Integrating Wet Areas Mapping with NetMap's Virtual Watershed to Support Spatially Explicit Riparian Zone Delineation and Management in Alberta

For Alberta Environment and Sustainable Resource Development

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Executive Summary:

Two advanced watershed analysis technologies, Alberta's Wet Areas Mapping (WAM) and NetMap's virtual watershed coupled to tools, are combined to create a state of the art platform for various types of watershed analyses. 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 using Alberta's one meter LiDAR DEM. This required matching WAM flow direction and accumulation grids across the multiple, rectangular 14 km by 16 km WAM LiDAR-based tiles (e.g., from tile to tile), using a priority queue that required flow out of each cell, ordered from smallest to largest, with the objective of identifying the shortest flow path from each cell to basin outlets. 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 resulting 50 to 150 m stream reach segments of the Integrated WAM-NetMap are linked to the terrestrial landscape via local stream reach contributing areas, called drainage wings. Drainage wings are used to transfer terrestrial information such as terrestrial and riparian vegetation, roads, erosion potential and other attributes to stream reaches; this supports riparian zone delineation and comparative analyses between reach scale attributes, such as fish habitat potential, with riparian and other watershed processes. The Integrated WAM-NetMap is demonstrated using four 14 km by 16 km LiDAR-WAM tiles in the Simonette River watershed as part of a Phase I project focusing on spatially explicit riparian zone delineation and management; Phase II will apply the Integrated WAM-NetMap in an analysis of cumulative watershed effects, focusing on road analyses, in conjunction with the University of Alberta.

Spatially explicit riparian zone delineation and management require information on selected riparian processes and on environmental settings – e.g., those watershed conditions that influence how riparian processes affect aquatic habitats. Selected riparian processes in the Integrated WAM-NetMap in the Simonette River pilot project area include: (1) depth to water or wet areas (WAM), (2) floodplains, (3) current vegetative shade effects on thermal energy to streams and (4) in-stream wood recruitment. Environmental settings can include channel types, habitat types, hillslope erosion potential, channel

migration zones, thermal refugia, tributary confluences, wildfire risk and climate change; however, the demonstration analysis of delineating spatially explicit riparian zones in the Simonette River pilot area does not include the environmental setting component, although it could be added in the future by other analysts. Attributes in the WAM-NetMap that support riparian zone delineation and environmental settings include drainage area, channel gradient, bankfull width, bankfull depth, and floodplain extent, among many others.

Delineating riparian zones using the Integrated WAM-NetMap in the Simonette River pilot project area involved user selected sets of riparian processes (one through four as listed above). Individual riparian zone dimensions associated with selected riparian processes are combined to create a single, composite riparian zone with left-right channel distinction. However, riparian zones associated with each riparian process can be limited in extent laterally according to user specified constraints on depth to water threshold and width of the WAM, width of the floodplain and proportion of in-stream wood protected (e.g., some proportion of a tree height). The spatially explicit delineation of variable-width riparian zones provides a robust approach to riparian zone management that distributes protection based on site ecological processes, resource economics, recovery of environments following disturbances and the increasing susceptibility of riparian forests to fires, insects, disease and other factors related to climate change.

1.0 Introduction

The Province of Alberta contains a high degree of physical and biological diversity in its river and riparian environments. Montane riparian areas may have minimal floodplains and wet areas but streamside vegetation is important in influencing aquatic ecosystems, including fish habitats, via the supply of woody debris and reduction in thermal energy by vegetative shade. In lower portions of larger river basins, riparian areas with extensive floodplains and wetlands, combined with channel migration, lead to complex and productive aquatic habitats, including in the boreal ecoregions of northern Alberta. In the context of Alberta's resource development programs, the protection of riparian areas, and by association aquatic environments, is a challenge given the high degree of spatially variable environmental conditions.

Riparian protection is often considered in the context of fixed width, one size fits all buffers in many areas of North America, including in Alberta. Although fixed width buffers are administratively easy to apply and regulate, they often do not reflect the spatially variable nature of site specific riparian and aquatic environments (Everest and Reeves 2007, Richardson et al. 2012). Prescriptive uniform riparian buffers may not adequately distribute protection based on ecological processes, resource economics, recovery of environments following disturbances, or the increasing susceptibility of riparian forests to fires, insects, disease and climate change.

Knowledge of riparian functions and their spatial variability within watersheds and across landscapes, in conjunction with new analytical tools that predict many aspects of riparian processes (Boyd and Kasper 2003, Miller and Burnett 2007, Benda et al. 2007, Fernandez et al. 2012, Murphy et al. 2009, Ogilvie et al. 2011, White et al. 2012), have set the stage for developing spatially explicit riparian management in Alberta. A spatially explicit approach offers ecological and resource management advantages including tailoring riparian management to highly variable site conditions (Everest and Reeves 2007).

A spatially explicit approach to riparian zone delineation and management requires information on riparian processes that can vary site to site and information on variable environmental settings through which riparian processes influence aquatic habitats. Riparian processes encompass channel-floodplain interactions (Naiman et al. 1998), soil hydrologic conditions including depth to water table (White et al. 2012), vegetative shade effects on thermal energy (Moore et al. 2005), in-stream wood recruitment (Murphy and Koski 1986), and including litterfall and food production (Wipfli 1997). Environmental settings refer to how different channels respond differently to riparian processes, including their sensitivity to terrestrial inputs; environmental settings can include channel morphology and fish habitats but also channel migration, erosion potential, cold water refugia, wildfire risk and climate change.

To enable spatially explicit riparian zone delineation and management and to take advantage of existing high resolution digital elevation data in Alberta (1 m LiDAR), this Phase I pilot project in the Simonette River basin in northwestern Alberta integrates two advanced mapping technologies: (1) Alberta Wet Areas Mapping (White et al. 2012) and (2) NetMap's virtual watershed with decision support tools (Benda et al. 2007) (**Figure 1**). The resulting integrated WAM-NetMap includes state of the art methods for analyzing riparian processes including depth to water (wet areas), shade effects on thermal loading, in-stream wood recruitment and floodplains. In addition, the Integrated WAM-NetMap provides information on Alberta's diverse environmental settings thus providing context for designing streamside protection or buffer zones.

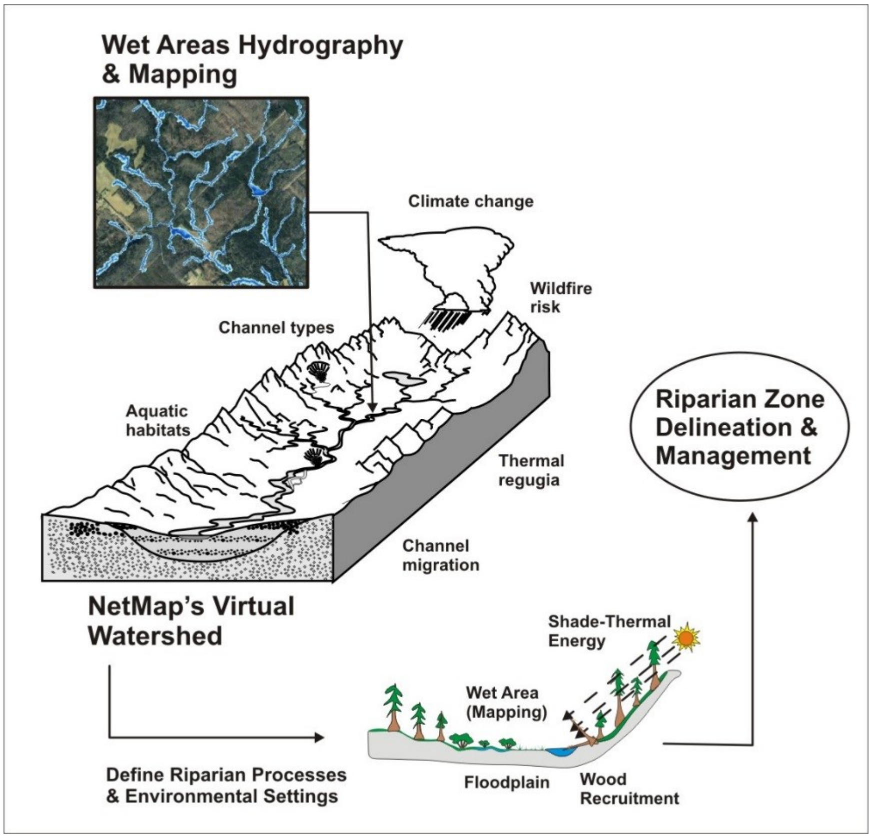


Figure 1. The conceptual basis for the integration of WAM with NetMap.

In addition to supporting riparian zone delineation, the Integrated WAM-NetMap will support Phase II of this pilot project, developing and applying a cumulative effects methodology (A. Anderson, University of Alberta).

2.0 Background and Objectives

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 (**Figure 2**).

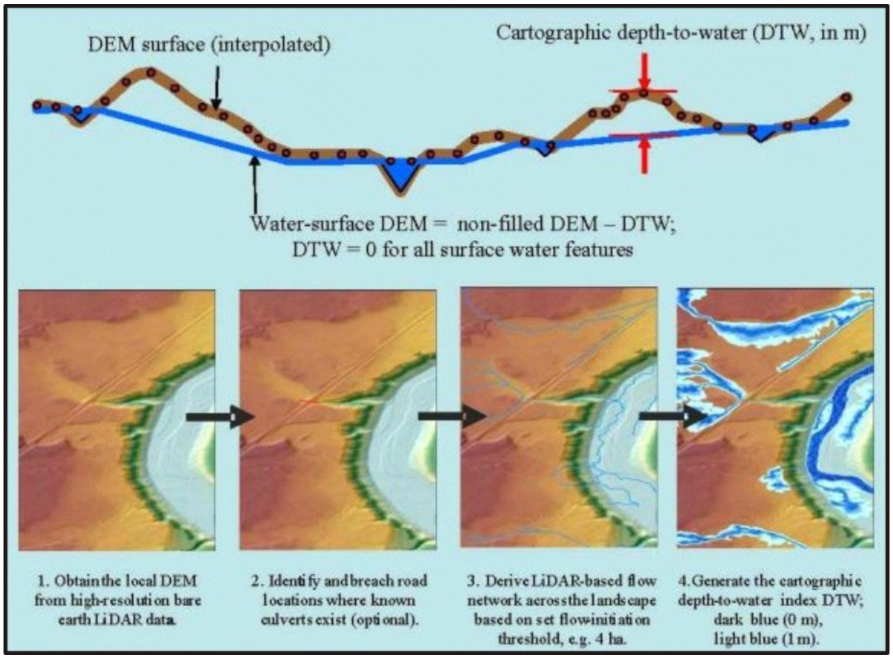


Figure 2. Alberta's wet area mapping (from Ogilvie et al. 2011).

NetMap is a multi-faceted watershed analysis platform that creates and utilizes a synthetic river network within a virtual watershed (Benda et al. 2007, 2009, www.terrainworks.com) to support resource management, risk mitigation, restoration and conservation. NetMap's virtual watershed is characterized by the highest resolution DEM, a routed, attributed and segmented synthetic stream network derived from the DEM, landform and process characterization, landscape and land use discretization and multiple modes of connectivity. The virtual watershed is accessed and manipulated by a set of 90 decision support tools as an add-in in ArcMap 10.x. NetMap includes analysis capabilities of watershed processes pertinent to resource management including: (1) fluvial characteristics (channel width, depth, gradient, shear stress, substrate size, floodplains, terraces and fans), (2) aquatic habitats (fish and beaver), (3) erosion potential (landsliding, debris flow, surface erosion, gullying), (4) road analyses (road drainage, road surface erosion and sediment delivery, road stability, roads in floodplains, and habitat length above all road-stream crossings), (5) riparian management (shade-thermal energy, in-stream wood recruitment, thermal refugia and riparian delineation), (6) wildfire (pre and post), and (7) climate change (**Figure 3**).

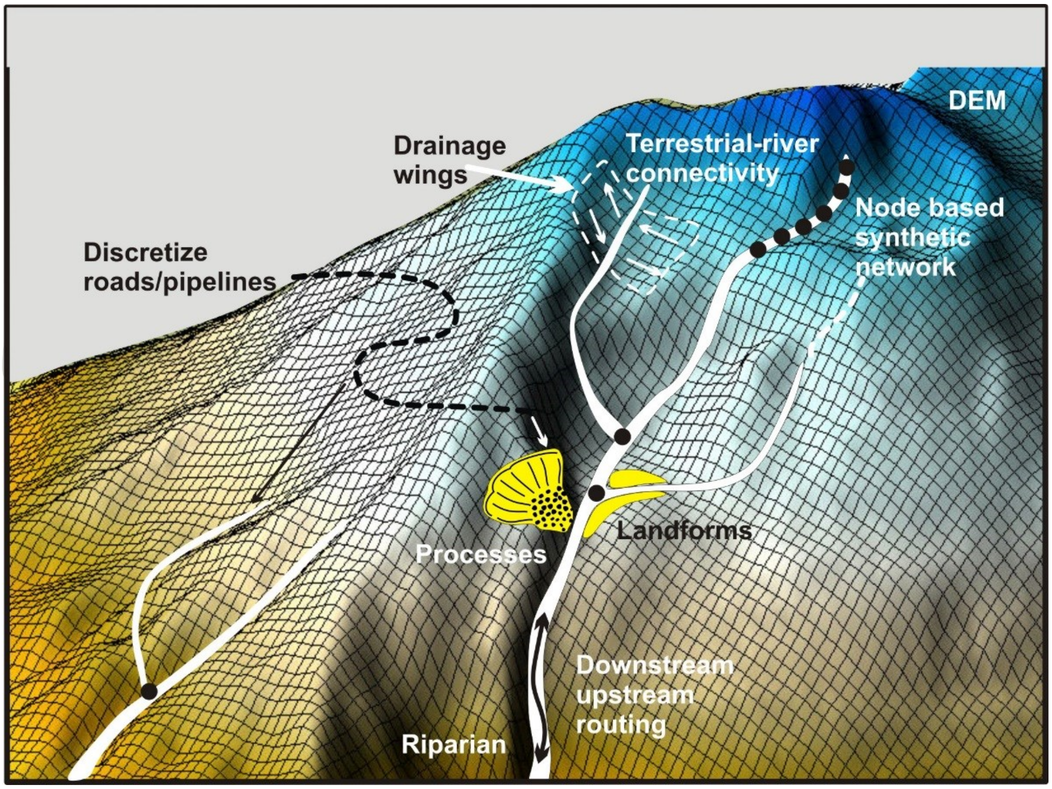


Figure 3. NetMap's virtual watershed coupled to tools.

The primary objective of the Phase I pilot study in the Simonette watershed is to combine WAM and NetMap technologies in the form of a single uniform synthetic stream layer (using WAM as the spatial benchmark, Figure 1) incorporated within a virtual (digital) watershed. This integrated tool will support analysis of riparian processes, riparian area delineation, including within the context of riparian-aquatic environmental settings. This objective requires completion of four tasks:

1. Integrate the WAM and NetMap technologies to create seamless and routed (e.g., downstream and upstream transfer of information, similar to actual river network) synthetic river networks (e.g., GIS stream layers). The existing Alberta-wide WAM stream layer (and associated flow direction and accumulation grids) will be used as the benchmark for stream line locations.
2. Attribute the Integrated WAM-NetMap stream layer with information necessary to inform spatially explicit riparian zone delineation and analysis, including bankfull channel depth,

channel width, gradient, floodplains, terraces, elevation, stream order, among others. Implement the virtual watershed including to inform environmental settings.

3. Evaluate riparian processes including: i) depth to water (wet areas), ii) current shade – thermal energy, iii) floodplains and iv) in-stream wood recruitment (current vegetation).
4. Apply a spatially explicit approach to riparian zone delineation using results from tasks (1) through (3) as a demonstration to evaluate its utility across larger areas.

3.0 Study Area

The pilot study area is located within the Simonette River basin, (5,220 km^2) a tributary of the Peace River in north-central Alberta (**Figure 4**). The study area consists of four rectangular LiDAR WAM tiles that are 16 km wide by 14 km tall (encompassing WAM flow direction, flow accumulation, depth-to-water-WAM, and synthetic stream lines in an area of 896 km^2).

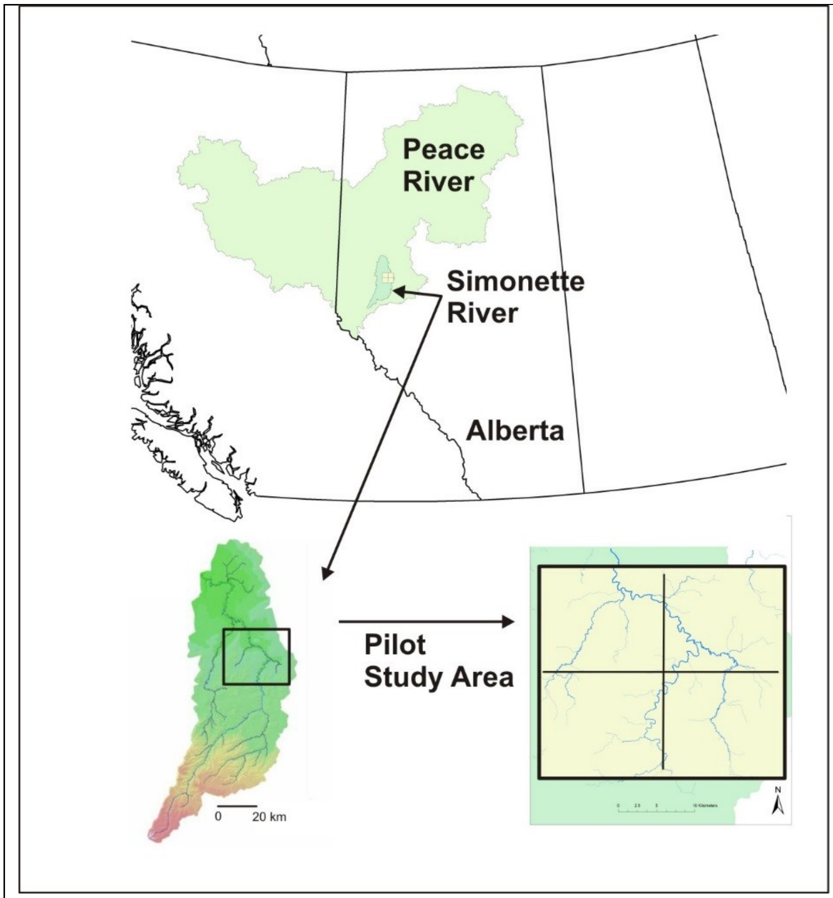


Figure 4. Simonette River pilot project area.

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 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). Salmonds include Trout-perch (*Percopsis omiscomaycus*), Arctic grayling (*Thymallus arcticu*s), Bull Trout (*Salvelinus confluentus*) and Rainbow trout (*Oncorhynchus mykiss*).

4.0 Methods and Results

Spatially explicit riparian zone delineation and management require information on riparian processes including: (1) stream adjacent wet areas (e.g., wet areas mapping), (2) vegetative shade effects on thermal energy to the stream, (3) in-stream wood recruitment and (4) channel-floodplain interactions (Figure 1). This information can stand alone in delineating riparian zones (see below) or it can be combined with information on environmental settings to enhance design of riparian buffers. For example, riparian processes have varying influence on aquatic habitats depending on their environmental setting. In-stream wood recruitment may be more important in low gradient channels where logs form pools and less important where boulder bed channels limit pool formation by downed trees. Vegetative shade may be more important in certain locations based on topographic settings of the channel compared to other locations.

In addition, non-riparian landforms and processes may also influence buffer design. For example, erosion prone areas adjacent to streams (such as inner gorges) could be encompassed within riparian buffers. Concerns about wildfire risk and climate change may also lead to other considerations in the design and management of riparian areas and buffer zones. However, environmental settings are not considered in this pilot study but information available in the Integrated WAM-NetMap could support it in the future.

4.1 Task 1: Integrate the WAM and NetMap technologies to create seamless and routed synthetic river networks

WAM and NetMap's synthetic stream layers are created differently because each is designed for a different purpose. The WAM stream layers built at the scale of individual 14 by 16 km tiles provide the fundamental hydrologic context for predicting depth to water, or wet areas (Murphy et al. 2009). NetMap's synthetic stream layer is designed to address questions pertinent to watershed processes that involve entire river networks (such as the routing of sediment downstream or the movement of fish upstream) and thus is built at scales of entire watersheds (e.g., organized by hyrographic watershed boundaries) and is routed (e.g., downstream and upstream transfer of information), coupled to terrestrial landscapes, and is attributed with parameters to support watershed analyses.

The Integrated WAM-NetMap requires only a single stream layer (and single flow direction and accumulation grids) and the WAM layer is chosen as the template upon which to incorporate NetMap's node-based channel delineation technology and its virtual watershed. However, because WAM is built at the scale of individual rectangular LiDAR tiles, its flow direction and flow accumulation grids, and the resulting synthetic stream network, do not always match up at tile borders (areas of overlap) (**Figures 5 and 6**). To create a watershed scale, contiguous and routed stream layer for the Integrated WAM-NetMap requires adjustments to WAM's flow direction and accumulation in areas of mismatch along the boundaries, and to further enforce matching of flow directions and accumulation and of the synthetic networks.

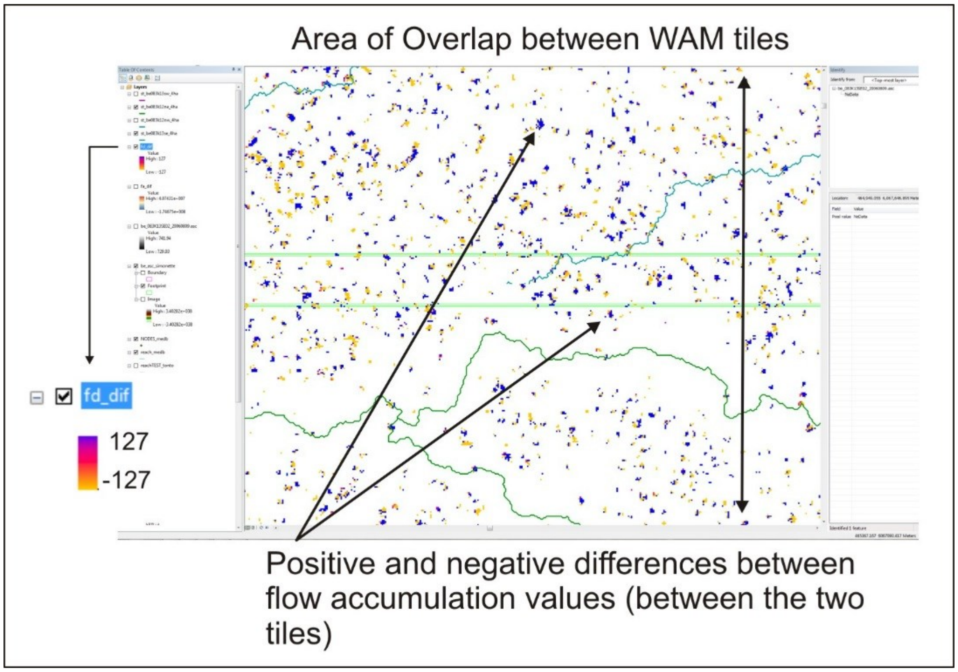


Figure 5. Overlap area of WAM-LiDAR tiles showing issues of mismatch in flow direction and accumulation.

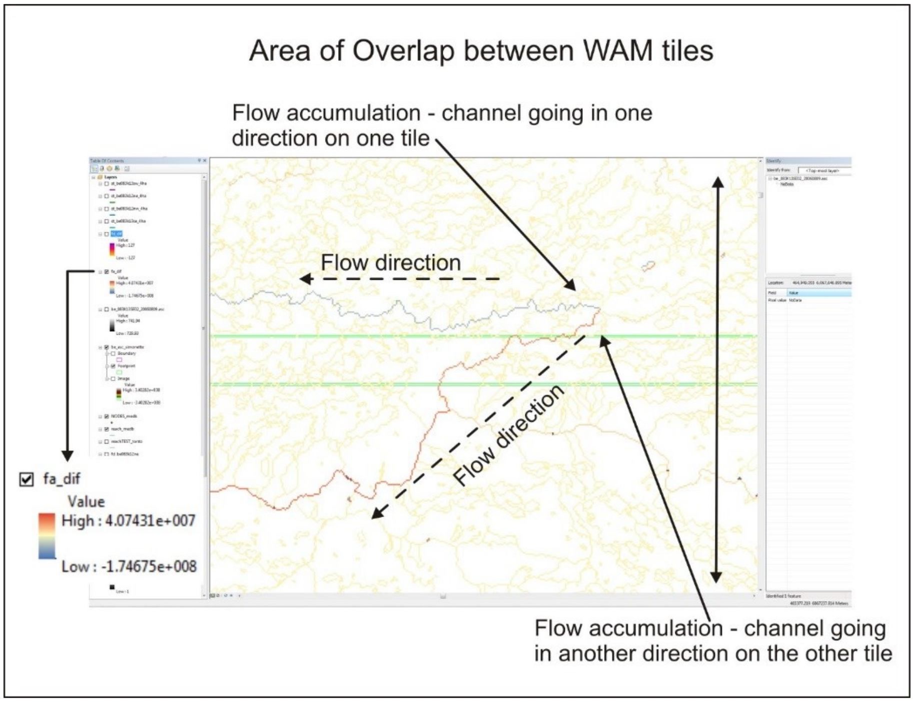


Figure 6. Solution for adjusting flow direction/accumulation and synthetic stream lines in the Integrated WAM-NetMap.

The solution to integrating the WAM and NetMap stream layers begins by creating (merging) a single, contiguous DEM grid (across the four WAM tiles encompassing 896 km^2). In the contiguous grid there are “drained” and “undrained” grid cells; drained cells have a continuous flow path out of the DEM, undrained cells do not. In some areas of overlap, the flow directions in individual cells (on the two adjoining tiles) do not coincide; these are referred to as “unmatched cells”. A priority queue is used to rank cells along the edge of undrained cells in order of the flow distance to exit the DEM, ordered from the smallest distance to the largest distance; it is assumed that the most likely flow path is that with the shortest flow distance to the basin outlet, as estimated from the DEM. A “priority queue” is similar to a regular queue with the added element that each possible flow path has a priority associated with it (in this case the shortest flow distance to basin outlet). Using multiple iterations (1.7 million to 9.1 million), the undrained and mismatched cells became drained and matched with corresponding shortest distances between each cell and the basin outlet (**Figures 7 and 8**).

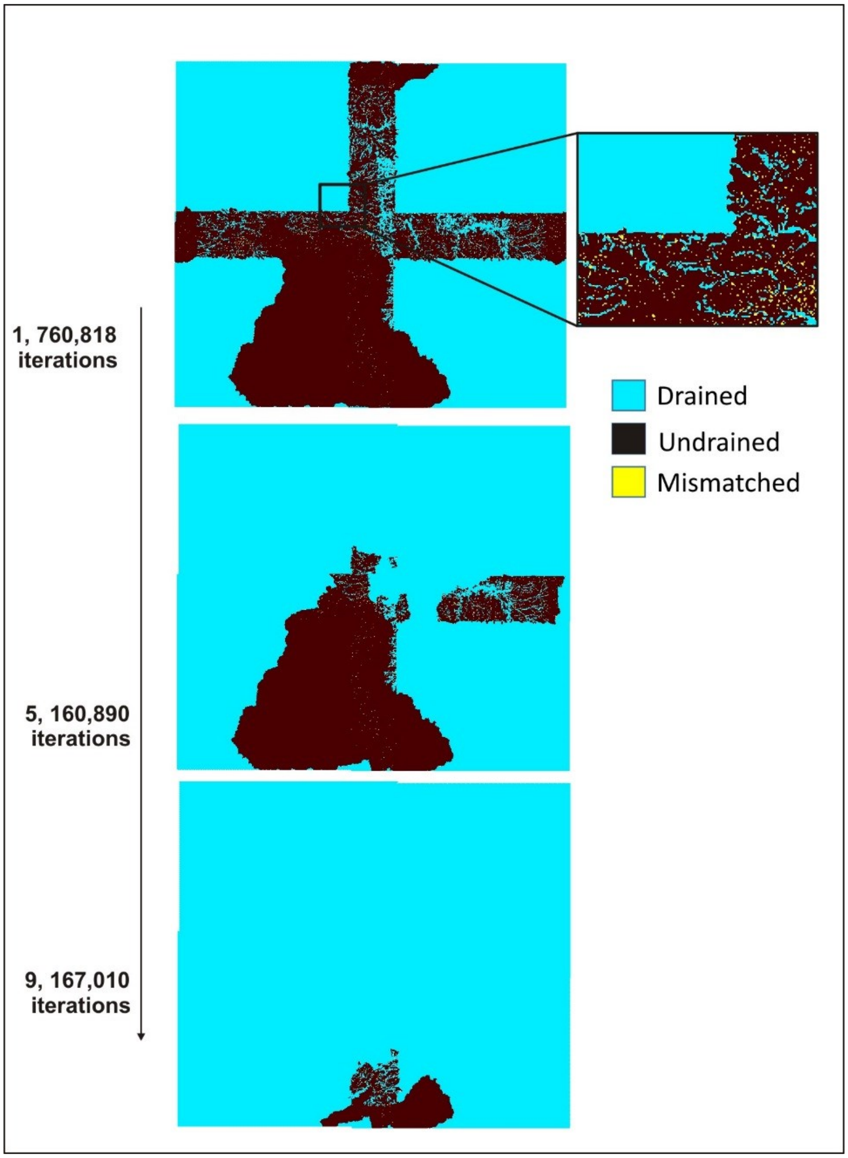


Figure 7. An illustration of drained, undrained and mismatched grid cells in the process of building an Integrated WAM-NetMap.

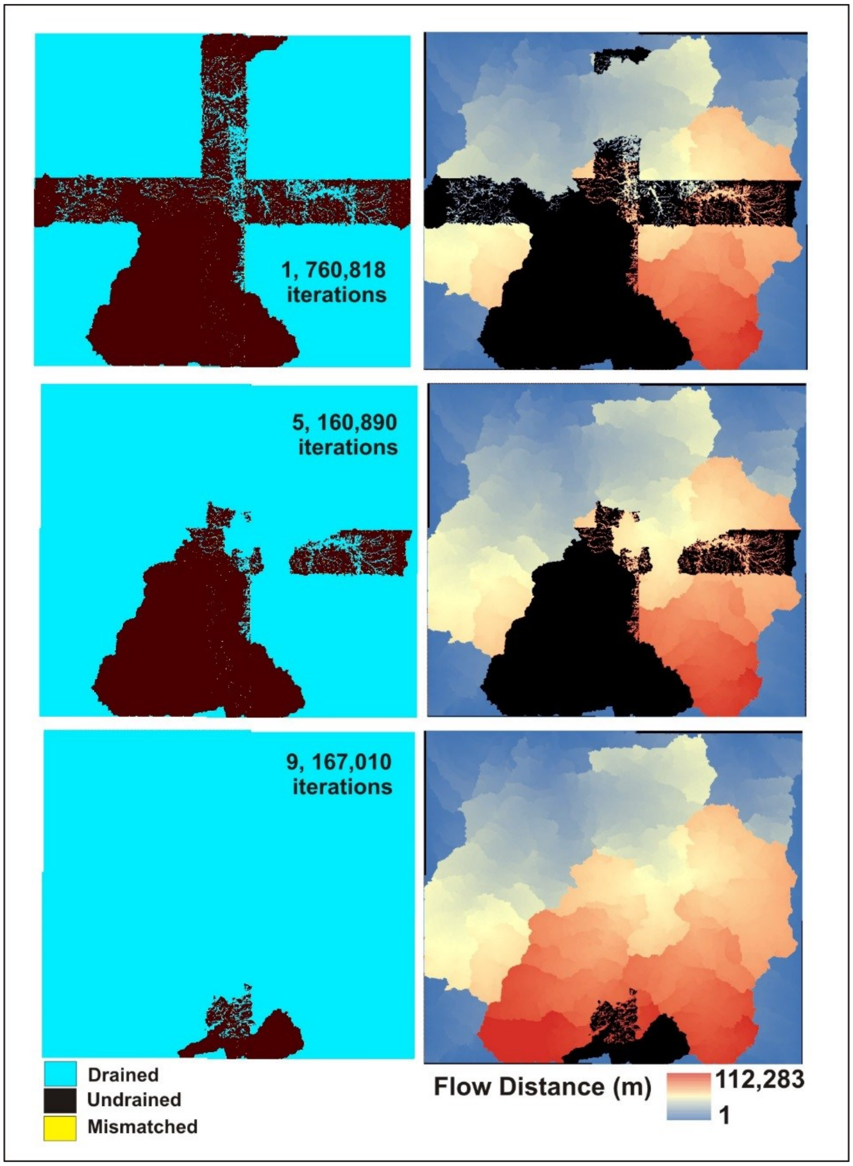


Figure 8. The solution space for creating a perfectly matched across tile set of flow directions and accumulations.

Once flow direction and accumulations are matched across tile borders (**Figure 9**), stream initiation requires that a WAM stream must be present and that there are at least four hectares of contributing area, an original WAM stream initiation criteria. D8 flow directions, using a node based (DEM cell resolution) NetMap data structure, are set to follow WAM stream lines, so that <u>WAM and NetMap streams match exactly</u>, except in rare cases where WAM stream segments do not extend as far as the original WAM segments because of updated contributing areas. All stream lines are completely routed in the Integrated WAM-NetMap hydrography - virtual watershed.

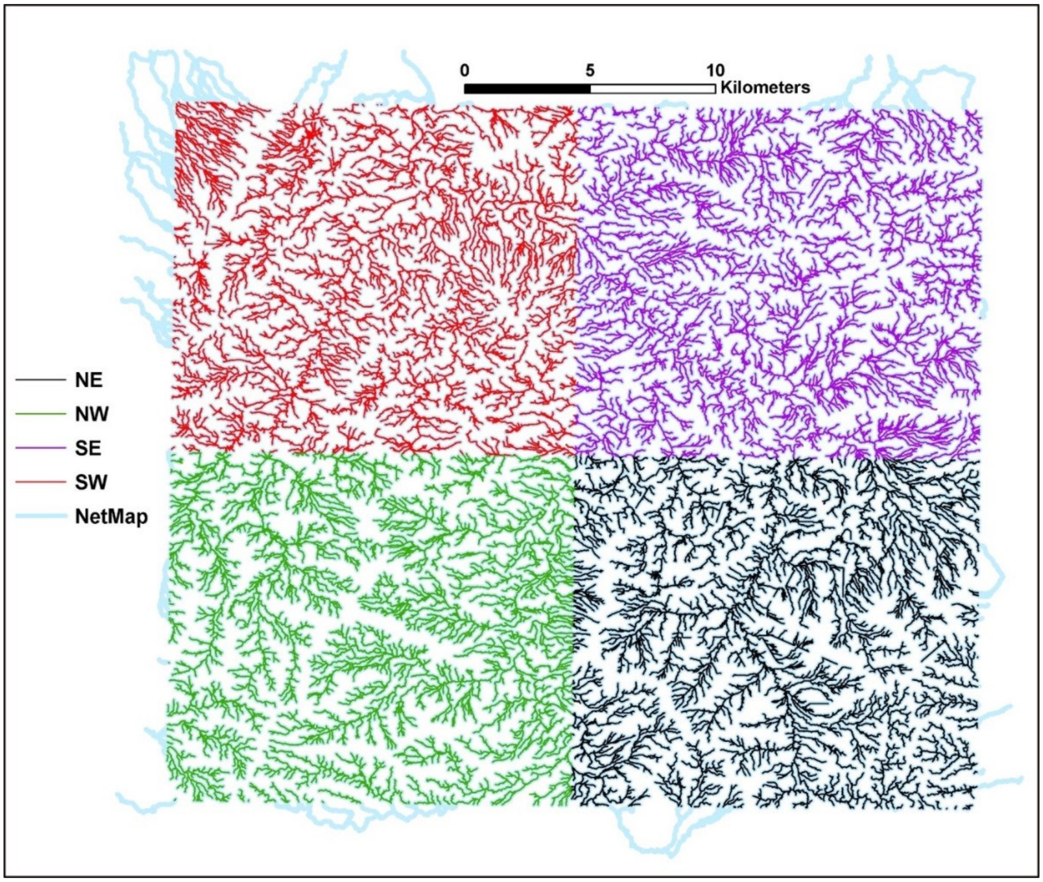


Figure 9. The four WAM LiDAR tiles with matched borders of flow direction, accumulation and synthetic stream lines, with NetMap's node based stream line data structure below.

Figure 10 shows an example of the Integrated WAM-NetMap stream layer at the boundary between two LiDAR tiles. In some areas the flow accumulation is somewhat less because flows are redirected in the process of solving the mismatched and undrained cells (e.g., Figures 7 and 8). All channels connect across all tile boundaries (Figure 10). The Integrated WAM-NetMap stream layer is fully routed and connected, including across tile boundaries, and matches the original WAM hydrography (**Figure 11**).

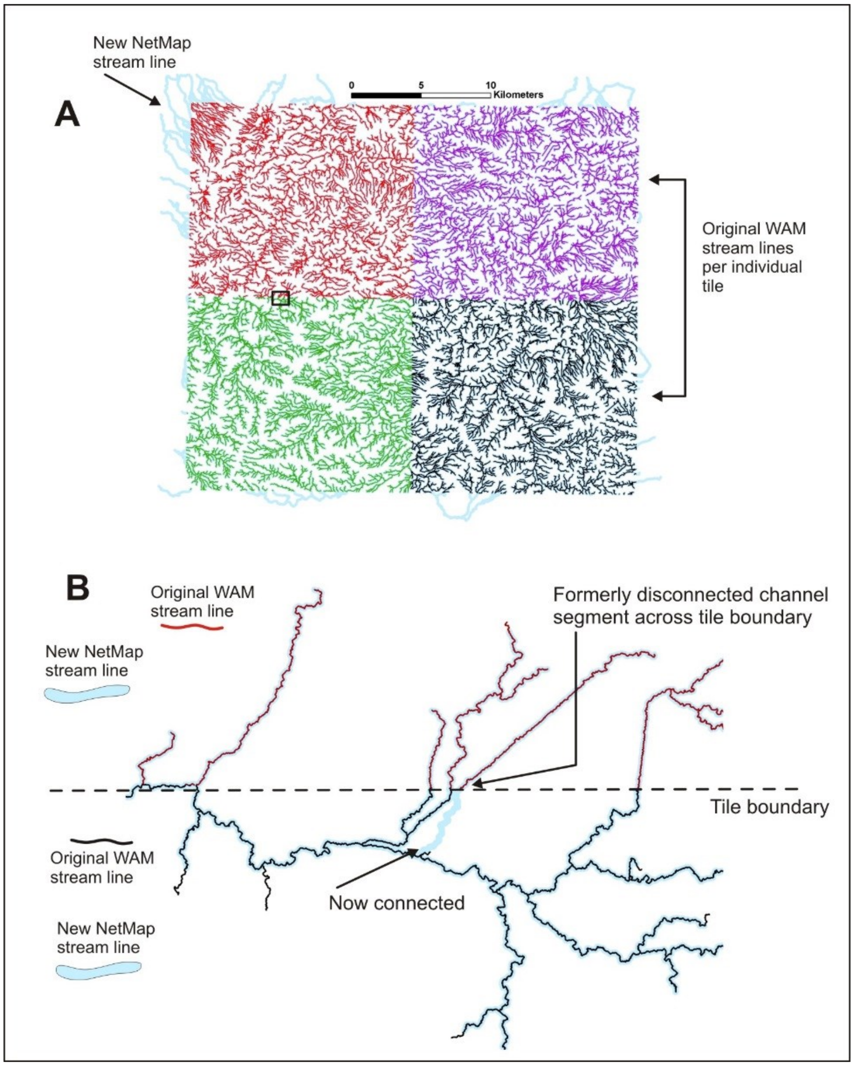


Figure 10. An example of the matched flow lines across a WAM-LiDAR tile boundary.

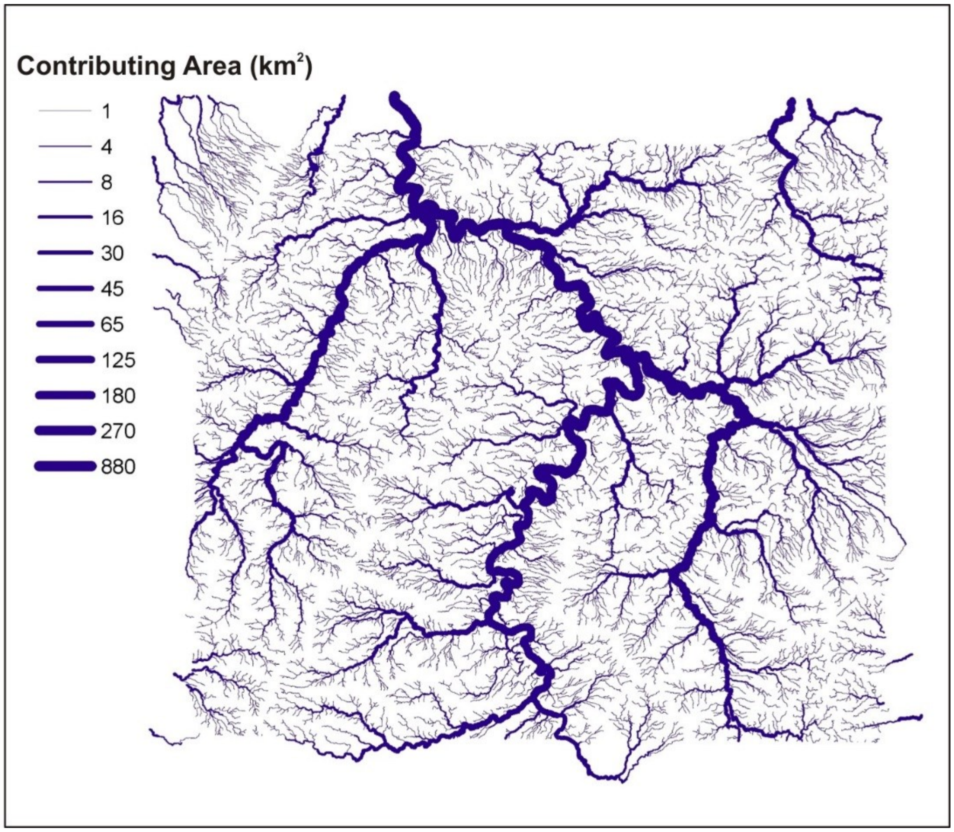


Figure 11. The completed and routed river shape file across all four WAM-LiDAR tiles, as the composite synthetic stream layer for use in the Integrated WAM-NetMap.

4.2 Task 2: Attribute the Integrated WAM-NetMap Stream Layer for Spatially Explicit Riparian Delineation and Environmental Settings

There are a range of riverine and terrestrial attributes that are necessary to create a spatially explicit delineation of riparian zones and for identifying environmental settings. The attributes are derived from the Integrated WAM-NetMap synthetic stream layer and its virtual watershed (Figure 1). Attributes include drainage area, gradient, azimuth, sinuosity, and channel hydraulic geometry (bankfull width and depth), among others (**Table 1**). The attributes are used in the riparian process and environmental settings analyses. A brief description of the primary parameters follow.

Table 1. List of attributes contained within the Integrated WAM-NetMap 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^3s^{-1})	Aquatic (Fish) Habitats*
Mean annual precipitation (m)	Mean annual flow (m^3s^{-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)	

* analysis not conducted but could be using the Integrated WAM-NetMap

**data not available

4.2.1 Riparian-Aquatic Attributes

Synthetic Stream Layer (Integrated WAM-NetMap).

The composite WAM-NetMap stream layer (Figure 11) is comprised of a node based data structure, delineated at the scale of the 1 m LiDAR (**Figure 12**). From the nodes, individual channel reaches are created at a length scale that ranges between about 100 to 150 m. Each stream reach delineates its local contributing watershed area draining to both sides of the channel, an attributed called ‘drainage wings’ (Figure 12). 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 between terrestrial, riparian and riverine systems to be identified. For example, drainage wings support lateral truncation of individual riparian process zones (in the riparian delineation tool, see below) and supports searches for overlaps between areas of the highest erosion potential and the most sensitive fish habitats.

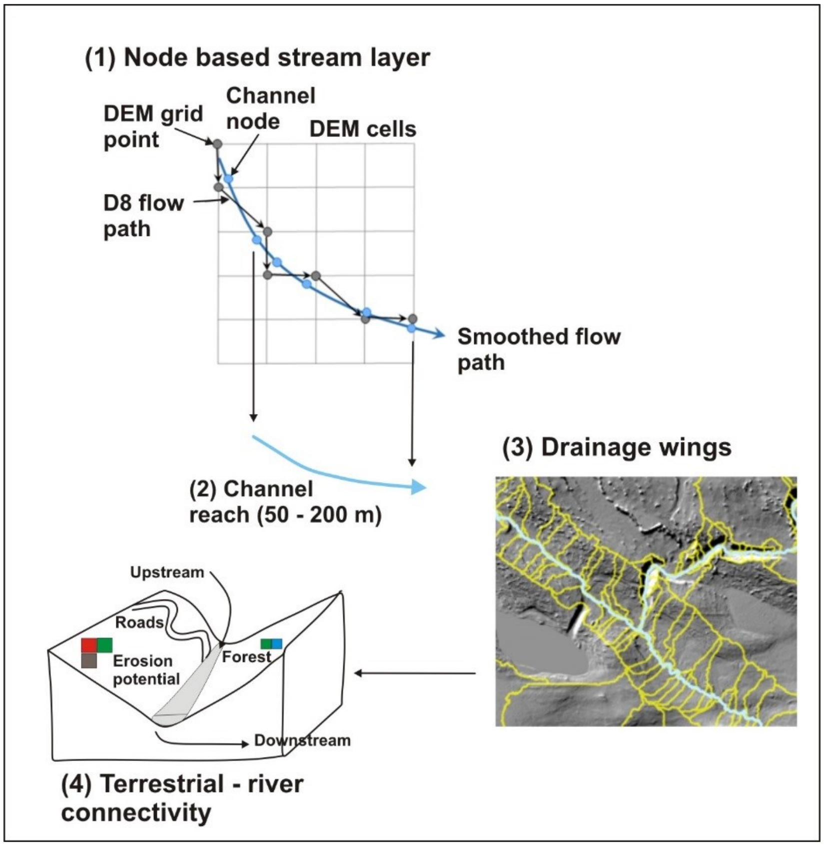


Figure 12. The Integrated WAM-NetMap node based synthetic stream layer with drainage wings.

Depth to Water (WAM)

The Wet Areas Mapping, or WAM, is a cartographic depth to water (DTW) prediction using topographic analysis of soil moisture and is developed by Alberta Provincial Government (White et al. 2012) and by University of New Brunswick (Murphy et al. 2009, Ogilvie et a. 2011) utilizing available 1 meter LiDAR DEMs (Figure 2). For additional information, see: http://watershed.for.unb.ca

Drainage Area

Drainage area is based on flow accumulation and is the sum of all pixels located upstream of every delineated channel segment.

Channel Gradient

Reach gradient is calculated from the DEM at the scale of channel nodes (e.g., Figure 12). The channel gradient calculation in the Integrated WAM-NetMap uses a dynamic window length that ranges from 500 m in lower, less steep areas of valleys (~0.001) to 50 m in the steeper portions of valleys (~0.20). The

DEM-inferred gradient using the delineated flow path applies a nine-point surface polynomial as described by Zevenbergen and Thorne (1987). NetMap's Calculate Channel Gradient tool can be used to recalculate channel gradients over any length scale, including the ability to search for waterfall barriers.

Azimuth

The angular distance along the arc of the horizon measured between a fixed point (as true north) and the predominant direction of the stream, in the downstream direction, clockwise from the north point through 360 degrees.

Bankfull Channel Width

Bankfull channel width is 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 (Table 2) but NetMap contains a tool to recalculate bankfull channel width.

Table 2. Hydraulic geometry relationships used in the Pilot Simonette 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

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 (Table 3) but NetMap contains a tool to recalculate bankfull channel depth.

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.

There are two types of valley mapping in the Integrated WAM-NetMap in the Simonette Pilot project area: 1) floodplains, at varying heights above the channel and (2) valley surfaces pertaining to terraces, off-channels, ox-bow lakes, and alluvial fans in absolute elevation (**Figures 13 and 14**). 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/ .

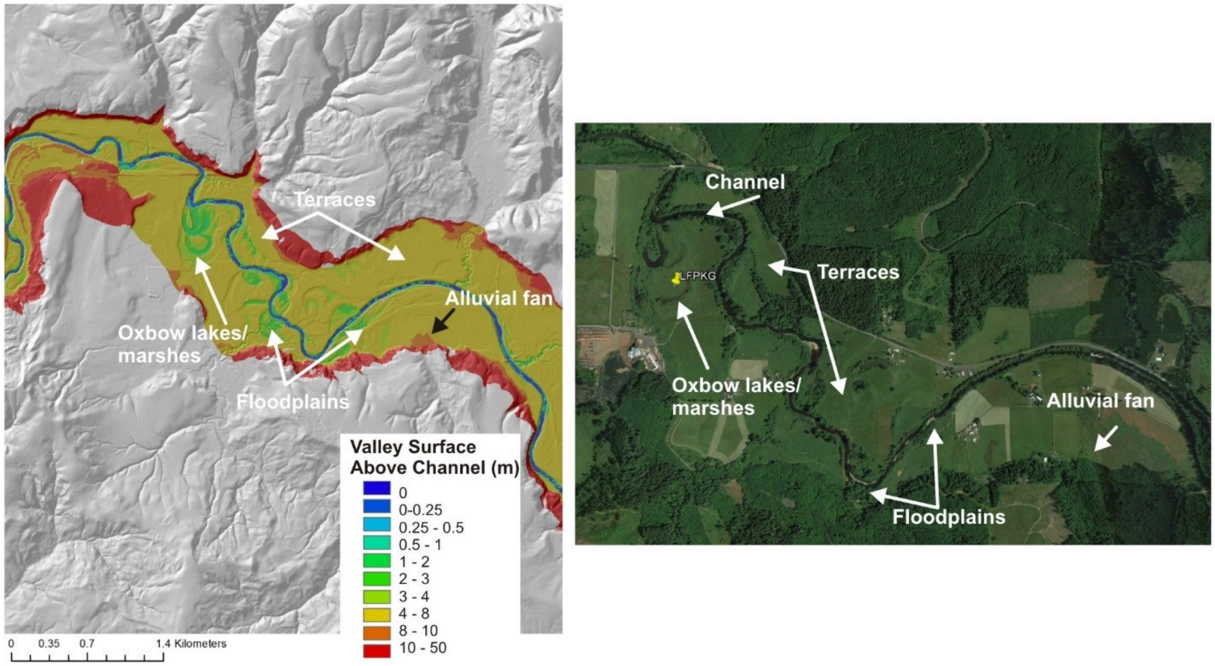


Figure 13. An illustration of valley floor mapping in the Integrated WAM-NetMap.

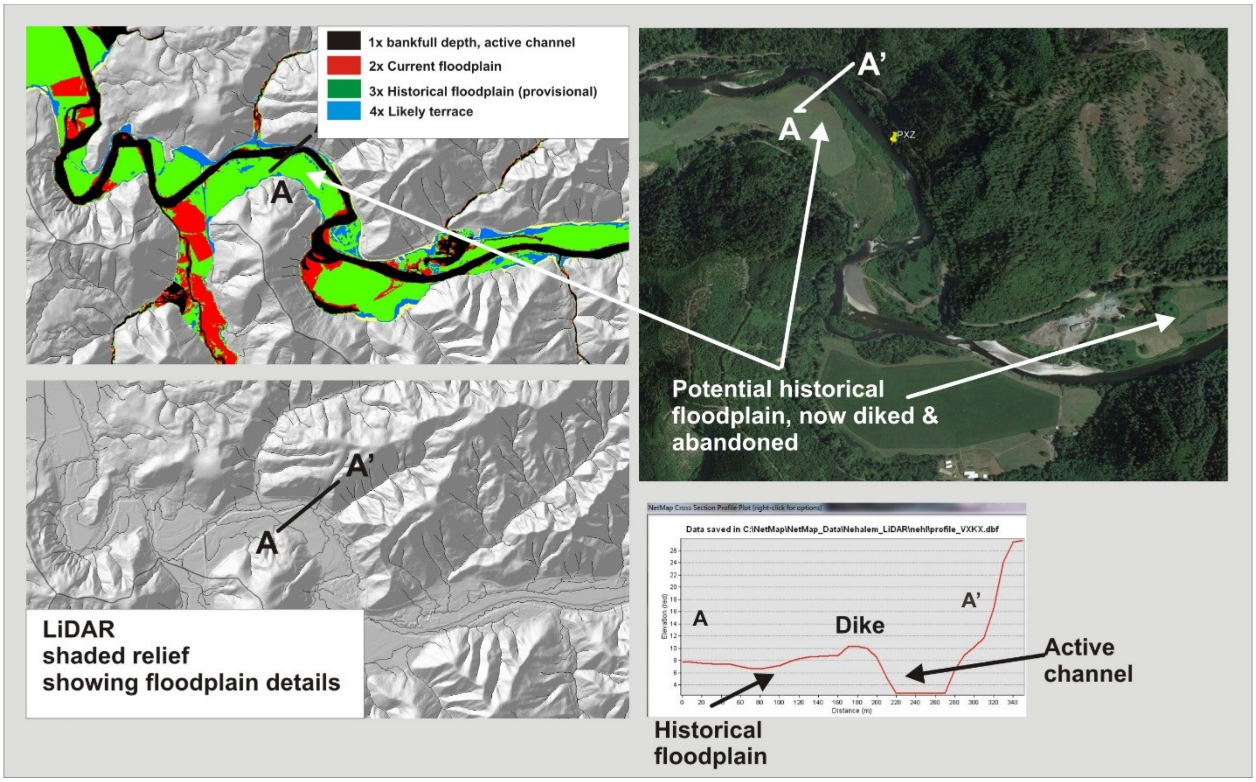


Figure 14. An application of floodplain mapping in the Integrated WAM-NetMap.

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, mean annual precipitation gridded data were obtained from PRISM.

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.

Channel Sinuosity

Channel sinuosity is the ratio of the length of the stream channel (including its meanders) divided by the straight line distance between any two points along the channel. The dimensionless ratio of sinuosity provides an index of how meandering a channel is. The WAM stream lines that were used in the Integrated WAM-NetMap have a high degree of sinuosity that is significantly greater than the sinuosity of the actual channels (**Figure 15**). In future analyses involving the Integrated WAM-NetMap, a smoothing algorithm could be applied to reduce the sinuosity of the synthetic stream network.

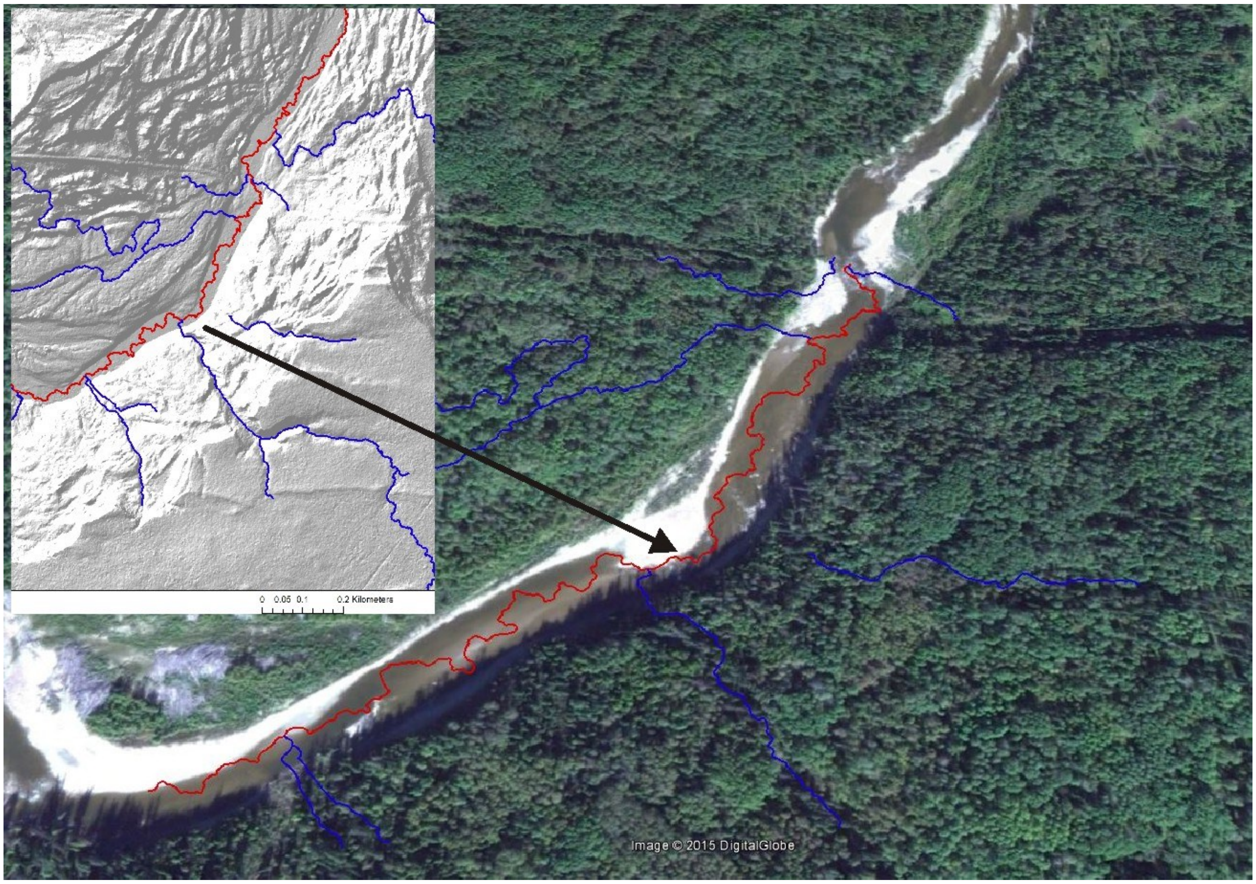


Figure 15. Sinuosity of the stream lines in the Integrated WAM-NetMap is significantly greater than natural river channels in the study area.

4.2.2 Environmental Setting - Attributes

The primary objective of the Phase I Simonette pilot project is to evaluate riparian processes and delineate riparian zones. Environmental settings can be optionally used to enhance designs of stream side protection areas or buffers, but is not considered in this study. However, the Integrated WAM-NetMap can be used to identify various environmental settings (Table 1) and to incorporate them into riparian buffer design in the future by other analysts. Several environmental setting attributes in the Integrated WAM-NetMap are briefly described below.

Channel Types (Stream Classification)

Channel morphology influences how riparian processes affect aquatic habitats. For example, steeper boulder bedded channels are less sensitive to inputs of large wood compared to lower gradient channels with gravel substrate (Benda and Bigelow 2014). Popular empirically based channel classification systems include Rosgen (1996) and Montgomery and Buffington (1997) and they have been used to consider channel response to riparian processes. However, given the unique boreal landscape of the Simonette River system, new classification systems may need to be developed.

One example of a site specific, locally calibrated classification system in Alberta was developed by the University of British Columbia (UBC) and the Foothills Research Institute (FRI). Categories included uplands, swales, seepage-fed channels, and fluvial channels; it also included a classification for ephemeral, intermittent, and permanent channels that could be incorporated into riparian management (McCleary et al. 2011). This classification could be potentially applied to the upland areas of the Simonette basin.

Fish Habitats, Distribution, Likelihood and Quality

Predicting the distribution, abundance and quality of the habitats of freshwater dwelling species is becoming common and can be used as an environmental setting to support watershed management planning, including design of riparian buffers (Burnett et al. 2007, Peterson et al. 2008, Bidlack et al. 2014). In the Rocky Mountain foothills region of Alberta, locally calibrated fish habitat models were developed for bull trout [*Salvelinus confluentus*] and rainbow trout [*O. mykiss*]) (McCleary and Hassan 2008). This type of fish habitat model could be used in the more montane areas of the Simonette River basin, but other more site specific fish habitat predictions might be required for boreal areas.

Riparian zone dimensions in the Simonette basin could be influenced by fish habitat distribution and quality. For example, larger buffer widths could target high value fish species (habitats) while smaller buffers may be more applicable along streams with no fish or less sensitive species; often regulatory fixed-width buffers differ based on fish-bearing versus non fish-bearing streams (Young 2000).

Hillslope Erosion Potential

Hillslope erosion can impact riparian areas and associated aquatic habitats including by shallow landslides, debris flows and surface erosion. Landforms, often referred to as “inner gorges”, form next to streams because of heighted channel erosion and they have been highlighted in forest practice rules and included within riparian buffers (WFPB 1997). Similar to the other remote sensing capabilities in the Integrated WAM-NetMap, erosion potential, particularly for shallow failures, can be predicted accurately using 1 m LiDAR DEMs.

Using a topographic index that combines hillslope gradient, planform curvature and drainage area per unit contour length, NetMap’s Generic Erosion Potential provides an index measure of shallow landslide susceptibility in the Simonette River pilot project area. In addition, there are gully erosion, debris flow and surface erosion tools available that can be used in the Integrated WAM-NetMap. See NetMap online Technical Help for descriptions of available erosion tools.

Channel Migration Zones

Channel migration zones (CMZ) are often considered in the context of riparian buffer design (WFPB 1997). In areas where channel migration is likely, riparian management may need to account for lateral channel movement. CMZs are often identified through ocular analysis of sequential sets of aerial imagery that reveals the rate and direction of channel movements. However, in the context of the Integrated WAM-NetMap, remote sensing analysis using LiDAR of valley floor elevations, wet areas and associated landforms such as oxbow lakes and off-channels, can be used to identify provisional areas of channel anastomosing and areas of avulsions (Figure 13).

Often CMZs are considered separate from riparian buffer zones, including in regulatory programs. However, they can be considered in conjunction with riparian management alternatives.

Thermal Refugia

Thermal refugia refers to locations within a channel network where intrinsic landscape controls on thermal energy loading to streams, combined with current shade conditions, lead to cooler (or conversely warmer) water conditions. In the Integrated WAM-NetMap, bare earth thermal energy is an environmental setting attribute, values of which are highly dependent on physical parameters such as latitude, solar angle, topographic shading, channel width and channel orientation (azimuth); see more information about thermal loading in NetMap here. In addition, the WAM-NetMap uses estimated shade (reducing bare earth thermal energy) derived from available tree height and basal area (see tool here).

The shade-thermal energy model (in the Integrated WAM-NetMap) allows analysts to predict where, along channels at the scale of reaches, thermal refugia might form, or at the scale of entire tributaries (e.g., downstream aggregated shade-thermal energy conditions). In addition, the confluence of different aggregated shade-thermal energy conditions at tributary junctions can reveal which channel junctions may offer thermal refugia, particularly for thermal sensitive fish species, such as salmonids.

The shade-thermal energy analysis in the Integrated WAM-NetMap can be used to identify where additional shade may enhance cold water conditions such as in areas where streamside vegetation has been impacted by wildfire, timber harvest or other activities. Hence, shade can be incorporated into riparian zone delineation (see below) or be considered from a restoration perspective in designing riparian buffers.

Tributary Confluence Effects

Tributary confluences are known ecological hotspots because they provide additional flow, food, nutrients, cool water, migration avenues and habitat diversity (Benda et al. 2004). Tributary confluence zones may also have higher rates of channel migration. This, riparian buffer design could incorporate protection of key tributary confluences. The Integrated WAM-NetMap includes a prediction of potential tributary confluence effects in the Simonette River pilot project area. For additional information on the confluence effects model, see here.

Wildfire Risk

Wildfire risk, in terms of fire probability and severity, may be an important consideration in the design or riparian buffers and in their management. In some areas due to past timber harvest and suppression of wildfires, streamside riparian areas may have high fuel loads. Although often riparian buffers are often put off limits to timber harvest (selection or thinning), management within buffers might be warranted to reduce wildfire risk.

In the Integrated WAM-NetMap, data on fire probability and severity can be incorporated into the synthetic river network; for additional information on this capability, see here. However, data on wildfire risk were not available in the Simonette pilot project area, but could be incorporated in the future when such data becomes available.

Climate Change Vulnerability

Climate warming is a growing concern in many areas of North America, including in Alberta. It can lead to increased stresses including more intense droughts and wildfires, as well as changing flow patterns and warming water temperatures. Climate change forecasts can include winter and summer temperatures, snow accumulation, snowmelt runoff and summer and winter flows. Thus, modified climate may have implications for aquatic ecosystems and the design of riparian zone protection areas.

Climate change forecasts can be incorporated into the Integrated WAM-NetMap to aid in the design of riparian buffers. For example, in areas predicted to have higher summer temperatures, lower summer flows and higher stream temperatures, buffers that ensure full stream shading or that preserve or enhance thermal refugia, could be strategically located. For additional information about this capability, see here.

No climate change information was incorporated into the Simonette River pilot project but such projections could be incorporated into the Integrated WAM-NetMap as they become available.

4.3 Task 3: Evaluating Riparian Processes

The third task involves evaluating riparian processes in the Simonette pilot project area using the Integrated WAM-NetMap. The analysis of riparian processes can stand alone in support of watershed management and or they can be used to delineate riparian zones (presented in Section 4.4). The riparian processes considered in the WAM-NetMap in the Simonette River basin include: (1) Wet areas (WAM), (2) Floodplains, (3) Shade-thermal energy, and (4) In-stream wood recruitment.

4.3.1 Wet Areas Mapping (WAM)

The depth to water prediction from the WAM is used to locate small streams, ephemeral channels, wet swales and associated wet soil areas in Alberta (White et al. 2012). WAM analyzes local flow patterns, soil hydrologic conditions and natural vegetation, and in context of topographic analysis of soil moisture (Murphy et al. 2009, 2011), predicts depth to water (**Figure 16**). The WAM is designed to provide decision support in the regulatory process involving forestry operations, oil and gas exploration, associated road networks and drill platforms, road-stream crossings and for parks and recreation.

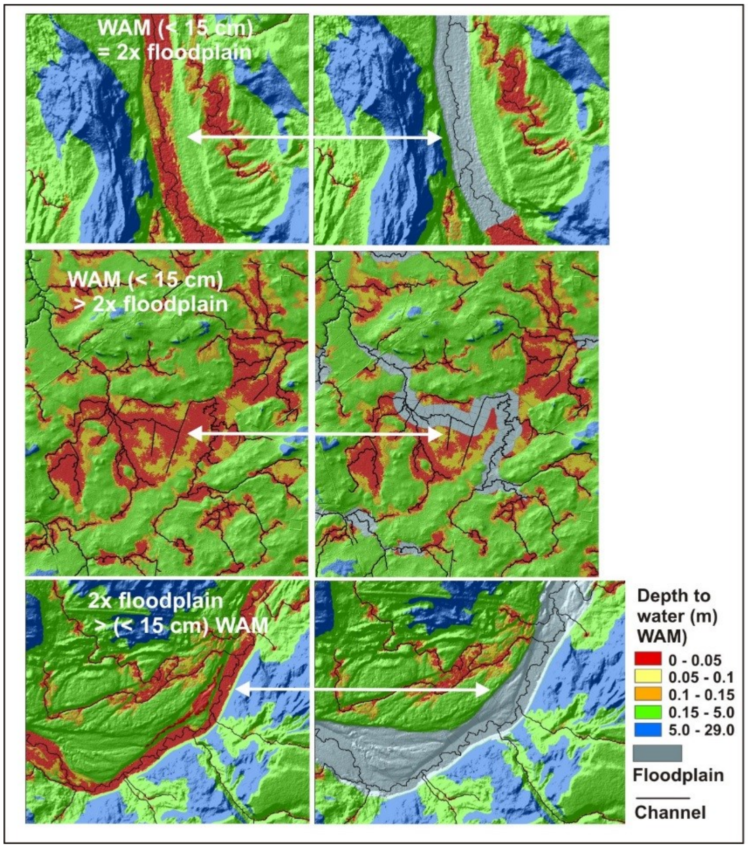


Figure 16. The WAM depth to water in the Simonette River pilot project area.

The WAM depth to water is incorporated within the Integrated WAM-NetMap in the Simonette pilot project area and it is used within the tool to delineate riparian zones (Section 4.4).

4.3.2 Floodplains

Floodplains are an important riparian zone feature and they are often considered within the context of riparian management. The method to delineate floodplains and flood prone areas is described in Section 4.2.1. A series of floodplains with increasing elevations above the channel, in terms of bankfull depths, provide a robust index of variable flooding potential in the Simonette River pilot project area (**Figure 17**). 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 Integrated WAM-NetMap are used to consider flooding potential beyond the lowest, most active floodplain and also to map the potential for channel migration.

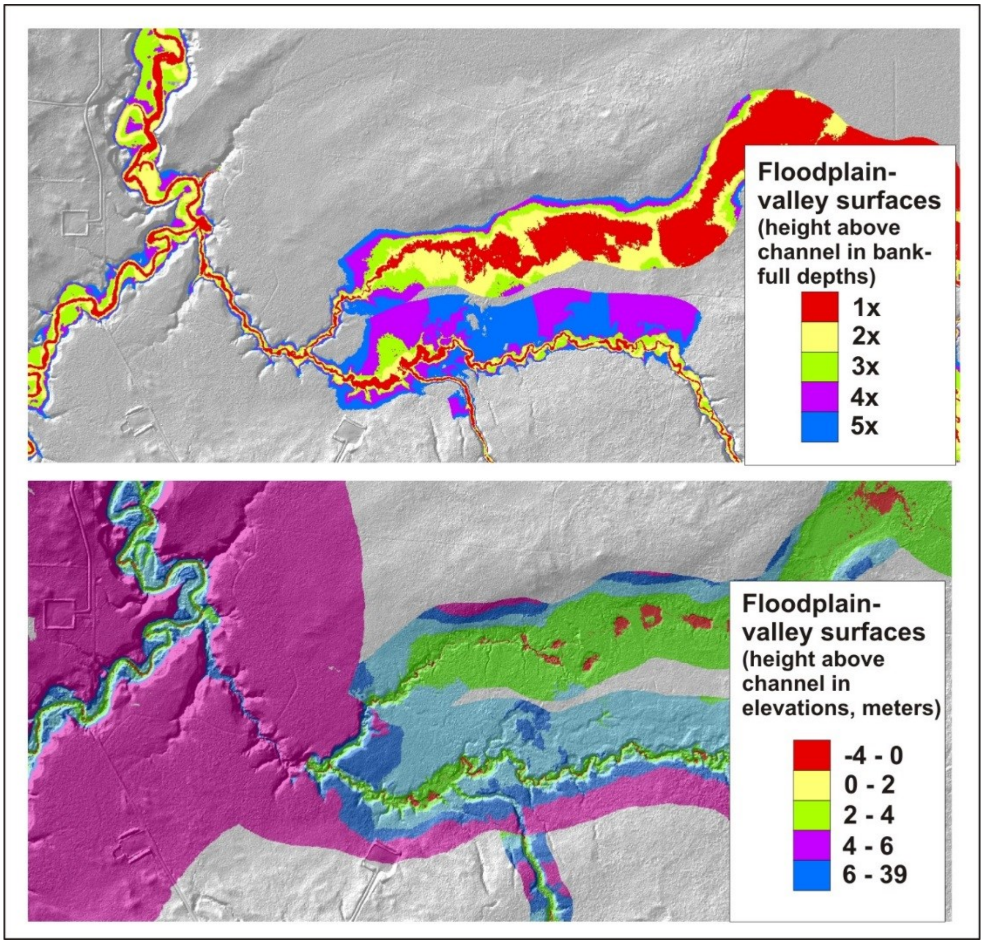


Figure 17. An example of two different types of valley floor and floodplain mapping in the Simonette River basin.

In the Simonette River pilot project area, there are locations where the lowest floodplain (e.g., elevation equivalent to two multiples of bankfull depth) is equivalent to the less-than-15 cm depth to water (WAM). In contrast, there are other locations where the WAM is greater than the floodplain and still other locations where the depth to water is less than the floodplain (**Figure 18**). The floodplain created in the Integrated WAM-NetMap can be truncated laterally when delineating riparian zones, such as in certain locations with extensive low elevation areas are adjacent to channels in the Simonette River pilot project area.

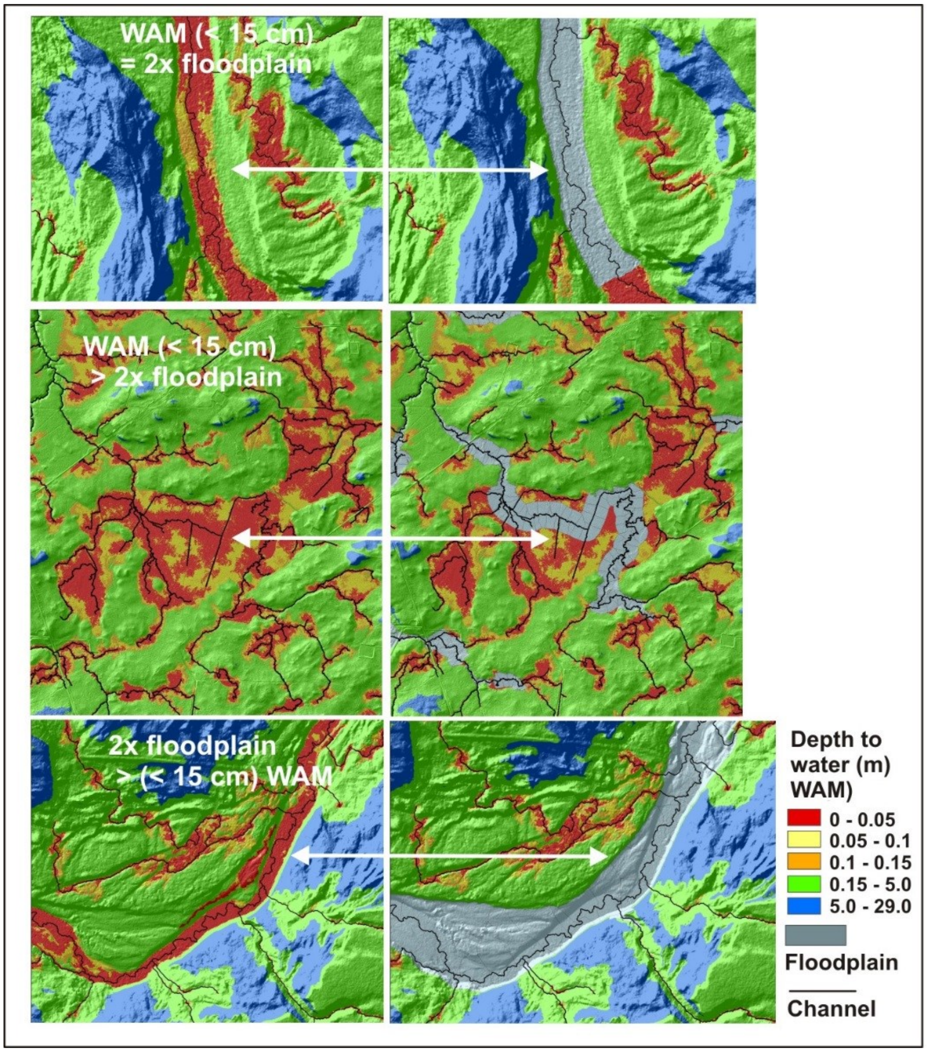


Figure 18. An example of a comparison between WAM and floodplain mapping in the Integrated WAM-NetMap.

4.3.3 Shade-Thermal Energy

The shade-thermal energy attribute in the Integrated WAM-NetMap is described in Section 4.2.1. The Integrated WAM-NetMap creates several data types including: (1) bare earth radiation to streams, (2) the role of current shade, using tree height and basal area, on reducing thermal energy to streams, (3) an estimated maximum shade level using an optimum tree height and basal area, and (4) the difference between (1) and (3) to determine where shade increases would be most effective.

The predicted bare earth radiation is shown in **Figure 19** and the current thermal loading to stream channels due to shade is shown in **Figure 20**. The remaining predictions described above can be accessed in the Integrated WAM-NetMap Simonette River pilot project.

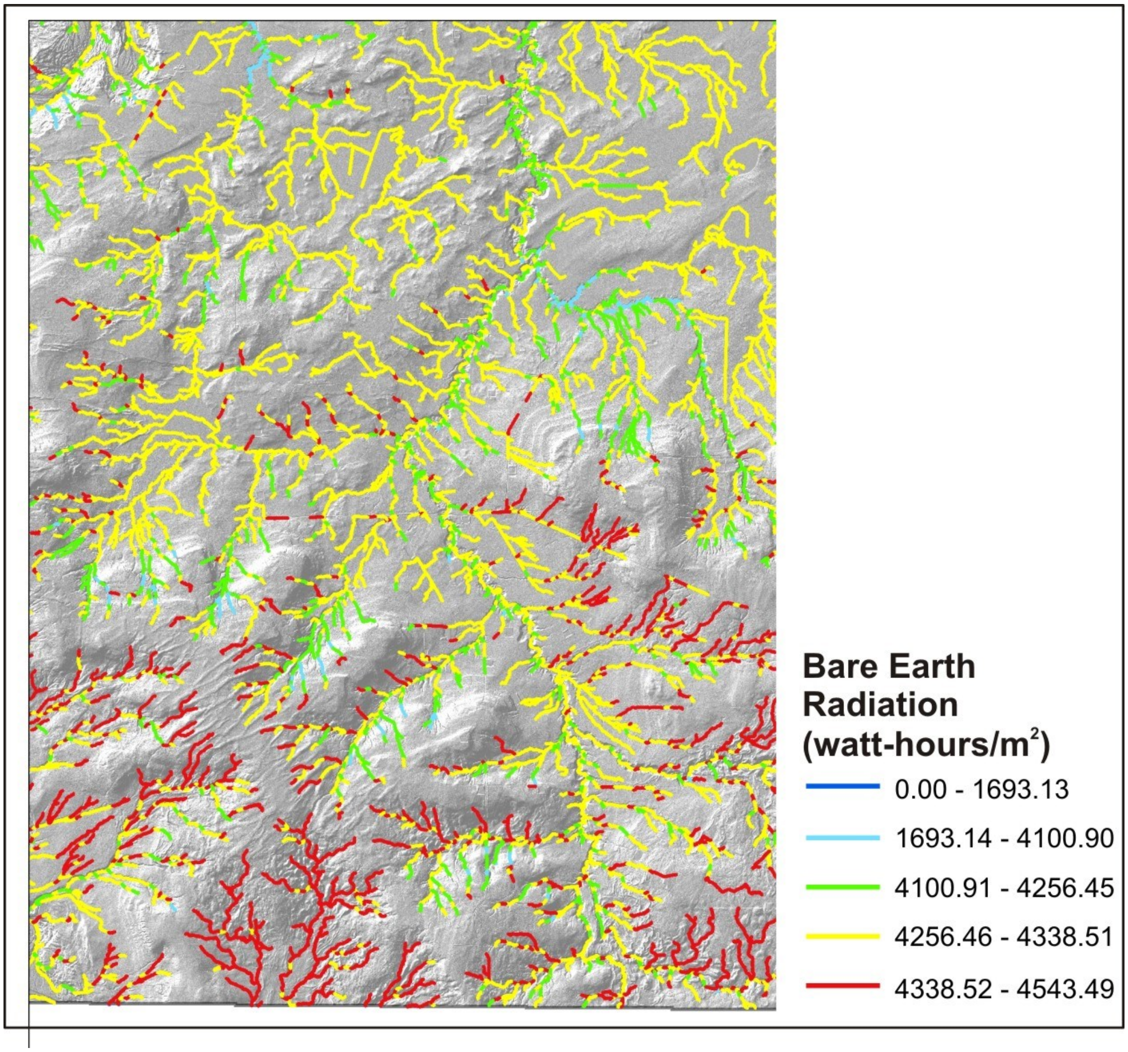


Figure 18. Bare earth radiation loading to streams in the Simonette River.

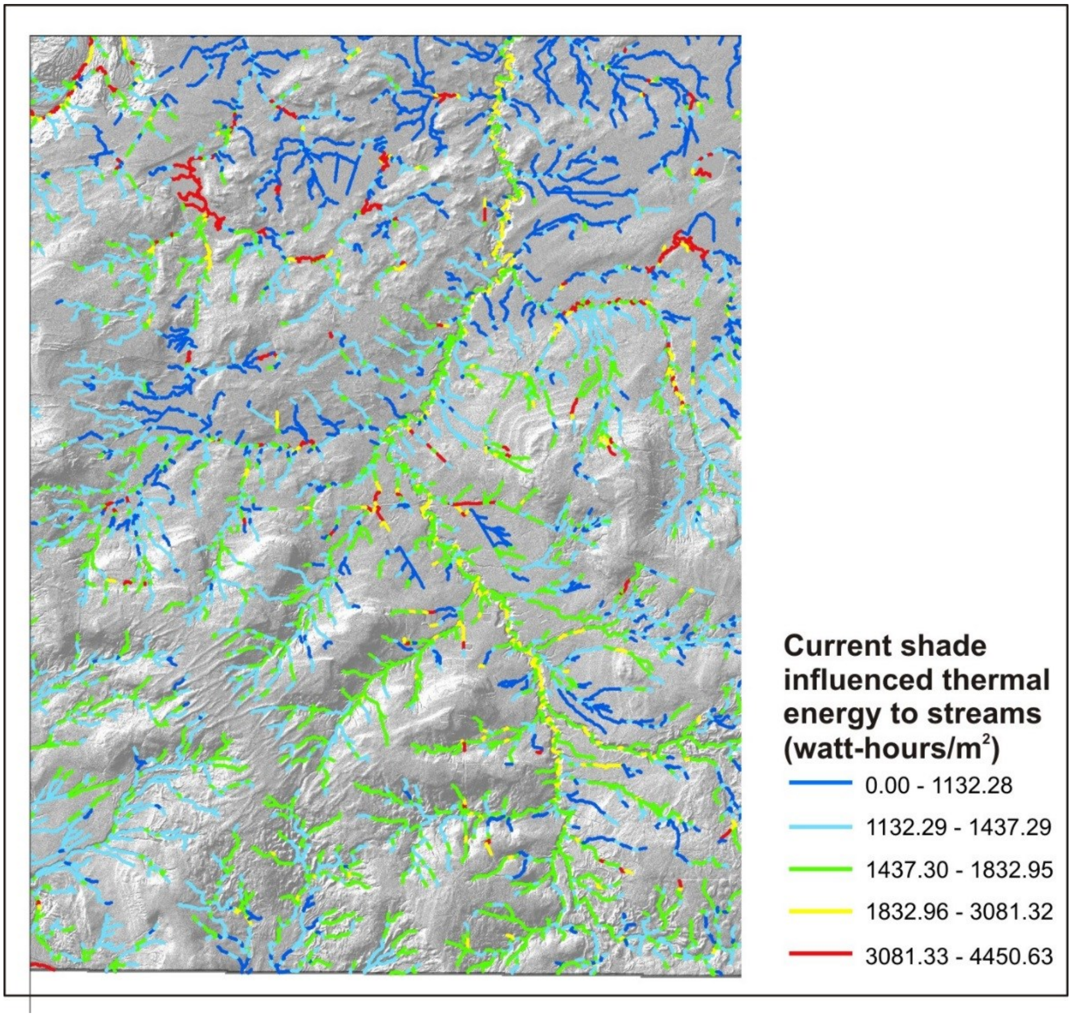


Figure 19. Current streamside shade influenced thermal energy to streams using basal area and tree height.

4.3.4 In-stream Wood Recruitment

The Integrated WAM-NetMap contains a tool for predicting watershed scale in-stream wood recruitment potential; see model overview here. The model uses remote sensing data on tree height, stand density and the mean quadratic diameter (which is expanded to include the full hypothetical distribution of tree sizes). The current Alberta vegetation data are not in the correct format to be used within NetMap's in-stream wood recruitment tool. This aspect of the analysis will be part of the Phase II Alberta project.

4.4 Task 4: Delineating Spatially Explicit Riparian Zones

The fourth and final task is to delineate riparian areas inclusive of four riparian processes in the Integrated WAM-NetMap system: (1) depth to water (WAM), (2) floodplains, (3) in-stream wood recruitment potential and (4) current shade - thermal energy to streams. The model framework (**Figure 21)** provides a flexible and site specific approach to riparian zone delineation. In the model, any combination of the four riparian processes are integrated within the delineated riparian zone at the watershed scale; the model is applied to the Simonette River pilot project area as a demonstration.

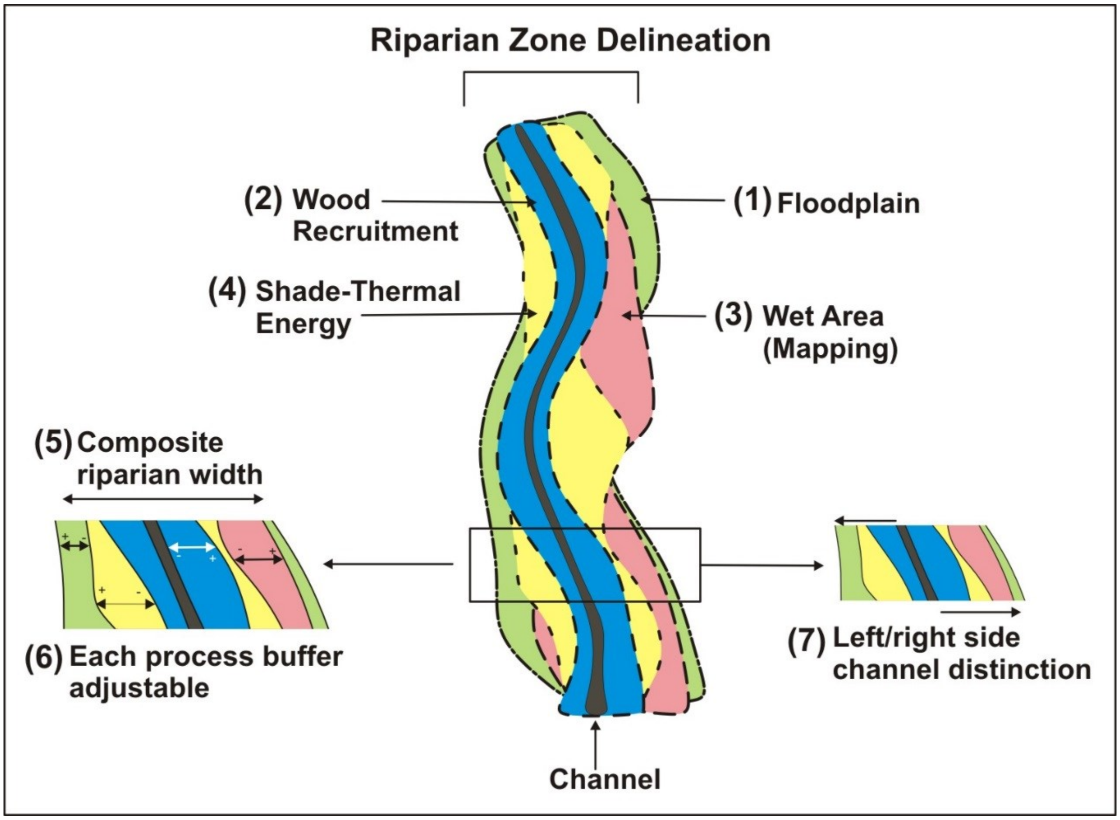
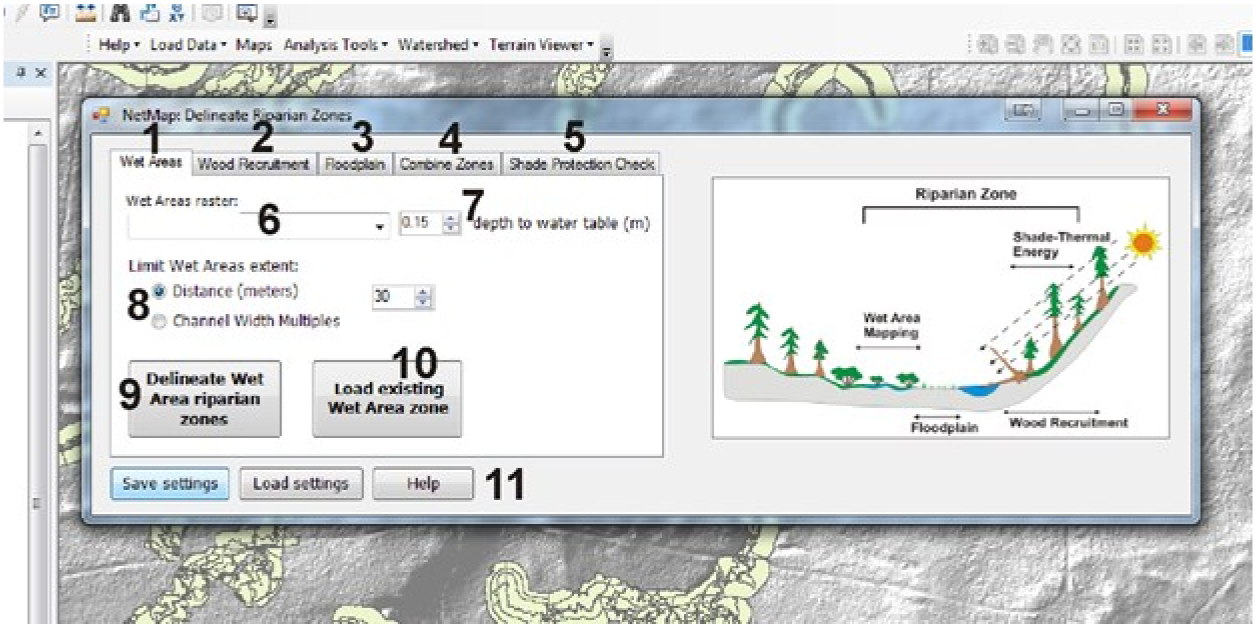


Figure 20. The Integrated WAM-NetMap Riparian Delineation Tools can encompass any combination of four riparian processes.
The delineated riparian zone, encompassing up to four riparian processes (1-4) is a composite of the selected ones (5). (6) Each process riparian zone extent can be adjusted with lateral extent thresholds. (7) The delineated riparian zone has left channel – right channel distinction.

An analyst selects which ones of the four riparian processes to consider (any number between one and four processes). NetMap's riparian delineation tool allows analysts to make adjustments to each of the riparian processes considered. 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). Running the model is illustrated in **Figures 22 through 28.**


NetMap: Delineate Riparian Zones

Wet Areas raster:

0.15 depth to water table (m)

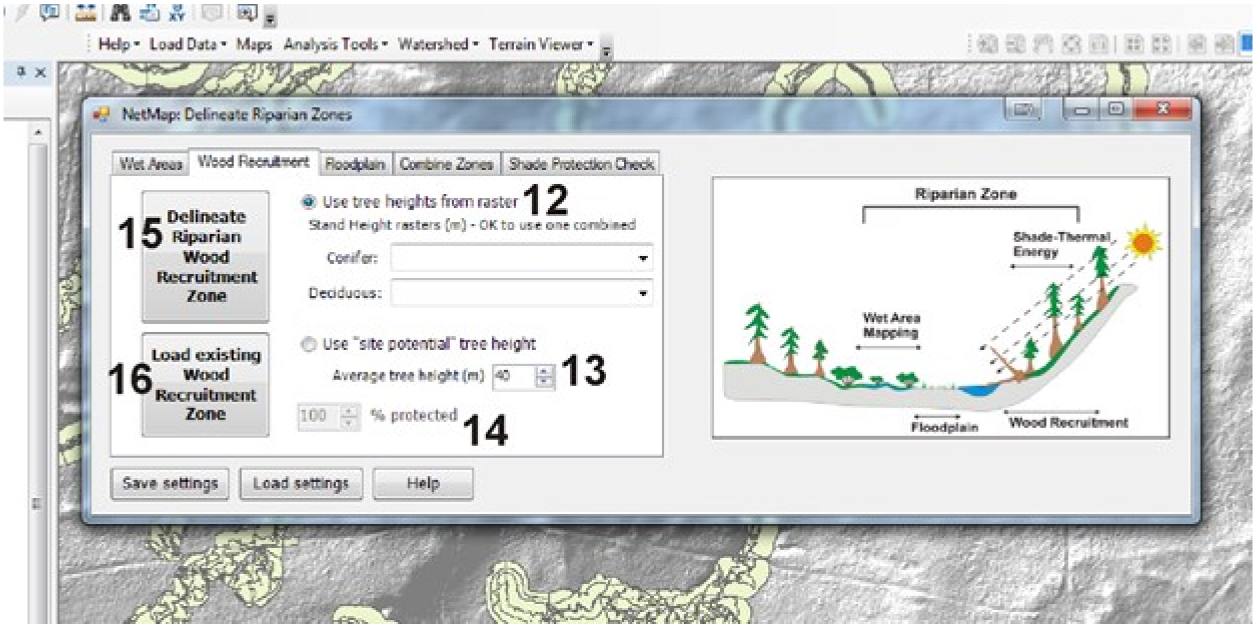
Limit Wet Areas extent:

● Distance (meters) 30

○ Channel Width Multiples

Figure 21. The Integrated WAM-NetMap Riparian Zone delineation tool has five components and five tabs.

Of the five tabs in the tool (1-5), the first one shown in this figure (1) addresses "wet areas". In this example wet areas are defined as the distance between ground surface and ground water table. (6) A wet area data file (raster shapefile) is selected. (7) A threshold for depth to water is defined, such as < 0.15 m. (8) The delineated wet areas can be limited in lateral extent. (9) The wet areas that are to be included in the riparian zone are delineated. If the analysis has already occurred, a user can simply load the polygon shapefile showing this zone (10). The tool contains a few save and load data settings (11).



● Use tree heights from raster 12

Stand Height rasters (m) - OK to use one combined

Conifer:

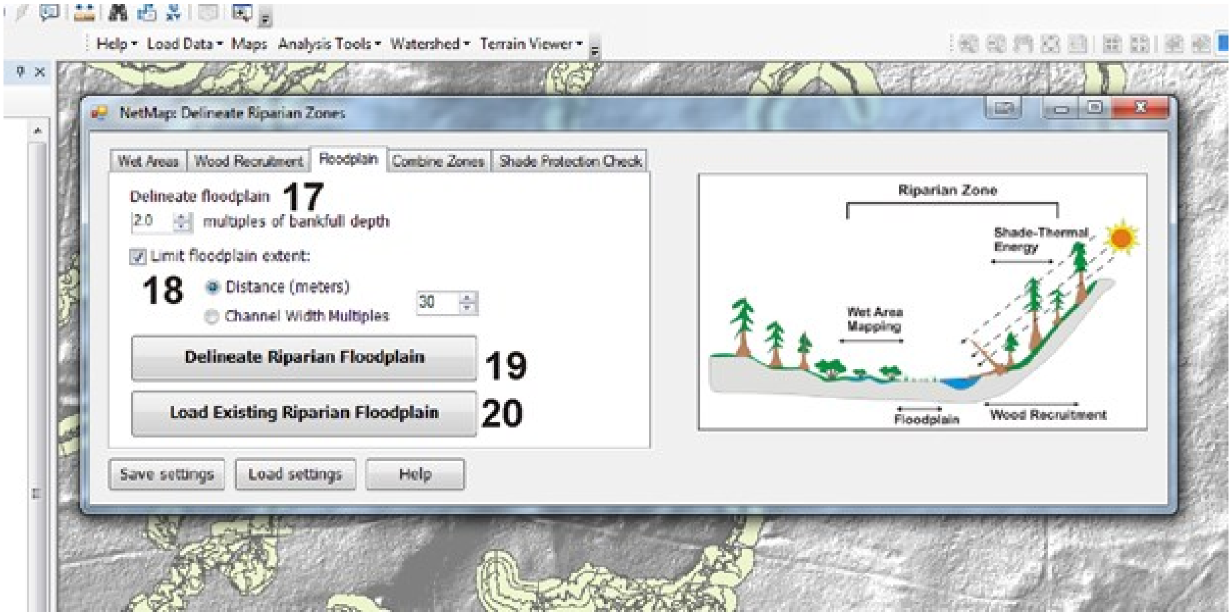
Deciduous:

○ Use "site potential" tree height

Average tree height (m) 40 13

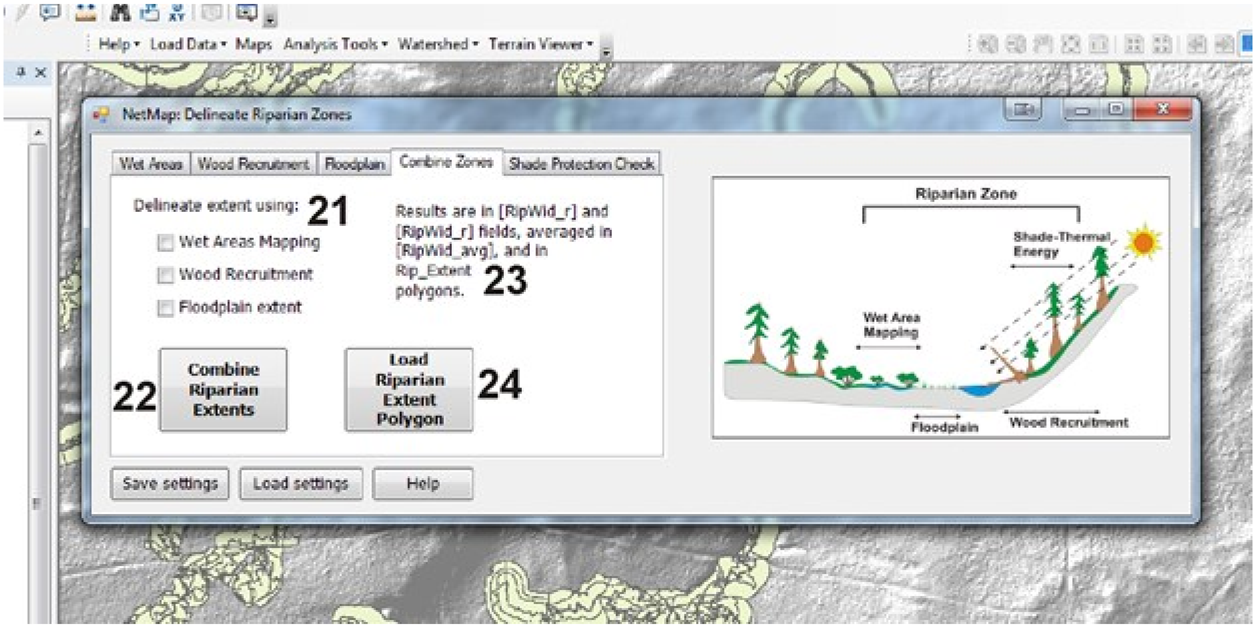
100 % protected 14

Figure 22. Step 2 in delineating riparian zones involves in-stream wood recruitment.
(12) A user can select a raster of tree heights, and separate rasters for conifer and deciduous can be selected if available; if both are selected, then the maximum tree height is used. If no tree height rasters are available or if they contain data that represents altered forest conditions (e.g., lack of trees, shorter trees due to fire or timber harvest), then a user can apply a "site potential" tree height everywhere along the streams. (14) The proportion of tree volume recruited to the stream (0 - 100%) can be selected (14); this feature will be activated by summer 2015. (15) The riparian zone predicted by in-stream tree recruitment is calculated. If the tool has already been run, a user can simply load the riparian instream wood recruitment zone, with left channel - right channel distinction (16).



Delineate floodplain **17**
2.0 multiples of bankfull depth
☑ Limit floodplain extent:
18 ● Distance (meters) 30
○ Channel Width Multiples

Figure 23. A floodplain type is selected, defined by the number of bankfull depths above the channel that was used in NetMap's floodplain mapping tool.
(17) A floodplain is selected, defined by an elevation above the channel in increments of bankfull channel depths. (18) The lateral extent of the floodplain can be limited; e.g., in low gradient and wide valley floors, active floodplains can extend for kilometers. (19) The floodplain component of the riparian zone is delineated. If the tool has previously been run, a user may simply load the floodplain - riparian zone, with left channel - right channel distinction (20).



Delineate extent using:

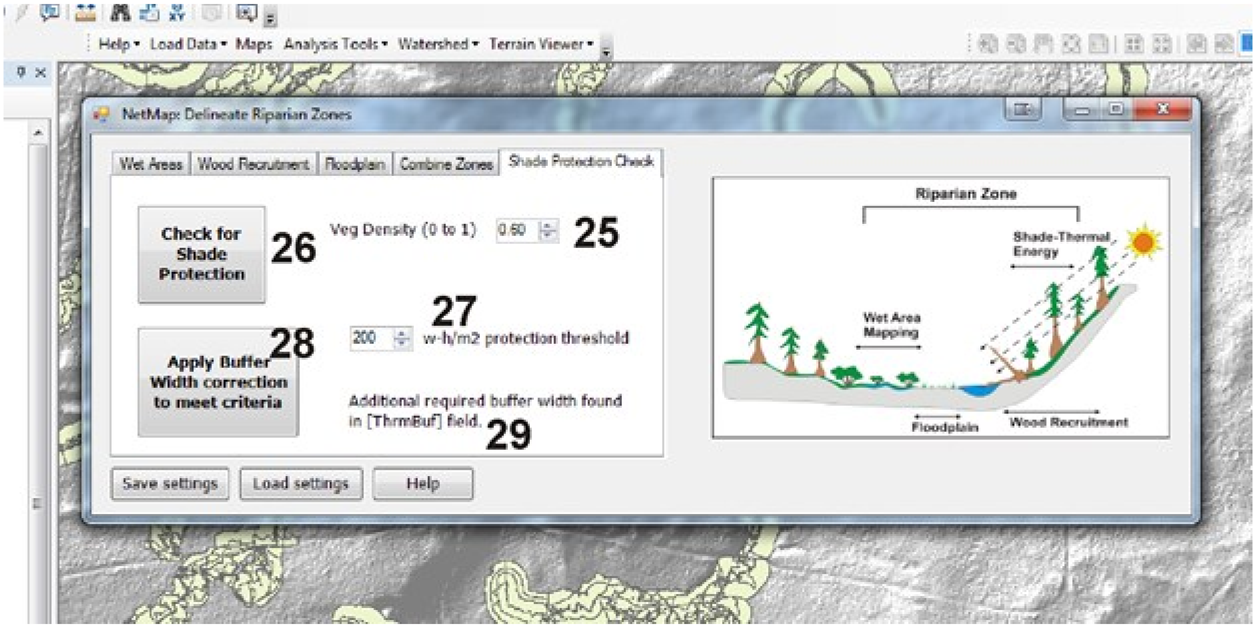
☐ Wet Areas Mapping

☐ Wood Recruitment

☐ Floodplain extent

Results are in [RipWid_r] and [RipWid_r] fields, averaged in [RipWid_avg], and in Rip_Extent polygons.

Figure 24. This tab allows a user to combine the delineated riparian zones for wet areas, in-stream wood recruitment and floodplains.
(21) A user can select one, two or all three riparian zone process to combine. (22) When combining the zones, the maximum extent of the three is used to delineate the single, riparian zone lateral extent, at the scale of individual channel reaches (of approximately 100 m length scale) with left channel - right channel distinction. The output data layer names are shown on the interface (23). If the tool had already been run, a user simply loads the polygon (24). Although the polygon encompasses the channel, the reach attributes include riparian zone left side channel, riparian zone right side channel, the average riparian zone width and the total riparian zone width.



Veg Density (0 to 1) 0.60

200 w-h/m2 protection threshold

Additional required buffer width found in [ThrmBuf] field.

Figure 25. An option in NetMap's riparian zone delineation tool is to check on whether the delineated riparian zone provides the required thermal protection.

In this calculation, the width of the delineated riparian zone (with channel right side and channel left side distinction) is used, along with a selected vegetation density (25), to estimate the thermal energy reaching the channel compared to a streamside vegetation with a large width component (1000 m). Users provide a thermal difference threshold value (27) in terms of watt-hours per square meter; this uses NetMap's Thermal Energy Sensitivity tool. (26) A user performs the check for shade protection and any reaches that do not meet the threshold difference (e.g., less than 200 watt-hours/m2 using the example in the interface) are identified. A user can then apply the tool (28) to calculate what additional width of the delineated riparian zone will meet the threshold difference in additional width increments of one meter (27).

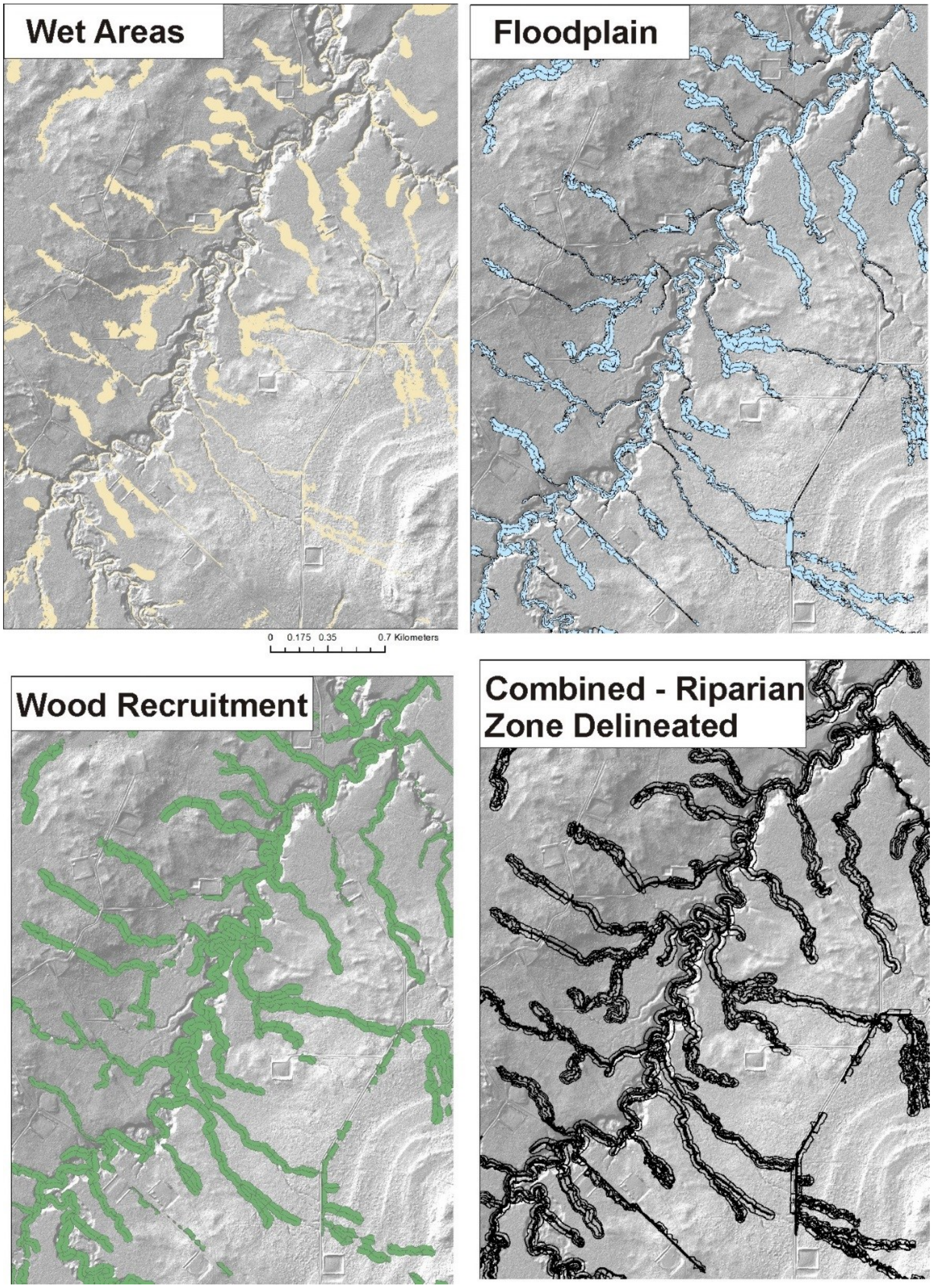


Figure 26. Each riparian zone process is delineated and then combined.
The lateral extent of each process can be adjusted by the analyst including setting thresholds for wet areas (depth to water, in this example less than 15 cm and maximum lateral extent of 30 m), floodplains (mapped at an elevation equivalent to two multiples of bank full depth and a maximum lateral extent of 30 m), and in-stream wood recruitment (100% wood recruitment included, but can be adjusted to be less than 100%).

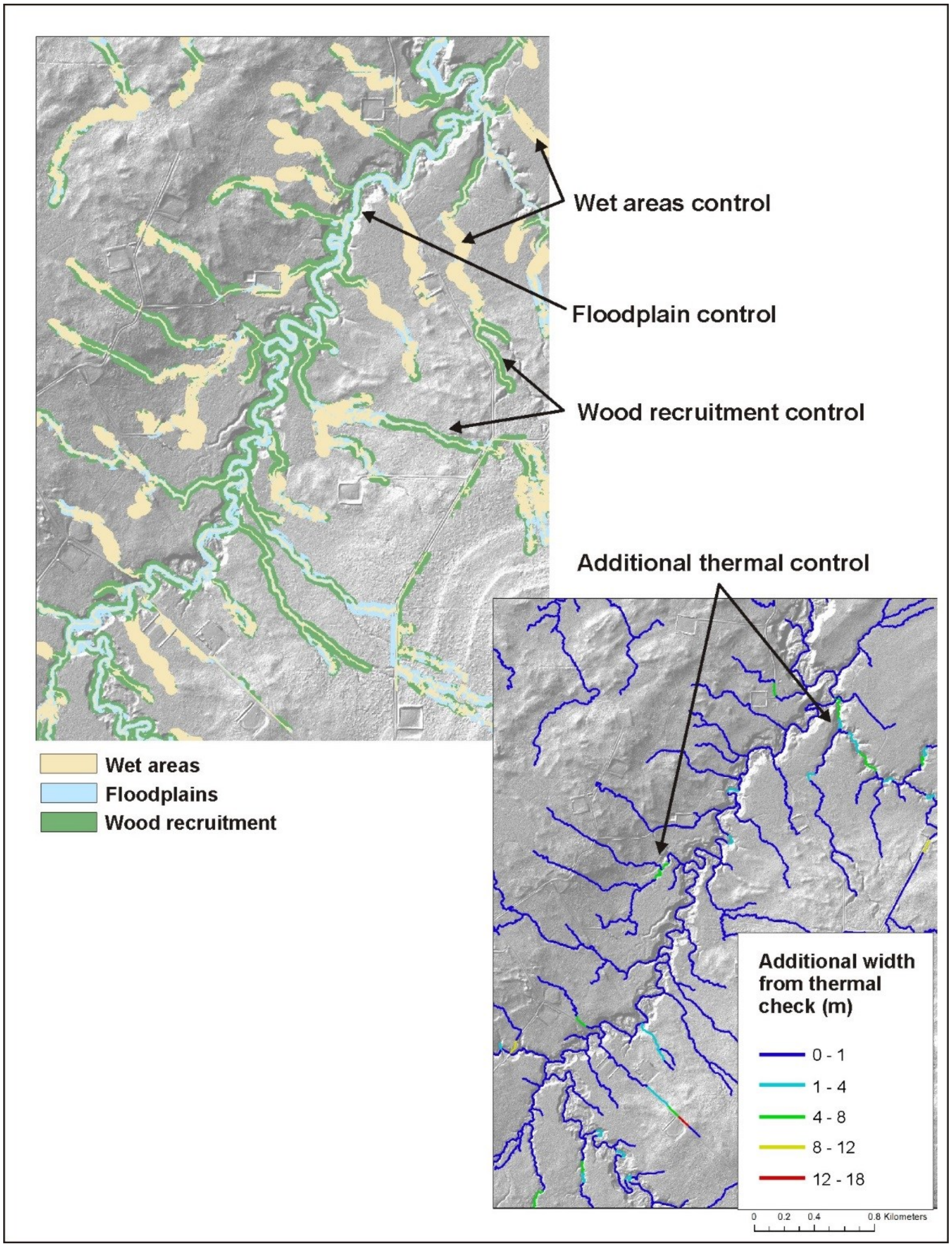


Figure 27. In a spatially variable riparian zone, wet areas control it in some areas, floodplain in other areas, and in-stream wood recruitment in yet other areas.
Thermal in-stream sensitivity can also be a factor in a subset of channel reaches.

In the Integrated WAM-NetMap, channel elevation profiles are smoothed by use of a fifth-order polynomial based algorithm to reduce the grid cell to cell variation in channel position driven by noise in the LiDAR DEM (due to dense shrub vegetation among other factors. This has the consequence, particularly in headwater basins, of sometimes altering the elevation differences between channels and the surrounding terrain, particularly in areas of subtle topography. In the Simonette pilot study area, this can result in overly narrow floodplains; this error of approximation is limited to small headwater channels. However, this issue appears to be inconsequential in terms of riparian zone delineation because the other riparian processes that can be considered, namely wet areas mapping (WAM) and in-stream wood recruitment, extend beyond the anonymously narrow floodplains, and result in an appropriate riparian zone delineation.

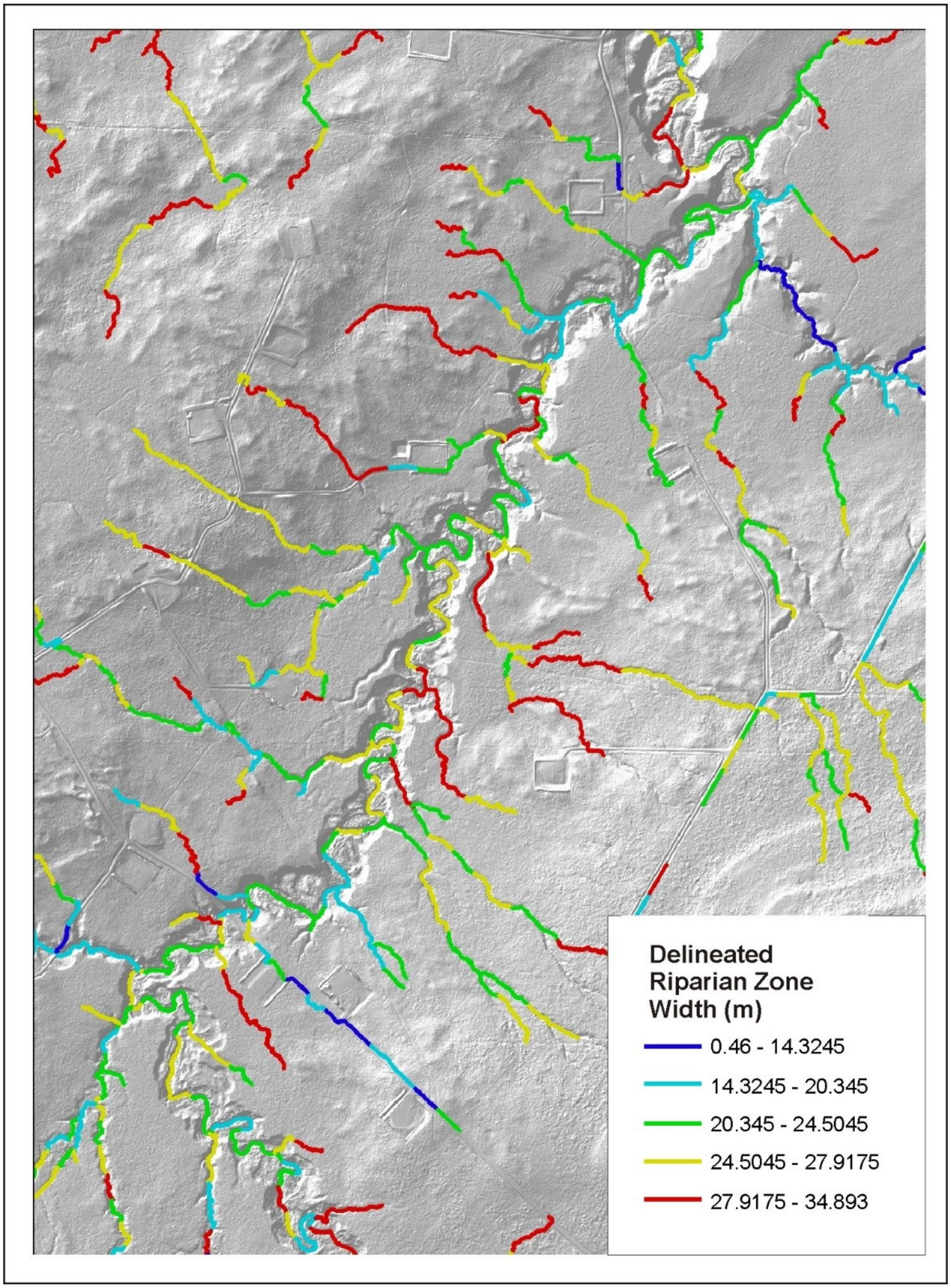


Figure 28. The width of delineated riparian zones varies from less than 14 m to 35 m, depending on the spatial variability in riparian processes, including wet areas, floodplains, wood recruitment and thermal loading.

5.0 Discussion

5.1 Toward Spatially Explicit Riparian Zone Delineation and Management

The protection of stream ecosystems through the protection of riparian forests has become a guiding principle in forest and watershed management (FEMAT 1993, Young 2000, Naiman et al. 1998). The rules and strategies for managing riparian forests and protecting aquatic ecosystems have been rapidly evolving over the past 35 years (Everest and Reeves 2007). Riparian forests are important for the habitats of fish and habitats of other aquatic organisms because they supply large wood, shade, litter, and terrestrial invertebrate fallout from the canopy that overtops stream channels. In addition, riparian forests that parallel streams and rivers are often preferentially used by wildlife, including providing migration corridors through watersheds.

During the past 15 years, streamside protection in the form of uniform buffers (e.g., 30 m-wide buffers located on both sides of a channel) has been the dominant paradigm in watershed management including on both federal (FEMAT 1993) and on state and private lands (Ice 2005). Certain types of forest management are sometimes allowed in riparian areas (buffers) involving selective harvest or thinning of smaller dense stands (Young 2000, Liquori 2006) but often riparian zones are no touch zones. Uniform buffers, however, do not rigorously account for spatially variable riparian functions that occur within watersheds involving wood loading, thermal loading, biological productivity, aquatic habitat quality and sensitivity, wildlife use and wildfire risk (Everest and Reeves 2007). As such, uniform buffers represent an environmental averaging approach that may not adequately distribute protection based on ecological processes, address forest (and stream) restoration, or consider increasing susceptibility of riparian forests to disturbances. The uniform buffer concept is accepted as 'business as usual' by many watershed practitioners not because it is better but because it is simpler in regulation and compliance.

Spatial variability in riparian processes that affect stream habitats is the rule rather than the exception and it would argue for a more site specific and tailored approach to riparian protection, including in Alberta. For example, wood loading to streams is governed by chronic forest mortality, bank erosion and streamside landsliding. Depending on which process is dominant, the distance from the channel to sources of large wood to the stream will vary by tens of meters (Benda and Bigelow 2014). Thermal loading is highly variable at the watershed scale, including canyon reaches that are intrinsically cool and north-south oriented streams (with little topographic shading) that are intrinsically warm, particularly in the absence of vegetation (Moore et al. 2005). In addition, uniform buffers do not account for watershed disturbances that may impact stream ecosystems. This may include fire that can preferentially move through riparian buffers if they have higher fuel loads (because of their protected status) compared to adjacent forests; windthow within buffers that occur preferentially in certain topographic settings; and insect and pathogen outbreaks; many of these may be increasing due to climate change.

Knowledge of riparian functions and their spatial variability within watersheds and across landscapes, in conjunction with new analytical tools that predict many aspects of riparian processes have set the stage for developing spatially explicit riparian management. A spatially explicit approach may offer ecological and management advantages over the environmental averaging approach of uniform buffers. Tailoring riparian management to highly variable site conditions may better protect ecological processes (FEMAT 2003, Everest and Reeves 2007). For instance, larger protective buffers could target areas that have higher ecological value (low gradient, wide meandering streams with high levels of bank erosion) while less protection may apply in other, less sensitive areas (steep, boulder bedded channels that are north facing with less erosive soil types).

The Integrated WAM-NetMap provides a robust and flexible platform to create spatially explicit and thus tailored delineation of riparian zones.

6.0 Conclusions

The Phase I pilot project in the Simonette River provides a proof of concept and a demonstration about how two advanced watershed analysis technologies, Alberta's Wet Areas Mapping (WAM) and NetMap's virtual watershed coupled to tools, can be integrated to produce a state of the art approach for riparian zone delineation and management. The Integrated WAM-NetMap stream layer builds on the successes of both approaches and provides a robust spatial platform, within a virtual (digital) watershed environment, to conduct numerous types of watershed analyses and to provide decision support to agencies and the private sector for resource management, risk mitigation, restoration and conservation.

Acknowledgements

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