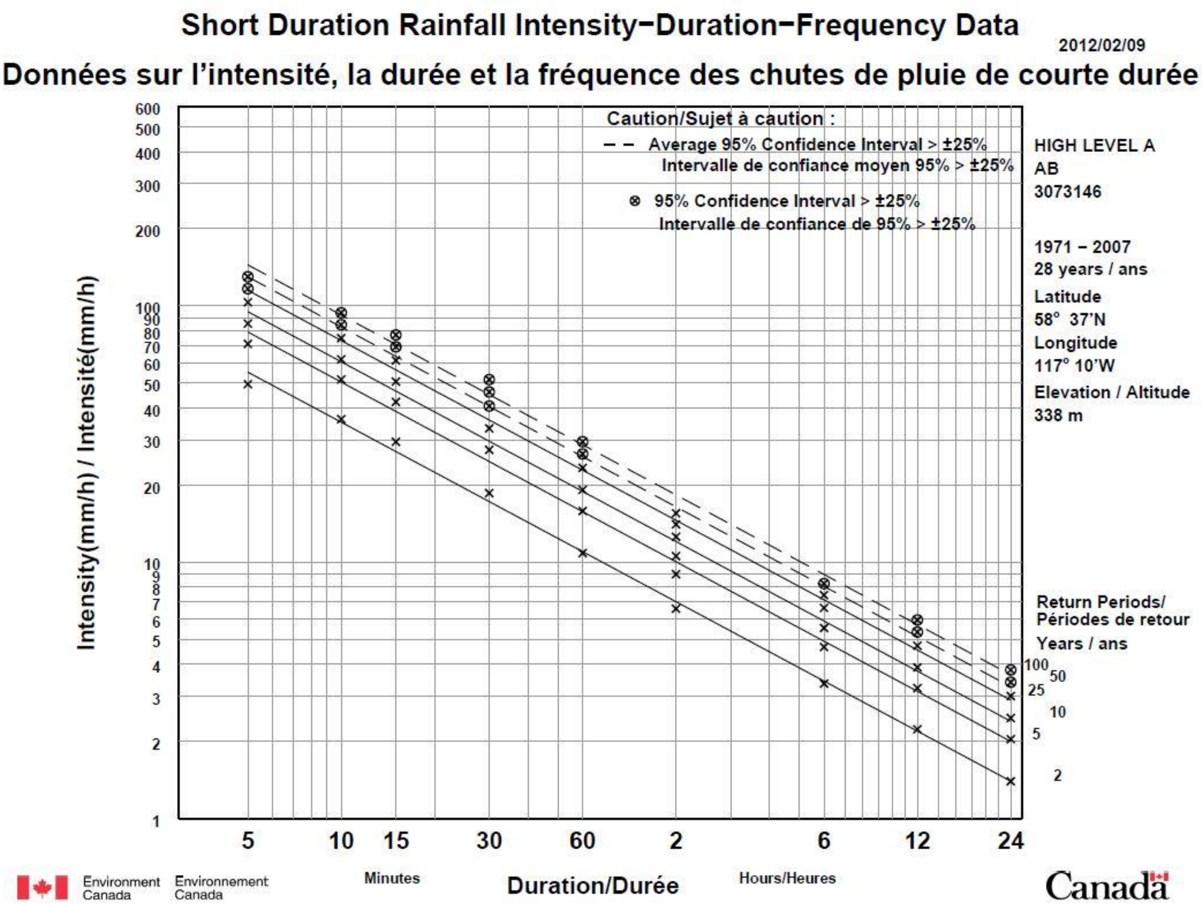

Figure 10. Storm intensity-duration-frequency data used in the Simonette River watershed.

READI model parameters included: 1) minimum road segment length of 300 m, 2) minimum segment relief of 1 m (Figure 7), 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 10**), 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).

Because information on empirical road erosion sediment yields (kg yr^{-1}) was not available, we applied READI as a dimensionless index (e.g., in eq. 0.10, a = 1, b = 0, and c is set to 1 in eq. 0.11).

The roads and current road drains are shown for a portion of the Simonette River watershed (si6 dataset) in **Figure 11**. Predicted (dimensionless) sediment production occurs on most road segments (**Figure 12**) but predicted sediment delivery to streams is only about 35% of sediment production (**Figure**

13, Table 2). In READI outputs, predicted sediment delivery can be represented at modeled drain points including road – stream crossings and via sediment plumes through the forest floor into streams (**Figure 14**). The largest predicted drain sediment delivery values are at road – stream crossings, where the delivery ratio (sediment delivered divided by sediment production) is 100%. Sediment delivery at non road to stream crossings, via sediment plumes across the forest floor, will always be < 100% and often << 100%.

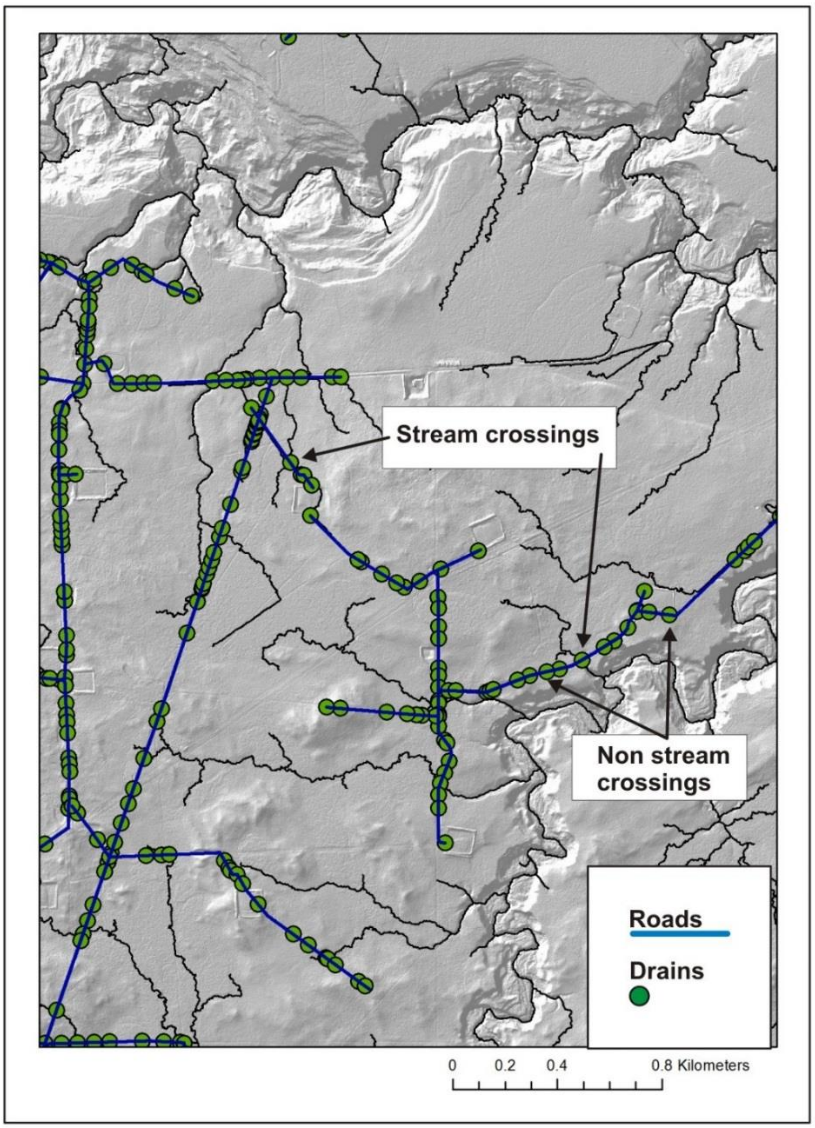

Figure 11. Locations of natural drains.

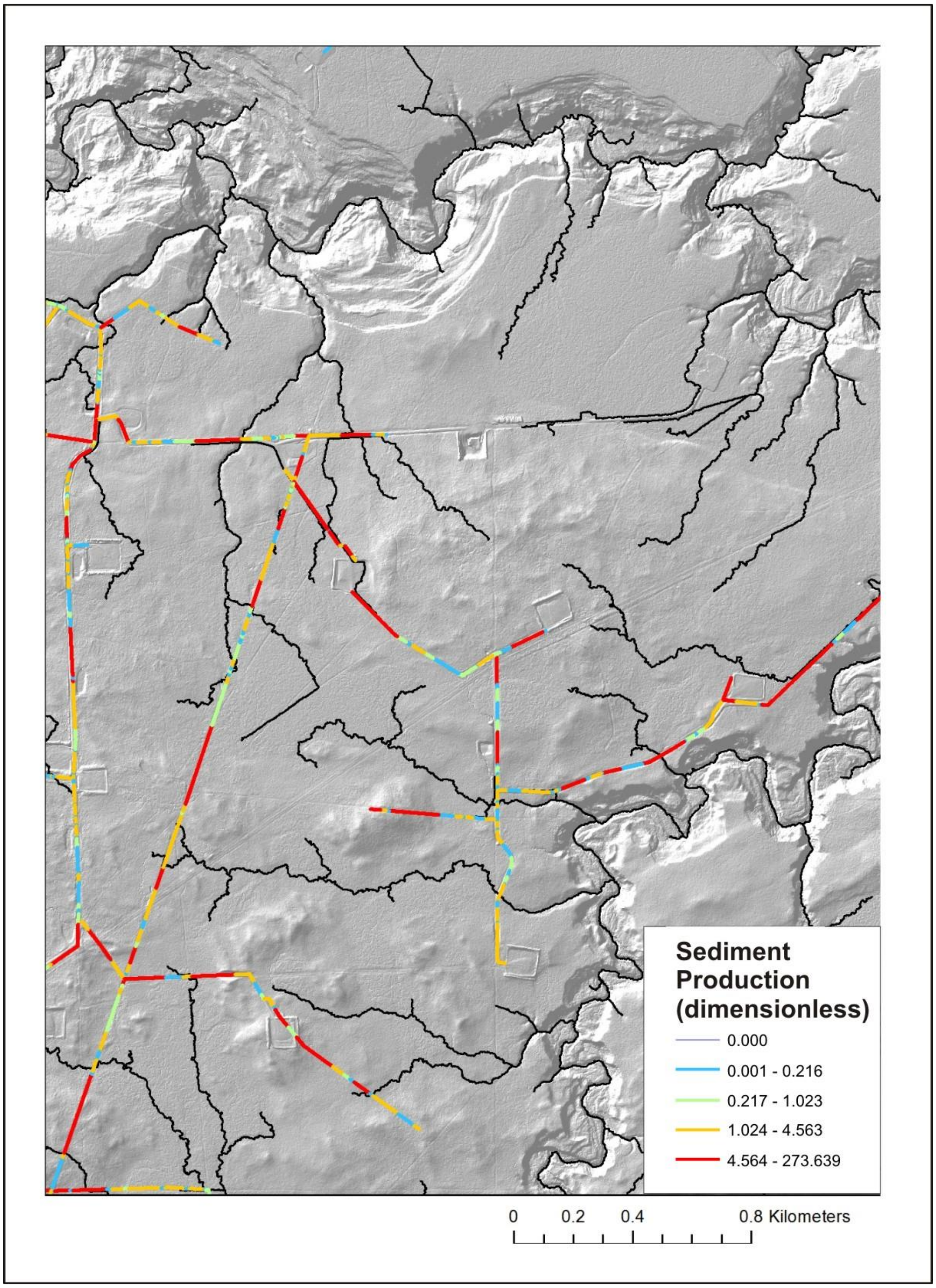

Figure 12. Predicted sediment production (y_o set to 1).

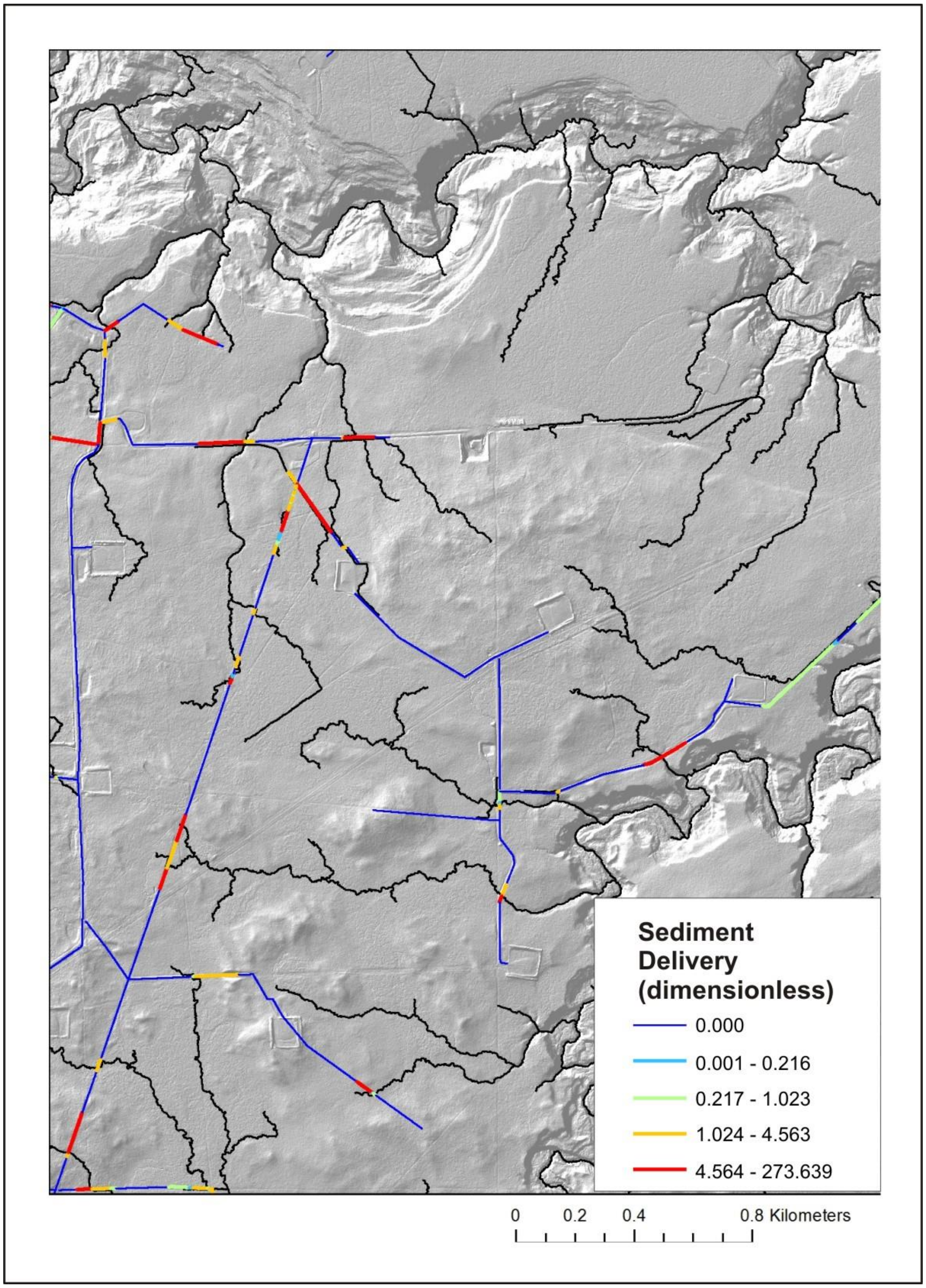

Figure 13. Predicted sediment delivery (yo set to 1).

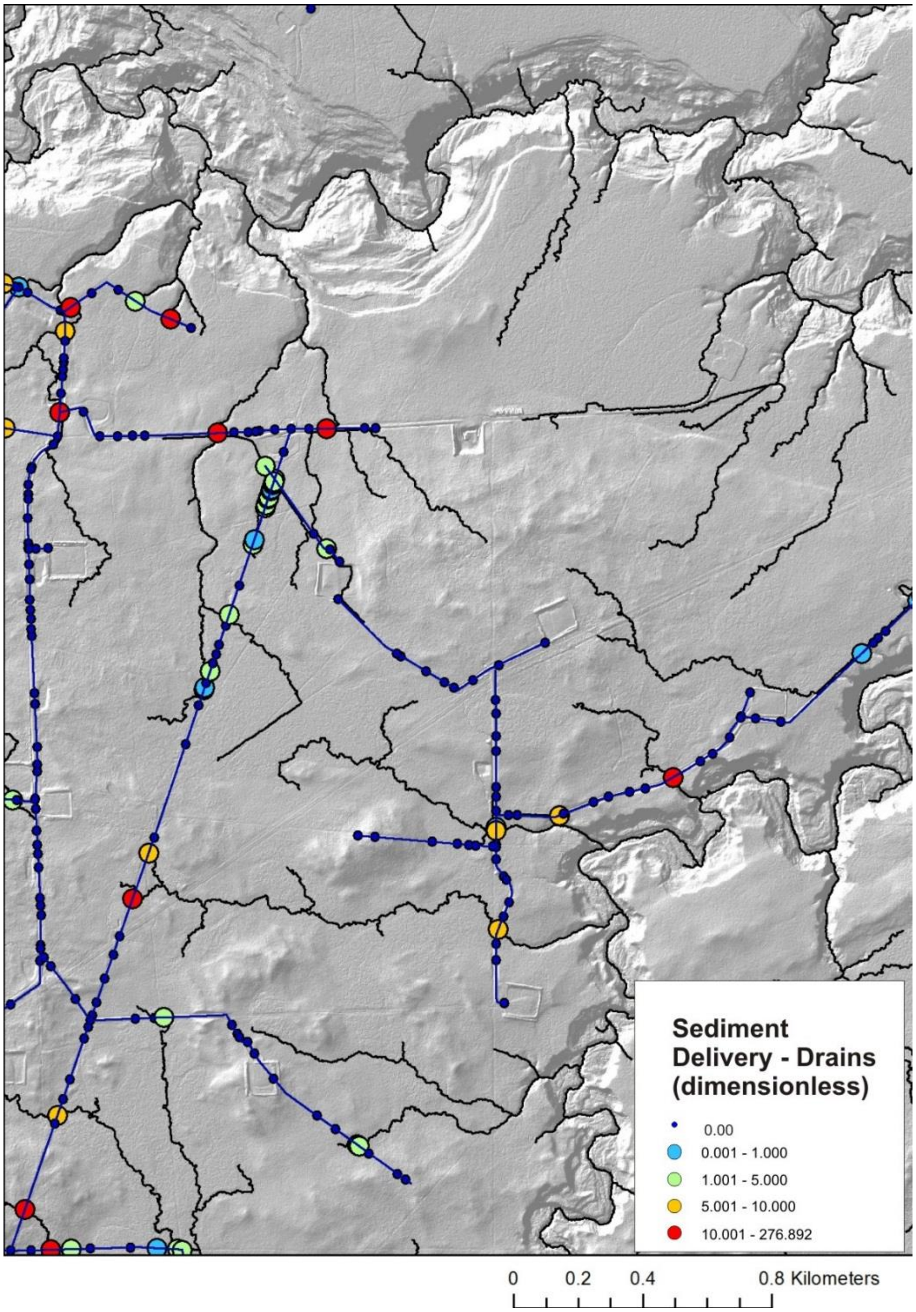

Figure 14. Sediment delivery predicted at individual drain points.

Table 2. Summary of READI outputs in the Simonette River watershed, dataset si6.

Parameter	**Current Condition**	**After Adding Optimized Drains**	**Percent Change**
Sediment Production (dimensionless)	43,824	43,824	0%
Sediment Delivery (dimensionless)	15,358	4,277	-72%
Fraction of Production Delivered to Streams	35%	9.8%	-72%
Percent Road Length Hydrologically Connected	32%	8%	-75%
Average Sediment Transport Length (plume length)	14.5 m	7.9 m	-45%

READI has the ability to determine the most optimum location for adding additional drains to eliminate or reduce sediment delivery for each individual road segment. The model starts with the drain with the largest predicted sediment delivery (including at road to stream crossings) and then adds additional drains at optimized locations (drains defined as any structure or modification to the road geometry that interrupts the accumulation of surface runoff along the road, such as a relief culvert, waterbar or rolling dip etc.), and thus reduces the predicted runoff and sediment delivery to streams. The locations of added optimized drains are shown in **Figure 15**.

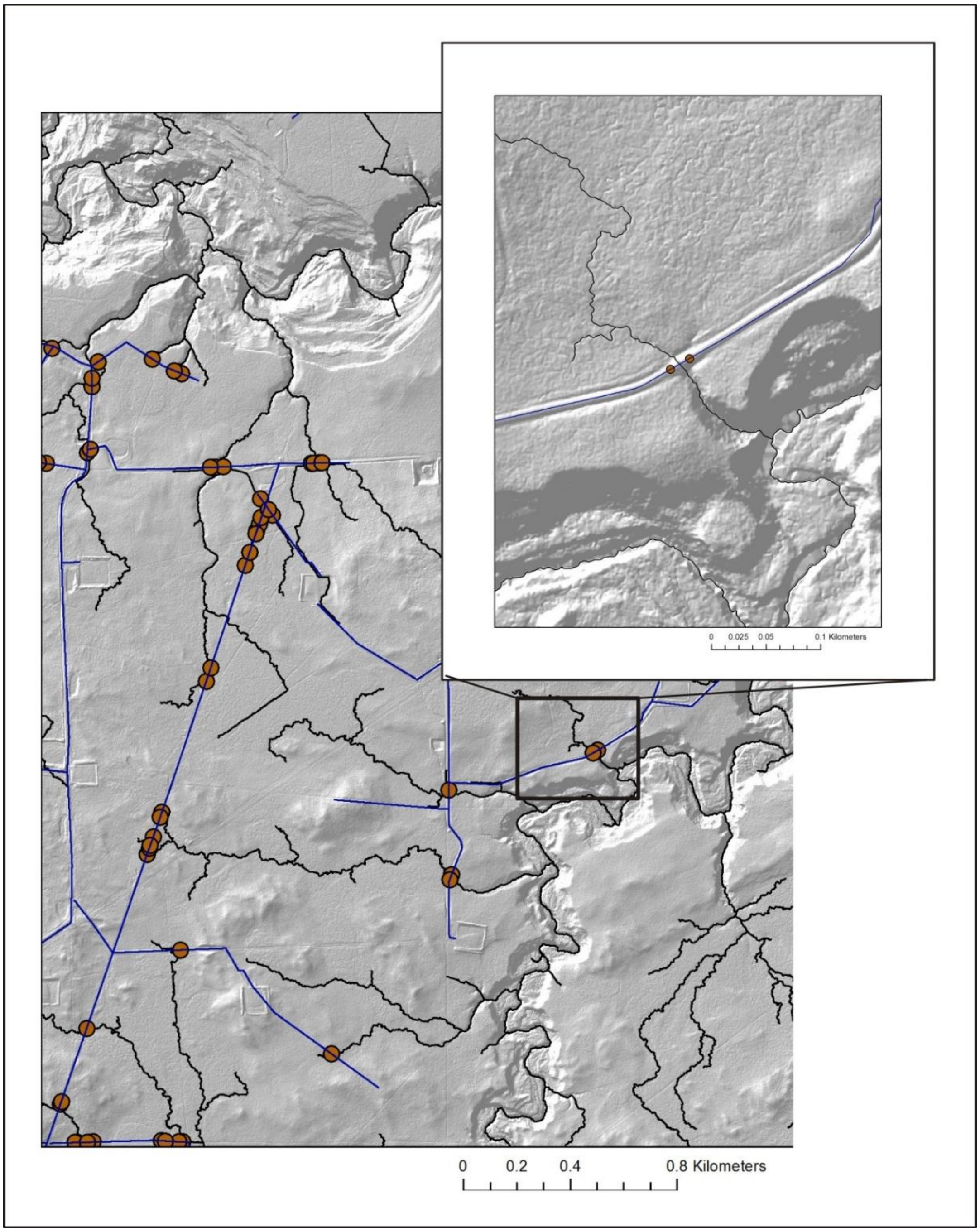

Figure 15. Optimized new road drain locations (added to natural drains, Figure 11).

The predicted reduction in sediment delivery to streams (**Figure 16**) is significant (72% reduction, Table 2) when compared with the non-optimized sediment delivery prediction (Figure 13). The effectiveness of adding new optimized drains decreases with increasing drain numbers because READI's optimization routine begins with the largest sediment delivery and continues to search for locations to reduce or eliminate the top sediment delivery segments. Consequently, drain effectiveness decreases with increasing drains; the first 150 drains in this illustrative applications are the most effective (**Figure 17**).

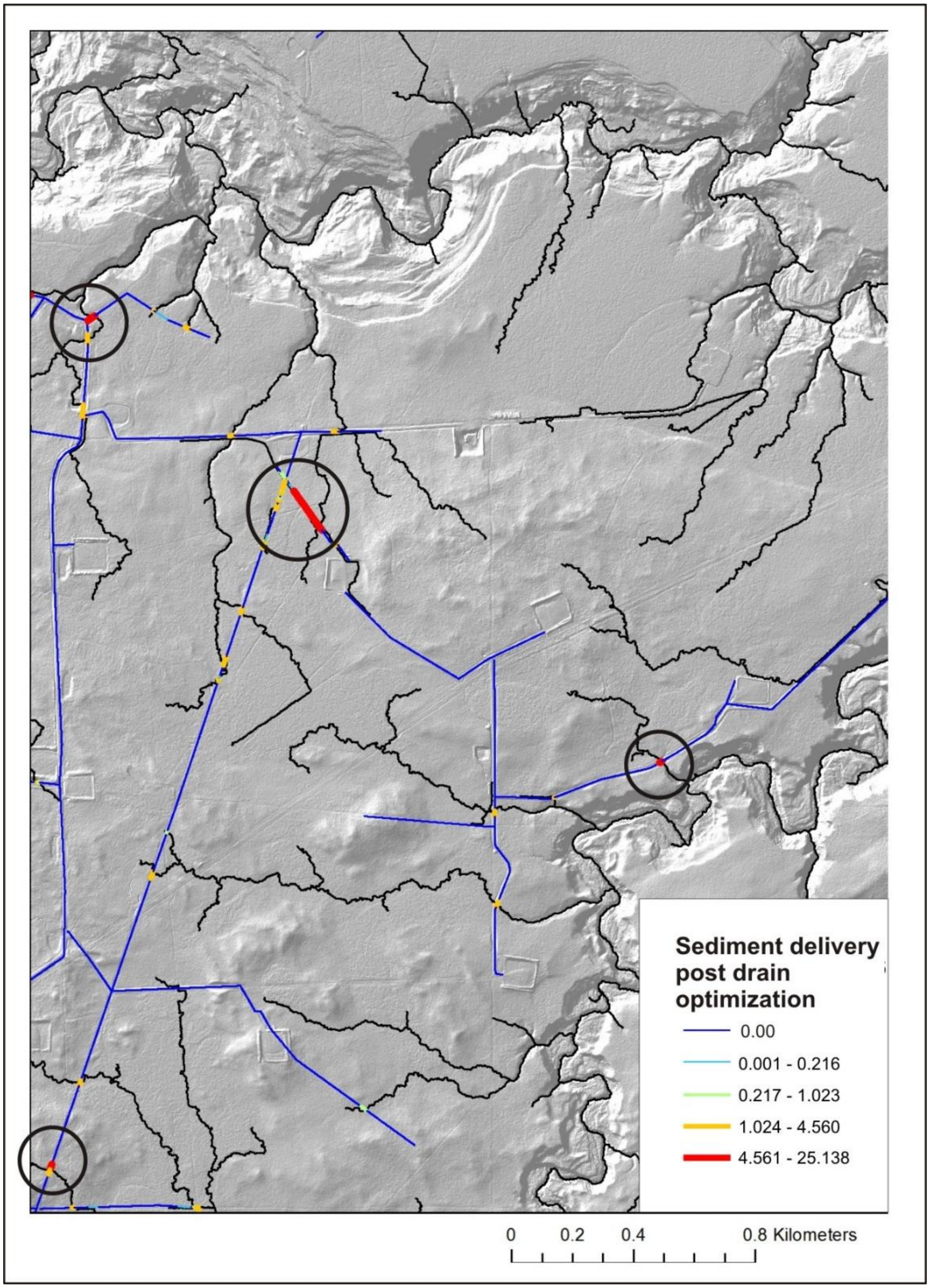

Figure 16. Sediment delivery following new drain optimization.

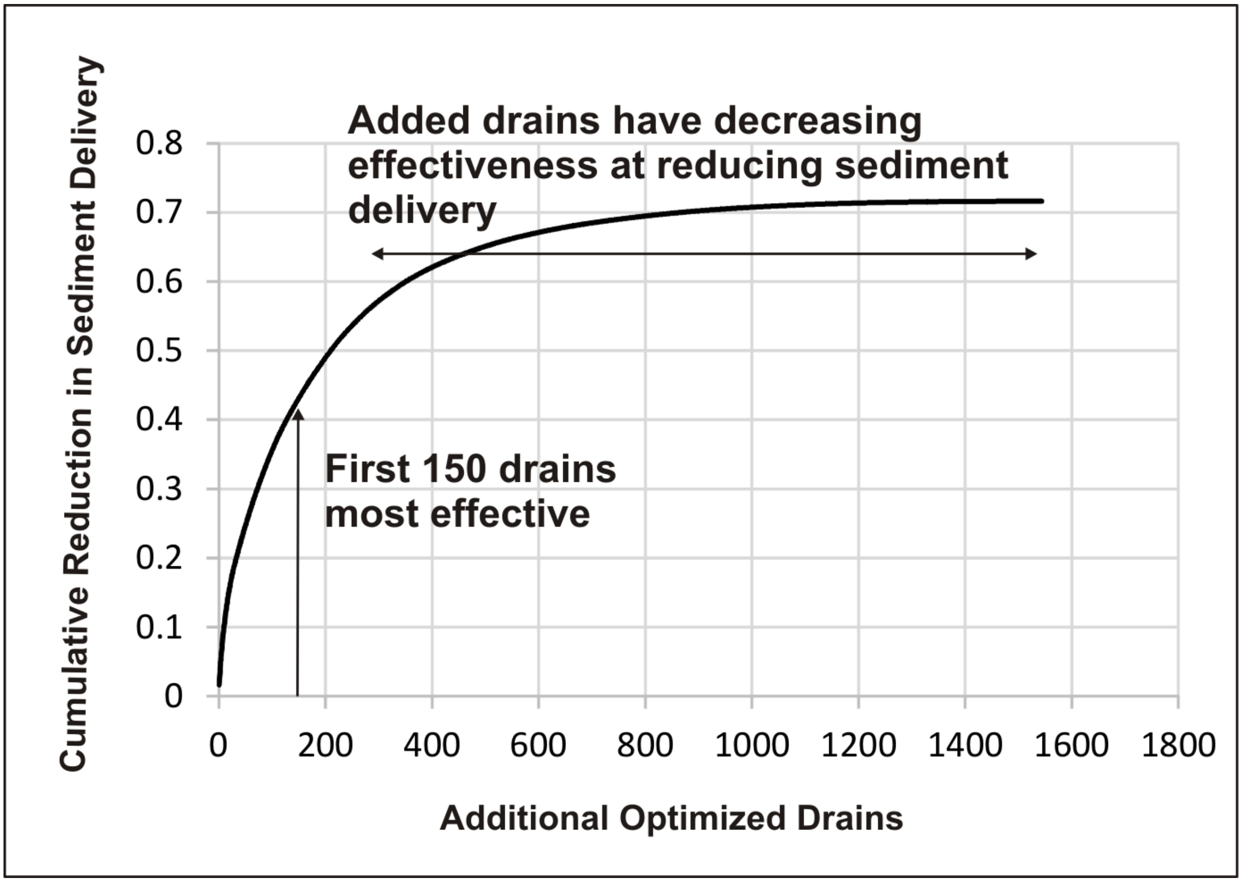

Figure 17. The cumulative effectiveness of adding new optimized drains.

Another type of road sediment delivery reduction optimization in READI is the analysis of effectiveness of altering the road surface erodibility in the model. The model result shows which road segments would have the greatest potential to reduce sediment delivery if surface erosion potential was reduced, by for example, adding rock to a native surface road or by out-sloping, or applying other erosion control (**Figure 18**). Factors that control the prediction include road segment length, road width (if variable), road slope, percent out-sloped (if variable) and distance of the road segment to the stream, and hence sediment delivery potential. The surface erosion reduction optimization module in READI can be applied on either the non-optimized drainage road segments (Figure 18) or on the optimized drainage road segments (e.g., Figure 16).

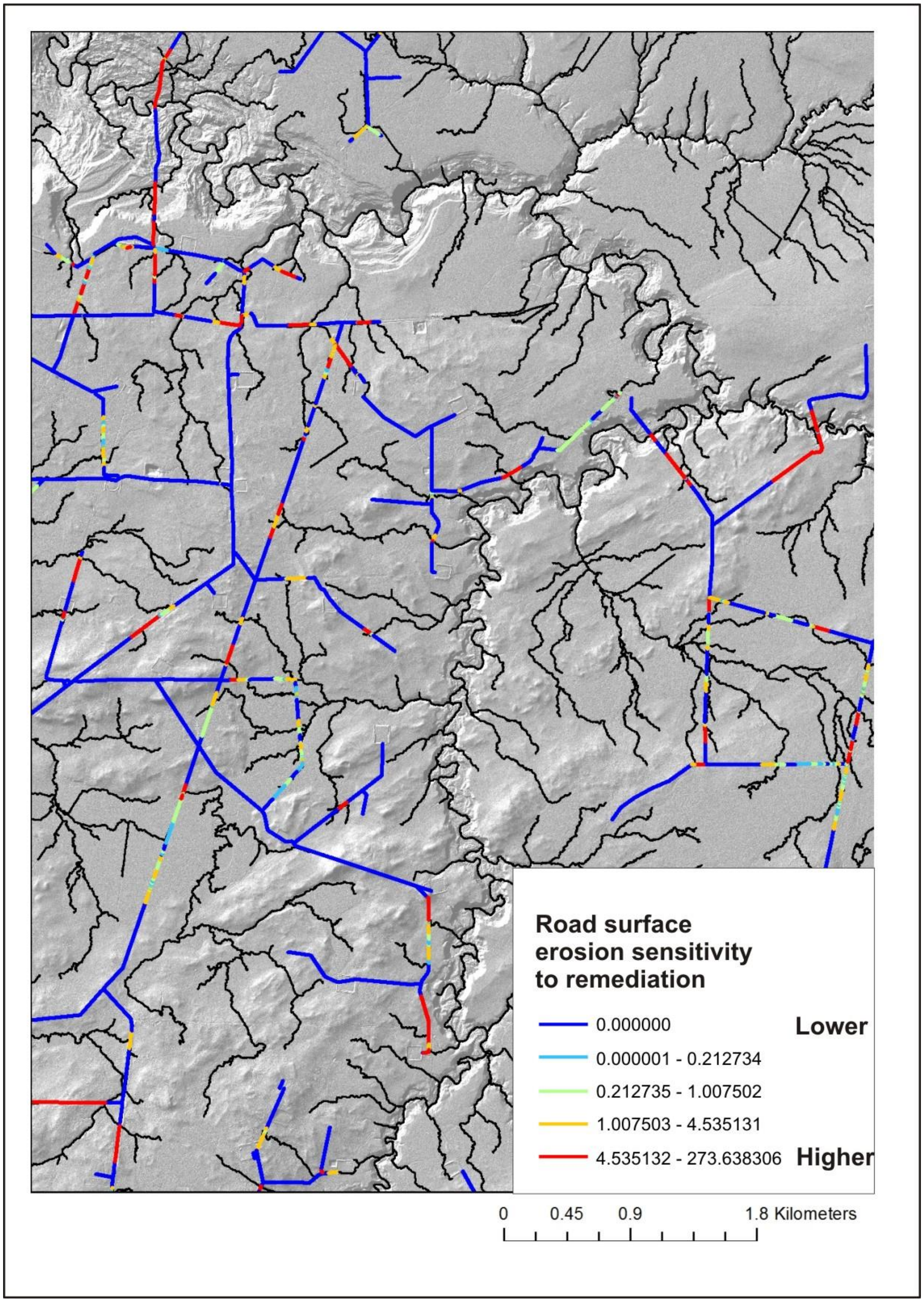

Figure 18. Relative effectiveness of road surface improvements in reducing erosion.

All of READI's analyses discussed above are represented in the road segment layers (shapefiles, Figures 12 to 16, 18). However, in the WIN-System predicted road sediment delivery can be reported to the synthetic stream layer in individual reaches because each road segment in the virtual watershed is referenced to individual stream segments that they drain into (**Figure 19**). This transfer of information (using the READI tool interface in NetMap) can also use the optimized drain predicted sediment delivery (**Figure 20**). In a WIN-System CWE analysis, predicted road sediment delivery mapped to stream channels allows analysis of overlaps of this type of potential land use stressor with valuable and sensitive aquatic habitats (see Habitat-Stressor Overlap Tool).

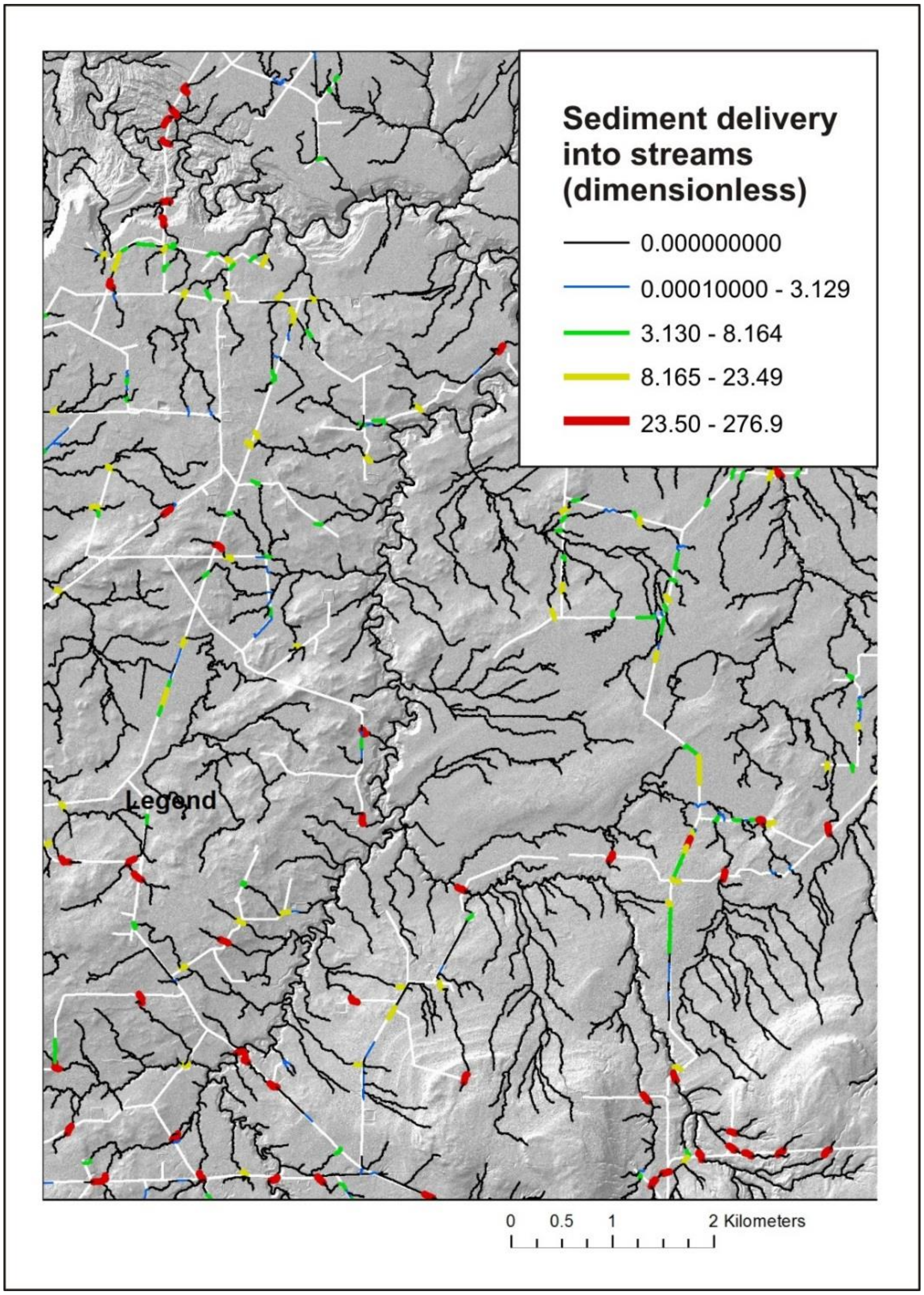

Figure 19. Predicted sediment delivery using non-optimized drains reported to reaches.

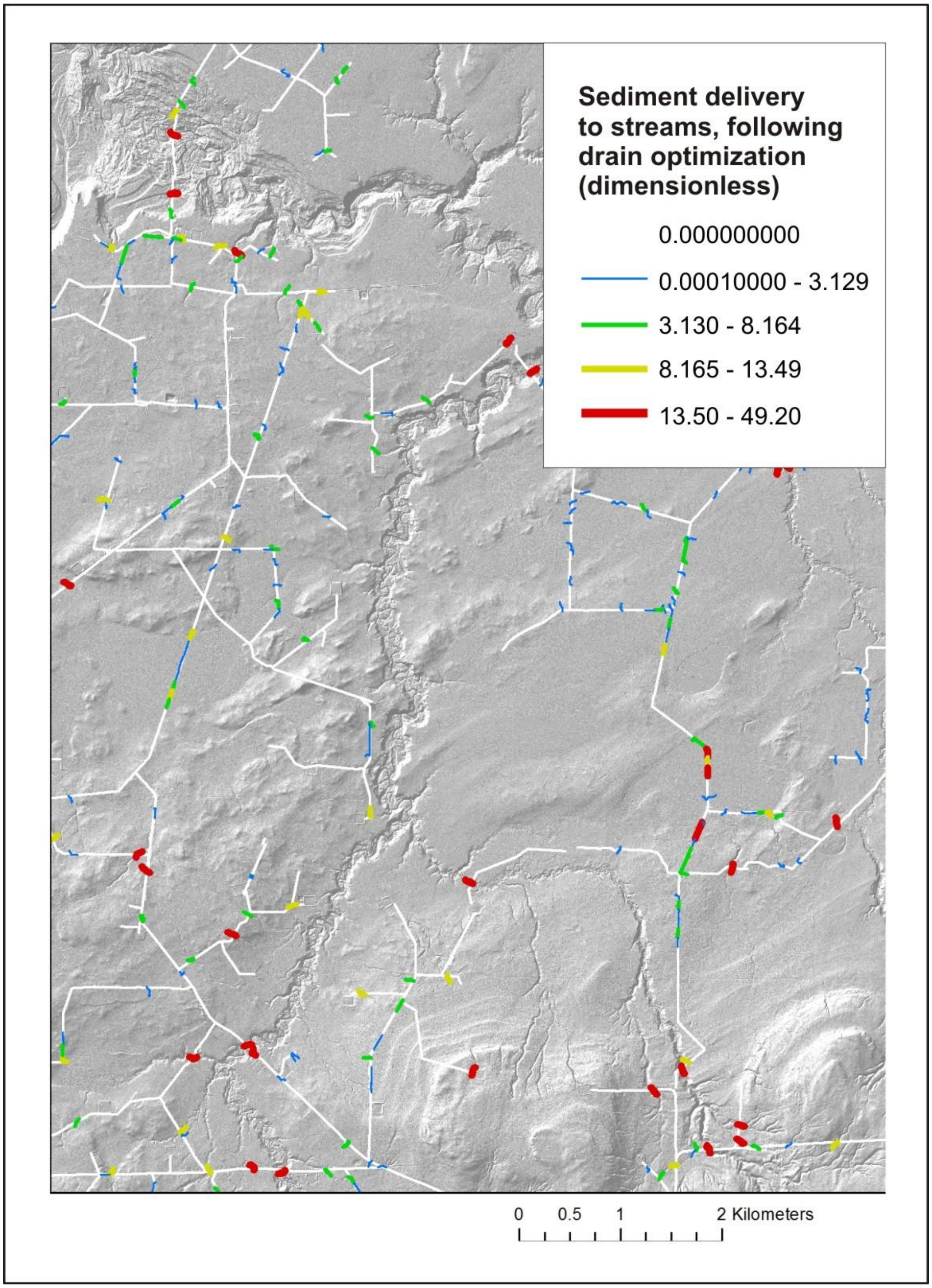

Figure 20. Predicted sediment delivery using added optimized drains reported to reaches.

5.0 Discussion

Unpaved roads utilized in forestry applications and in the oil and gas industry can be significant sources of fine sediment delivery to streams in Alberta. The READI model in the WIN-System was used to examine the potential impacts of unpaved roads in terms of predicted sediment delivery. The CWE analysis in the Simonette River watershed conducted for the University of Alberta and Canfor was limited to road sediment production and sediment delivery. Other NetMap analyses pertinent to CWE, and specifically for roads (road stability, road gully potential, roads in floodplains and habitat length above road crossings) were not implemented in this study. The Simonette virtual watershed datasets were designed solely to apply the READI and WEPP road erosion models in support of the road focused CWE analysis. The WEPP model was not applied during this analysis although other analysts can run the WEPP model in the future.

There are a suite of NetMap tools that can be used with the Simonette River Watershed road CWE analysis that could help in further analysis and decision support. These include:

1. Information on road impacts can be linked to 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. Predicted road sediment delivery represented in stream channels can be aggregated up and downstream, revealing spatial patterns defined by the channel network. Data outputs include rasters, points, arcs, or polygons.
3. Various types of road analysis outputs can be represented by 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 predicted road impacts can be used within the habitat-stressor overlap tool to search for locations (in the river network) where selected combinations of watershed and road attributes overlap. One can find, for example, where the highest 5% of road surface erosion intersects the highest 10% of fish habitat quality.

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