Final Report

Project # 2346
Development of the next generation of wet areas mapping model for the Oil Sands Region of Alberta

Submitted by:

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Abstract

This project produced an innovative software tool and resulting data layers that can be used as a quantitative innovation platform for the following Water Innovation Program priorities: (i) future water supply and watershed management; (ii) healthy aquatic ecosystems; (iii) water use conservation, efficiency, and productivity; and (iv) water quality protection. All these areas require scientifically derived region-wide flow accumulation numbers in raster and shapefile format to support the following:

(i) weather, season, and climate dependent stream discharge rates;

(ii) capacity of hydrological infrastructure to accommodate stream discharge rates under extreme weather conditions, as experienced or forecasted;

(iii) quantitative means to estimate the extent of flow-accumulation dilution of water-carried contaminants,

(iv) assessment of changes in stream and river water quality as affected by water flow from contributing catchments and sub-catchments.

This project

(i) developed the means by which flow accumulation numbers along entire flow networks can be generated comprehensively at 1 m resolution, and can be expanded into larger regions through the development of computationally efficient algorithms to deal with the underlying requirement for massive data processing (described below), and

(ii) did so within the established and well-subscribed wet-areas mapping context for Alberta, with focus on the oil sands region in particular (5,000,000 hectares), to be delivered to the Alberta Government with full flow-channel attribution in the Fall of 2018.

This was done through LiDAR tile processing coupled with seamless cross-tile stream-flow integration. This was done in three stages:

(i) establishing shapefiles for the hydro-conditioned sub-catchment and stream networks through tile-based raster calculations,

(ii) integrating the results piecewise across the tile borders, and

(iii) using the integrated shapefiles to correct the tile-limited flow accumulation calculations across the entire area of interest.

Background

Basic to all water and watershed management purposes is the proper delineation of the upslope water contributing areas (also called “flow accumulation areas”) as these range from small sub-catchments to entire trans-regional river watersheds. Traditionally, catchment areas and their stream networks were derived manually from locally available elevation contour maps. The increased availability of digital elevation models and the related development of raster-based flow-accumulation algorithms (Tarboton 1997) have essentially replaced the manual delineations by enabling nearly automatic determinations of upslope watershed and stream attributes for any points of water flow concerns, e.g., actual or potential road-stream or road-river crossings (Gautam 2012, Dixon & Uddameri 2016). Detailed examinations, however, have shown that the resulting watershed, stream and flow accumulation delineations are affected by DEM source, quality, and resolution (Pryde et al. 2007, Remmel et al. 2008, Gillin et al. 2015). To achieve hydrological reliability, DEMs therefore need to be modified to conform to hydrological expectations. For this project, this was done through:

(i) Removing/replacing elevation artifacts caused by (a) instrumental vertical resolution limits; (b) spurious single-point peaks and dips; (c) lack of reflectance from light-absorbing surface features and other data gaps. Various methods are employed, e.g., moving average smoothing, elimination of point-based outliers, and grid-based surface interpolation techniques.

(ii) Lowering the elevation of already delineated streams, rivers, and lakes so that the digitally derived flow patterns are consistently directed towards, along and through these features.

(iii) Breaching otherwise flow-blocking and depression-forming obstructions such as roads and beaver dams. Breaching requirements becoming more prominent with increasing DEM resolution.

Generally, the extent to which all of the above could be done was limited by available computational memory and processing capacities, with these capacities easily reached when processing large area at high resolution, e.g., 1 m resolution. For that reason, large-area DEM processing were “re-tiled” into 12,500 rectangular datasets, but this generated the challenge of ensuring flow connectivities across all DEM-processing tiles across the landscape. A solution for producing a seamless cross-tile stream network was found through processing overlapping tiles and one-on-one stream-segment matching across the overlapping tile zones (Ogilvie 2014). This process, however, did not by itself extend to developing seamless flow accumulation integration and stream segment attribution across the tiles (**Fig. 1**, **parts 1 and 2)**. Hence, it is necessary to develop an algorithm that systematically integrated flow accumulation and stream attribution across these tiles. **Fig. 2** provides insight and how this was done by way of the automated and fully cross-tile integration process called “Flow Accumulation Across Large Terrains, or FAALT for short.

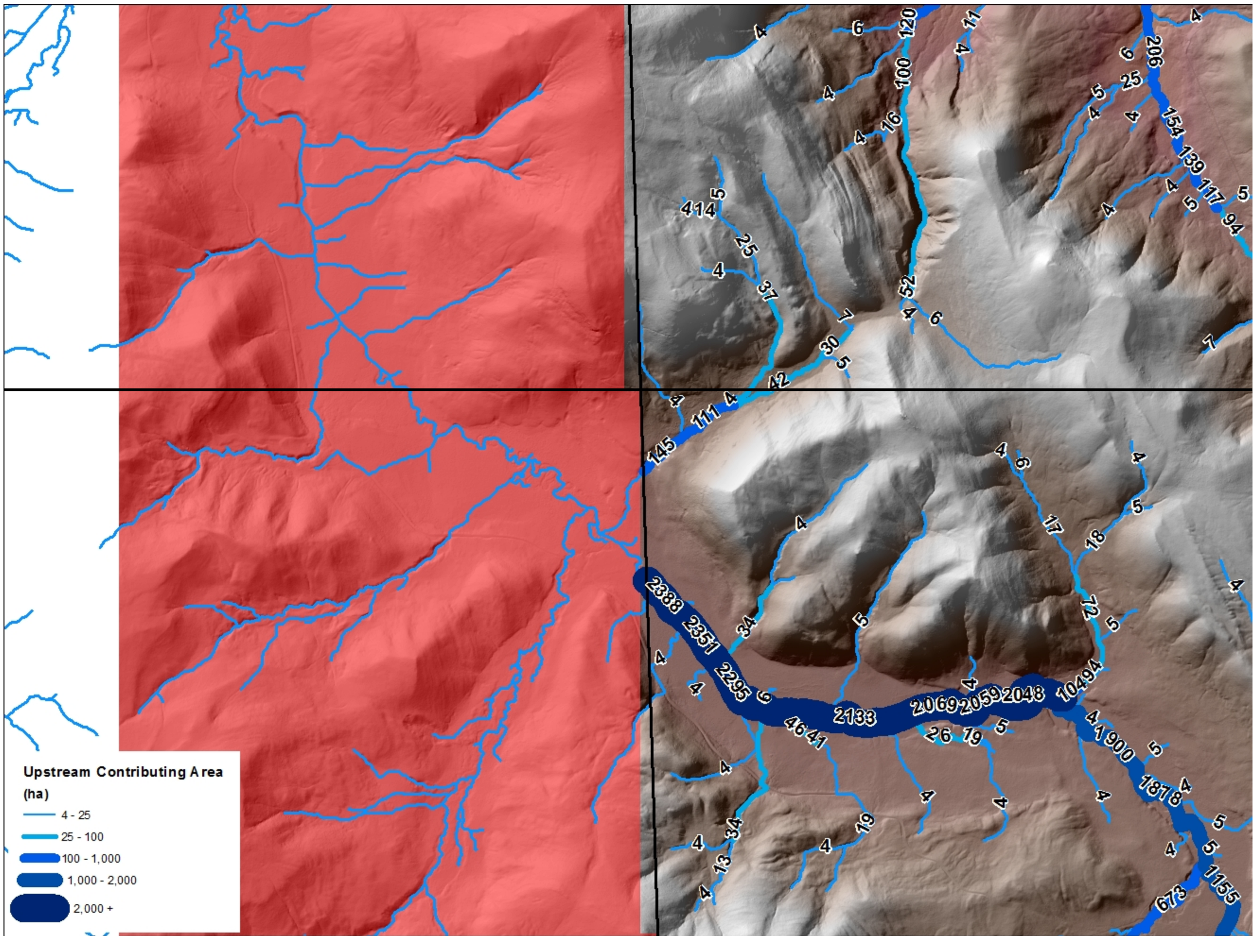


Fig. 1, part 1. Expanding the flow accumulation numbers by stream segment (units in hectares) from a processed to a non-processed DEM tiles, initial scene. The numbers on the right refer to the cumulative downslope end of each stream segment, starting with an upslope flow initiation threshold area of 4 ha. Main flow accumulation direction: lower right to upper left. Red zone: overlap zone between adjacent tiles. Black lines: LiDAR-DEM tile borders. Background: hill-shaded LiDAR DEM, 1 m resolution.

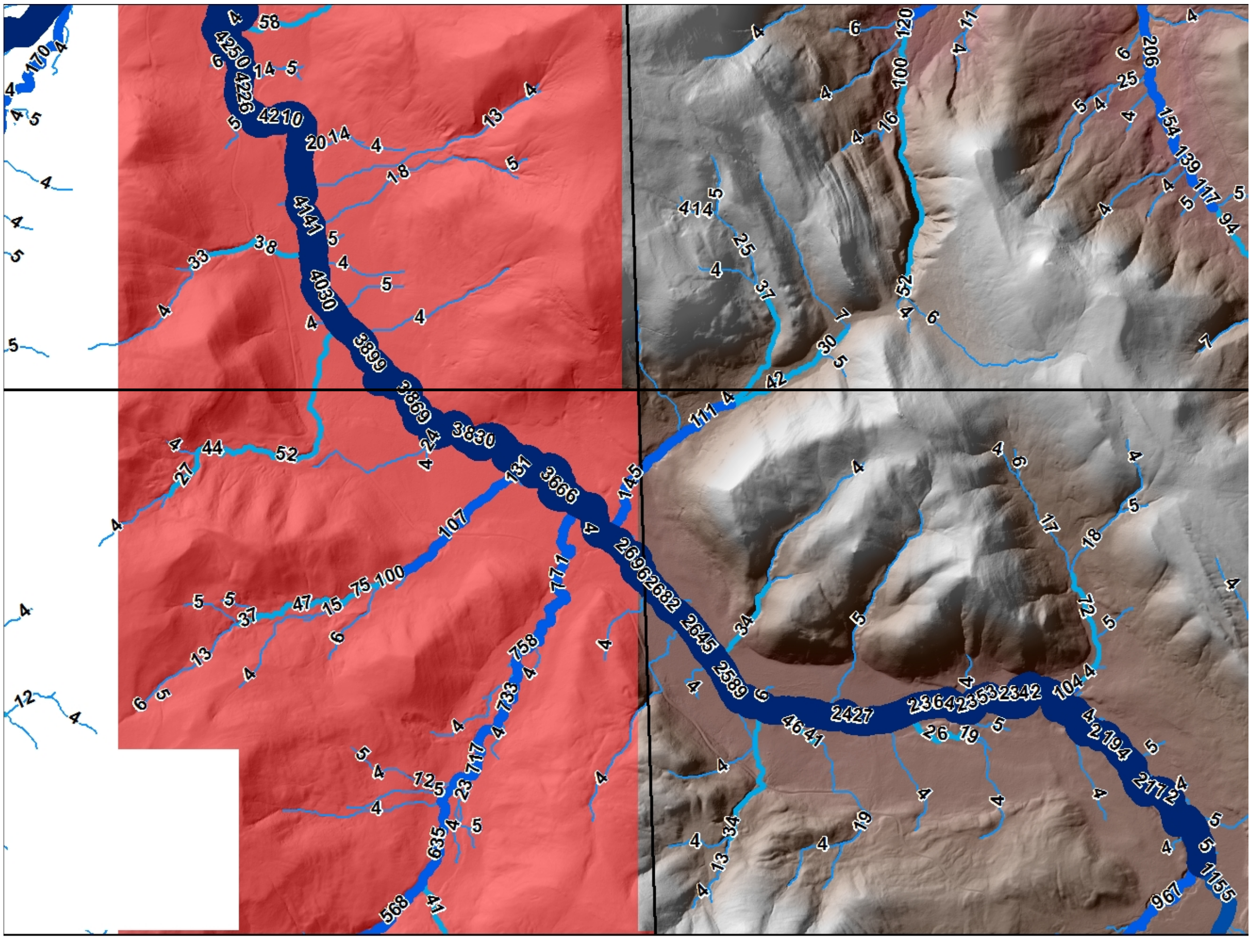


Fig. 1, part 2. Expanding the flow accumulation numbers by stream segment (units in hectares) from a processed to a non-processed DEM tiles, final scene. The numbers on the right refer to the cumulative downslope end of each stream segment, starting with an upslope flow initiation threshold area of 4 ha. Main flow accumulation direction: lower right to upper left. Red zone: overlap zone between adjacent tiles. Black lines: LiDAR-DEM tile borders. Background: hill-shaded LiDAR DEM, 1 m resolution.

Background, continued

Although various software solutions exist to process "massive" grid terrain datasets, their capacities to do so remain limited by computer memory and processing power. For example, the parallel implementation of "breadth-first searches" (Arge et Al. 2003) and the "minimum spanning tree algorithm" (Do et al. 2011) would require the entire DEM extent to be loaded into computer memory, with sections swapped into memory from disk. In addition, these algorithms require complete re-computations of upstream contributing areas should the areas of interest be expanded. In contrast, the proposed project simply works with DEM rasters and node-and-arc defining river-and-stream network shapefiles for the purpose of not only seamlessly integrating and also expanding already existing tile-by-tile DEM-generated catchment and stream segment attributes.

The objective of this proposal was to overcome the shortcomings of massive- and tile-based DEM processing through the development of computationally efficient and tile-expanding algorithms capable of integrating flow accumulation estimates across large landscapes. This was done by:

(i) creating the DEM-determined network of catchment polygons and outlet nodes to determine the flow accumulation numbers for each stream segment within each DEM tile (Stage 1);

(ii) integrating these numbers across the DEM tiles (Stage 2);

(iii) using the integrated flow-accumulation arc-and-node shapefiles to update the flow accumulation raster across the DEM tiles and tile-generated catchments and sub-catchments, cell-by-cell (Stage 3).

This 3-step process ensured complete and unambiguous flow connectedness in all clearly defined watersheds and sub-watersheds, working towards regional and cross-regional dimensions.

Research status preceding project

The Wet Areas Mapping (WAM) technology, developed at the Forest Watershed Research Centre (FWRC) of the University of New Brunswick (UNB), consisted of a suite of algorithms that predict stream channel locations and depth to water table from bare-earth DEMs (White et al. 2012). The resulting outputs included maps that can be used to systematically locate ephemeral and perennial channels, and associated wet areas as defined by the cartographically referenced depth to water (DTW) surfaces. Since 2004, Alberta's Forest Management Branch worked with the FWRC to refine the WAM process using 1 m LiDAR-derived DEMs. Currently, Alberta's Forestry Division holds some 33 million hectares of LiDAR data across the forested areas of the province.

The functional data layers produced by WAM algorithms quantify overland flow regimes. As such, these data layers still differ from most traditional remote sensing methods for estimating soil moisture in that they are associated with the accompanying DEM-derived flow network. Also of note are the WAM-based Trail (Campbell et al. 2013) and Spill (watershed.for.unb.ca) delineation tools. The former was and is employed for road and trail planning, while the latter predicts direction, timing and extent of the surface dispersion of water-borne contaminants away from a point source (i.e. a spill). While these tools do not eliminate the need for field visits, operational efficiencies have significantly improved by systematically reducing the level of cost-increasing "water surprises."

Cross-tiling algorithm steps

Project-preceding WAM algorithms processed DEMs as individual tiles which are based on the 1:50,000 National Topographic System reference grid. This Project focused on making the WAM algorithms completely functional for regional and provincial water management purposes. To do so, the tile-based production of flow networks needed to ensure that flow accumulation areas integrate consistently across all tile borders in a geospatially and hydrologically consistent manner and order. To do so, the cross-tile digital watershed and flow accumulation attributions by stream segment required (**Fig. 2**):

(i) An algorithm that identified which upslope stream segments connect with which downstream segments within and across the digitally process DEM tiles.

(ii) These connections needed to be established through tile-by-tile overlaps.

(iii)	The resulting segment-to-segment flow accumulation overlaps needed to be quantified to avoid double counting along the connected pieces.
(iv)	The non-redundant pieces needed to be summed along the flow direction along the stream segments prior to and at the point of segment convergences.
(v)	The numbers so produced entered into the segment-by-segment flow accumulation fields of the resulting stream segment shapefile table.

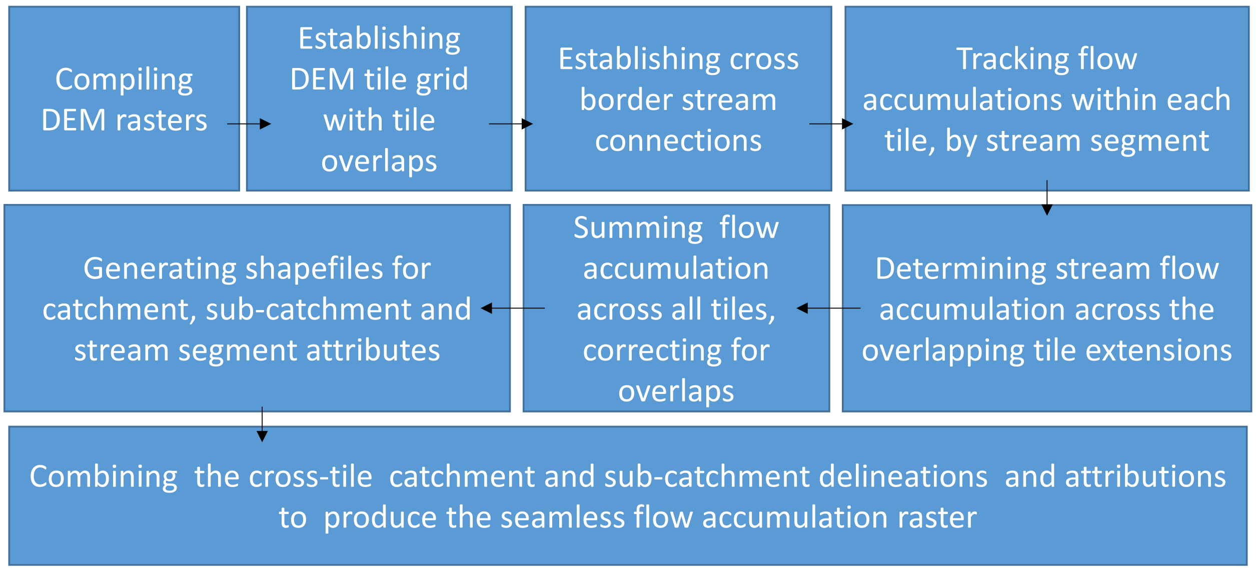


Fig. 2. Towards proper flow accumulation attribution per stream segments across LiDAR-DEM tiles.

Beyond LiDAR-based cross-tiling

The next challenge was to expand and connect the cross-tile flow accumulation algorithm with the flow accumulation patterns of adjacent DEM tiles based on coarser resolution (e.g., Canadian Digital Elevation Model Mosaic, CDEM; SRTM-DEM; ASTER DEM) in a hydrologically correct manner, as outlined in **Fig. 3.**

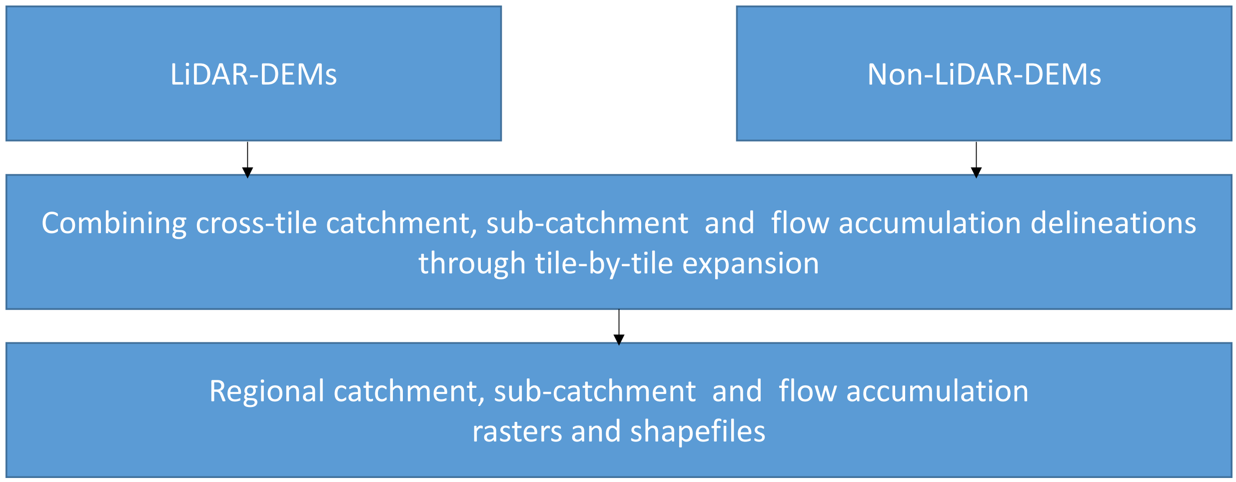


Fig. 3. Integrating and expanding the cross-tile flow accumulation algorithm from individual DEM tiles towards regional watershed borders and beyond.

Introducing FAALT

Apart from developing and testing the cross-tile flow accumulation algorithm, the project, as proposed, led to the development and licensing of a new ArcMap tool called FAALT, which stands for "Flow Accumulation Across Large Terrains" as outlined in **Fig. 4.** The development of this tool enabled:

(i) efficiently expanding tool applications beyond the area of immediate interest (**Fig. 5**), and

(ii) discerning minor to major alterations in local flow networks, as introduced, e.g., through construction, or through natural events such as slope slumping, ice jams, or severe storm events.

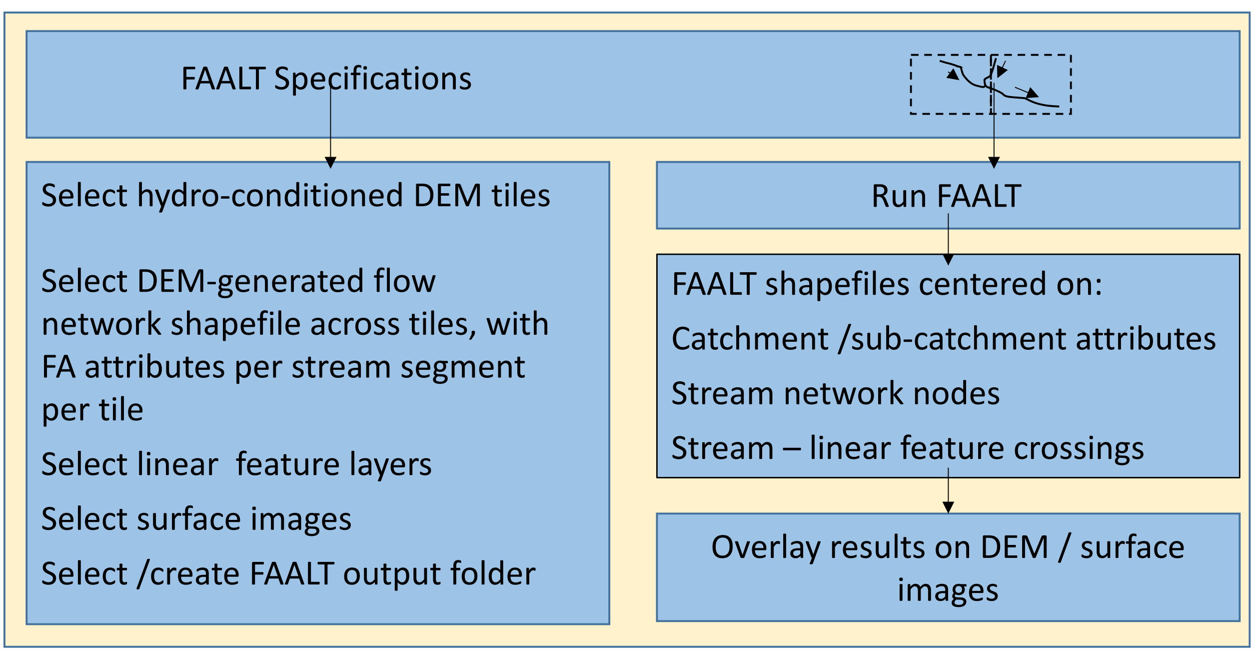


Fig. 4. GIS tool to automatically compile, list and overlay cross-tile flow accumulation values across the targeted area of interest.

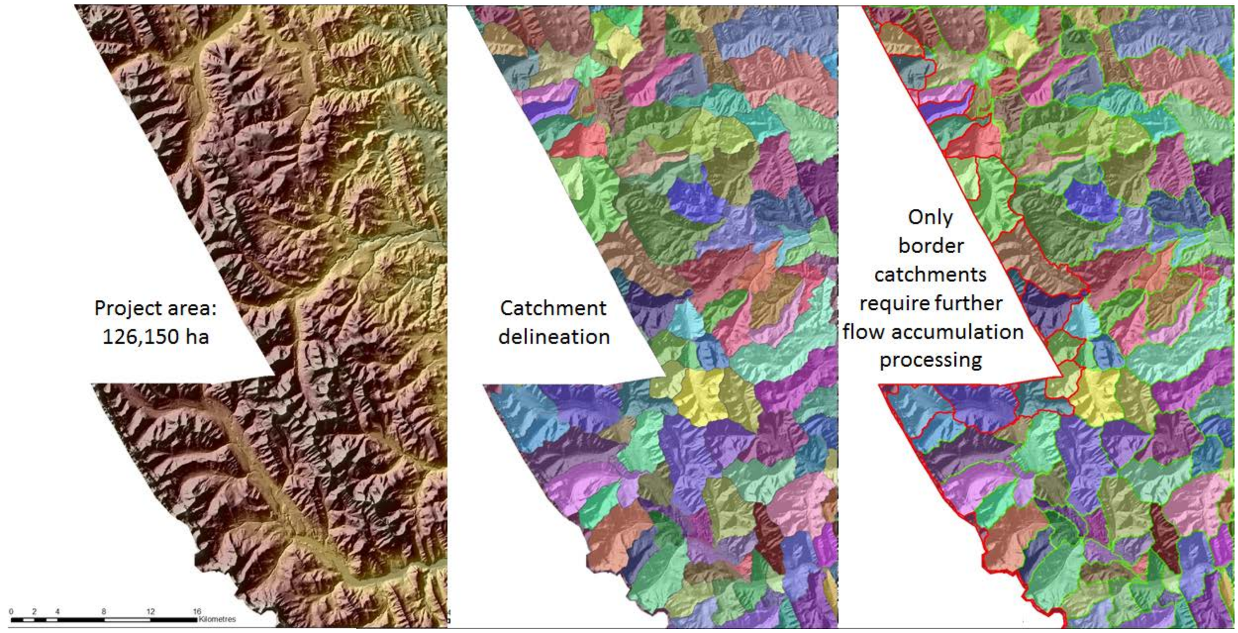


Fig. 5. DEM-tile base catchment delineations using FAALT (middle), also identifying incomplete border catchments for further DEM and flow accumulation integration (red borders, right) beyond the current border on the left.

Project outcomes

Project-based FAALT applications provide a point-and-click means to determine upstream flow accumulation areas at any point of interest, such as the intersections of streams with roads, pipeline, train tracks, powerlines, etc. As such, FAALT-generated data layers become part of geospatial decision-making tools that are designed to enable better land-use and resource management practices. The GIS processing suite listed and described by NetMap (2016) already provides a framework for which the project–generated data layers could be used for large areas for various purposes, e.g. building river and stream networks, and developing and applying equations to estimate flow channel attributes such as channel width, depth, cross-section, flow velocity and erodibility.

The means for systematic upscaling from sub-catchment to regional flow accumulation delineations will facilitate applications such as:

(i) proper culvert and bridge dimensioning as part of adapting existing and contemplated transportation infrastructure to the changing climate adaptation context;

(ii) assessing the amount of surface water flow within the combined groundwater–surface water management context;

(iii) tracing the channels along which contaminant water flows, and quantifying the extent contaminant dilution with increasing flow accumulation;

(iv) minimizing minor and major spill occurrences by relocating traffic routes between downstream communities and upstream fresh-water flow accumulation areas.

The above project formulation has the potential for wide cross-regional applications. The current execution of this project is focused on the flow accumulation network across Alberta's oil sands region, which amounts to about 5,000,000 ha (**Fig. 6**).

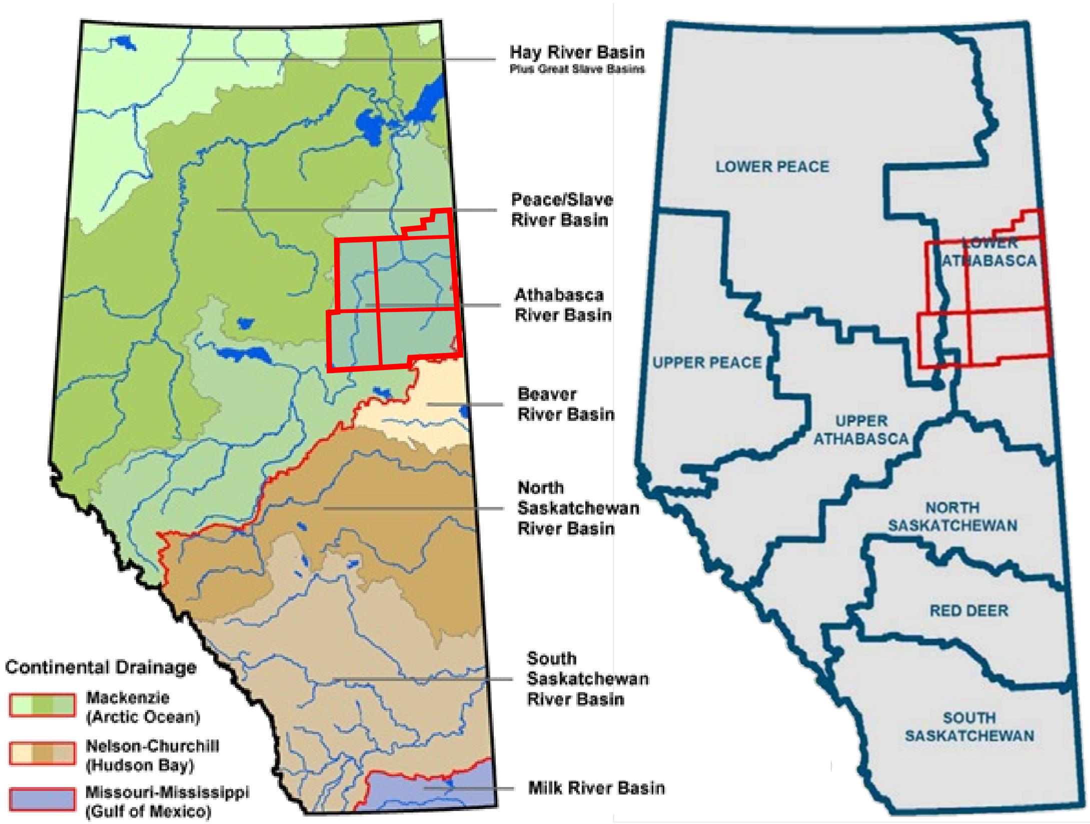


Fig. 6. Locator map for Alberta's oil sands region (red outlines) within the regional watershed (left) and land-use planning (right) units. Within the oil sands area, the terrain being generally flat, required hydro-conditioned LiDAR DEMs to enhance the accuracy of tile-by-tile stream network and across-tile flow accumulation delineations. This area was WAM processed, with the resulting datalayers available at https://geodiscover.alberta.ca/geoportal/catalog/search/resource/details.page?uuid=%7B95116572-91E1-4E49-8AF9-A8325626DB6F%7D. Still to be supplied: FAALT-generated stream attribution shapefile (Fall 2018).

Implementation Potential

The competiveness of Alberta's forest and oil and gas sectors is of great concern, and WAM data and associated tools offer significant opportunities to reduce cost structures and improve efficiencies. The use of WAM data does not preclude the need for field assessments and measurements, but efficiencies can be realized by moving to a paradigm of risk-based field work. With improved ease of access to data and training for staff, "desktop" exercises conducted prior to field visits may dramatically improve time spent out of the office. For example, a simple visual inspection of wet areas products may reveal hydrological features or sensitive soils previously not spatially identified. As previously mentioned, many companies are utilizing WAM for assessing hydrological risk and the TRAIL Tool for road and trail planning. Wet areas mapping data layers and tools will not replace the need for field visits, but they can do much to increase efficiency and, thus, both regulatory and industry competiveness.

Both the forest industry and oil and gas sector stand to benefit from LiDAR and other remote sensing technologies through improved planning and the establishment a well-considered, wise footprint. With improved knowledge of the landscape comes the opportunity to establish an industrial footprint that, though extensive, may minimize impact on numerous forest-related values, including soils, water, wildlife, and biodiversity. Through the use of these technologies, high risk and high value areas can be identified and preserved, often by simply relocating an operation nearby.

WAM data layers have proven to provide a new and exciting "*innovation platform*". Identifying soil moisture and hydrological connectivity across vast landscapes at exceptionally high resolutions and accuracy have allowed researchers to ask new questions. Alberta's Forest Management Branch has made significant cash investments (approximately $400,000) into new research undertaken at the University of Alberta to address questions related to reclamation, growth and yield, and biodiversity. The Branch has also invested both energies and cash ($150,000) to merge WAM data layers with the Netmap model as developed by the Terrain Works group of northern California. This new innovation partnership is investigating a new and innovation approach to map riparian zones at high resolutions and provide for cumulative effects assessments.

A primary advantage of wet areas mapping is that multiple parties can employ the same detailed knowledge of hydrological features and wet areas for planning purposes. It is anticipated that WAM data layers shall be a key data layer within the Alberta Landscape Analysis Toolbox (LAT): http://aep.alberta.ca/forms-maps-services/industry-online-services/landscape-analysis-tool/landscape-analysis-tool.aspx. The regulator in Edmonton, Regional offices, industry in Calgary, and contractors in the field would therefore have easy access to wet areas maps and be working off the same information layer.

In the future, a basic premise will be if industry has resource information at its disposal it will improve its ability to achieve Alberta's goals of sustainability. Approvals can be streamlined with enhanced digital information and accountability can be increased with better resource information. Accountability and scrutiny is increased because Albertans will have the ability to spatially identify the presence of a hydrological feature within the proposed study area with high accuracy and without always having to check in the field.

Project Progress

Phase 1: May 2016 – October 2016.

The development and testing of algorithms to produce scale-appropriate hydro-conditioned watershed and stream network delineations using high resolution LiDAR-derived DEMs for the oil sands region. The resulting output referred to the production of a seamless cross-tile flow direction raster and tile-generated stream arc-node network that is the basis for developing DEM-informed regional and cross-regional water management. Algorithm development and testing includes quality control and soft-validation was done through inspection of available ortho-imagery. **Phase 1 product: a seamless**

catchment /sub-catchment and stream arc-node network shapefile without cross-tile flow accumulation.

Phase 2: October 2016 – April 2017.

This included the enhancement and validation of the algorithms developed in Phase 1, leading to the development of tools for ensuring cross-tile stream connectivity, but still without stream attribution. **Phase 2 products: a seamless catchment /sub-catchment and stream arc-node network shapefile with cross-tile flow accumulation.**

Phase 3: April 2017 – October 2017.

The development of the FAALT tool and increasing its computational efficiency for cross-tile stream connectivity and attribution updating. T **Stage 3 products: (i) seamless cross-tile flow accumulation raster; (ii) FAALT tool established.**

Phase 4: October 2017 – August 31st 2018.

Continuous refinement of FAALT towards greater computational efficiency and accuracy of cross-tile stream attribution. **Phase 4 products: final project report, FAALT tool revised for licensing purpose.**

Project Presentations

Jae Ogilvie and Paul Arp 2016 Development of next generation of wet areas mapping model for northeastern Alberta. **Water Innovation Program FORUM 2016.**

Jae Ogilvie and Paul Arp 2018 Development of next generation of wet areas mapping model for northeastern Alberta. **Water Innovation Program FORUM 2017.**

Jae Ogilvie and Paul Arp 2018 Development of next generation of wet areas mapping model for northeastern Alberta. **Water Innovation Program FORUM 2018.**

Project Team and Partners

Dr. Paul Arp, Professor, Faculty of Forestry, University of New Brunswick; Senior research authority,

Jae Ogilvie, Research Associate, Faculty of Forestry, University of New Brunswick. Responsible for the development and testing of all algorithms. Oversees all mapping activities and data sharing with Alberta.

Chris Bater, Forest Management Specialist, Alberta Agriculture and Forestry. Scientific authority in the area of LiDAR and geomatics, served as key contact for university-based research team. Time commitment: 40%.

Dr. Barry White, Director, Alberta Agriculture and Forestry. Responsible for representing Alberta Government project interests.

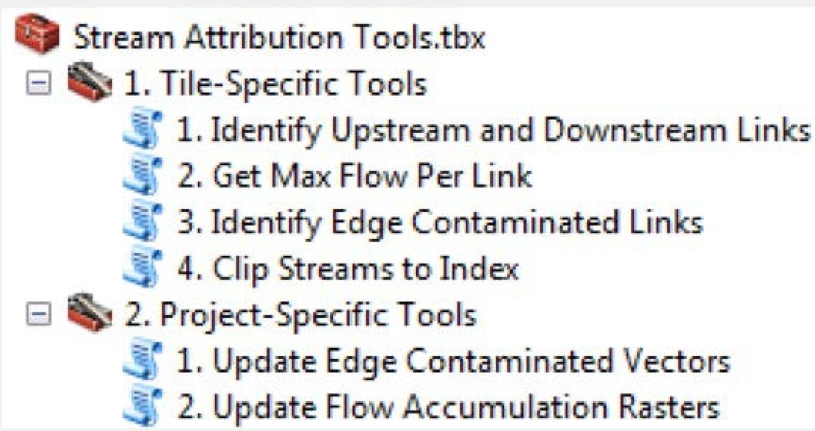
Appendix

FAALT: Flow Accumulation Across Large Terrains

Manual

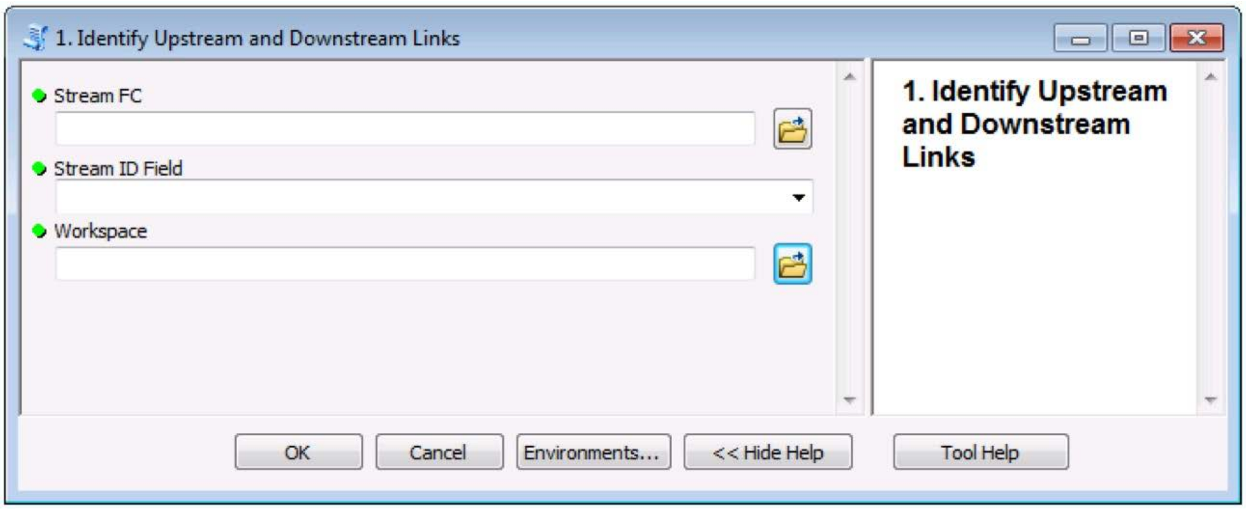
Deployed as an ArcGIS Toolbox (v. 10.5 or above), the “Stream Attribution Tools” toolbox was developed to assist users in the attribution of flow accumulation values of tiled stream vector and flow accumulation raster datasets across vast terrains. The toolbox consists of a series of tile-specific “helper” tools that assist in the preparation of tiled stream channel vectors, regardless of their derivation source. Predicted stream channel vectors derived and delivered as part of the UNB/GoA Wet Areas Mapping Initiative do not require these preprocessing steps.

This section describes each tool in detail and outlines the input data requirements and tool outputs.



Tile-Specific Tools

Step 1. Identify Upstream and Downstream Links



(i) Stream FC (Input): Vector representation of stream channel locations in Esri Shapefile or Geodatabase Feature Class format. The geometry/locations of these vector networks must be coincident with an available flow accumulation raster dataset for subsequent processing steps.

(ii) Stream ID Field (Input): Attribute field defining a unique identifier for each stream vector segment.

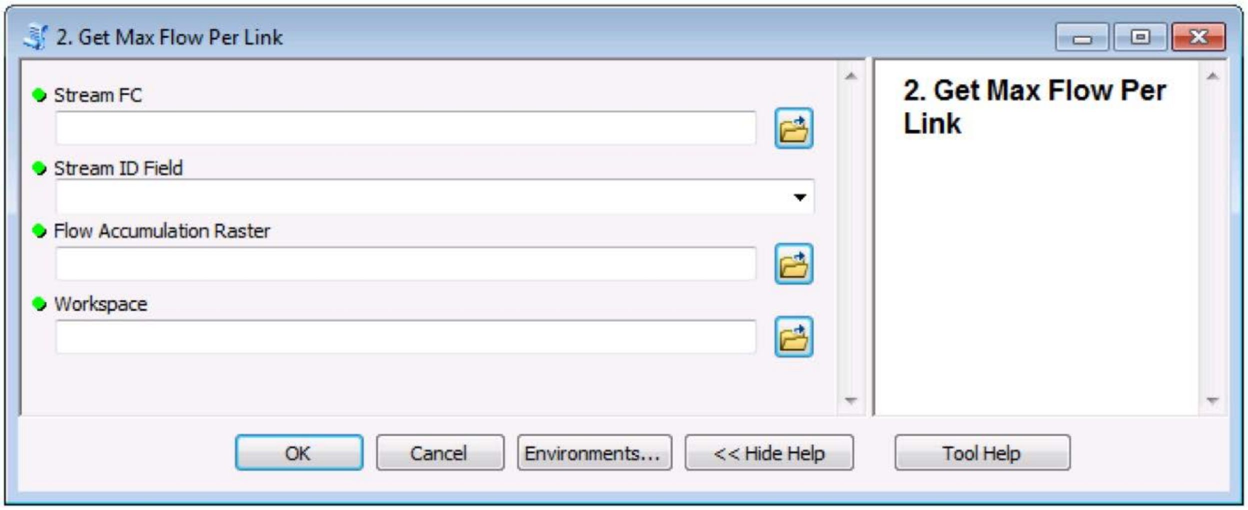
(iii) Workspace (Input): Workspace in which processing will occur. Please ensure you have read/write-access to this folder location for any intermediate datasets that may be required.

(iv) US_IDs field (Output): Comma separated list of immediately-adjacent upstream links, taken from the *Input Stream ID Field* parameter.

(v) DS_IDs field (Output): Vector identifier for immediately-downstream link, taken from the *Input Stream ID* field parameter.

(vi) Note: No new datasets are created with this tool, but the *US_IDs* and *DS_IDs* fields are appended to the input *Stream FC* dataset.

Step 2. Get Max Flow Per Link



(i) Stream FC (Input): Vector representation of stream channel locations in Esri Shapefile or Geodatabase Feature Class format. The geometry/locations of these vector networks must be coincident with an available flow accumulation raster dataset for subsequent processing steps.

(ii) Stream ID Field (Input): Attribute field defining a unique identifier for each stream vector segment.

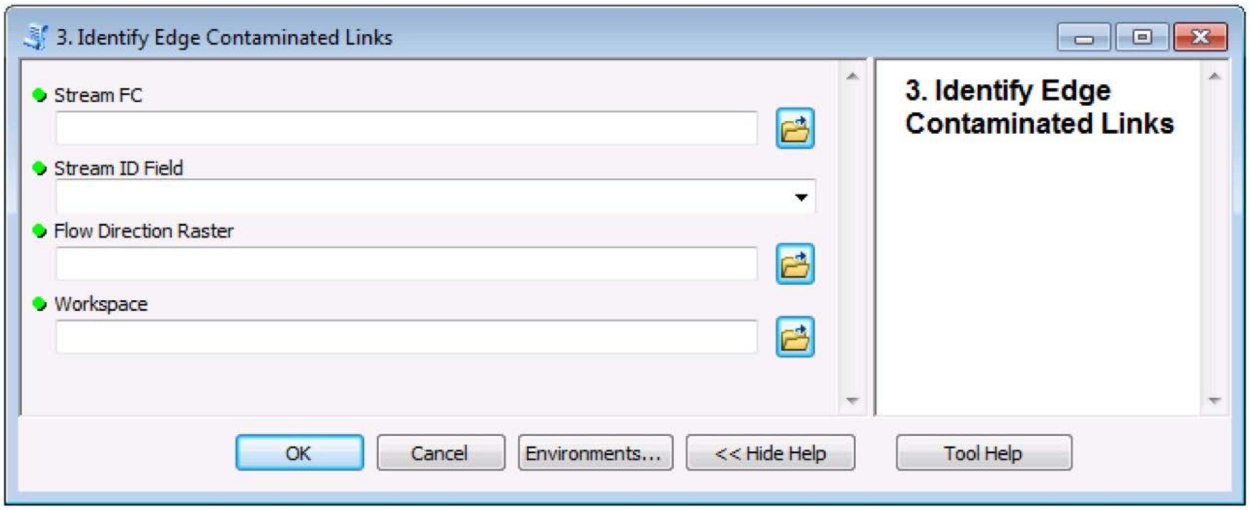
(iii) Flow Accumulation Raster (Input): Tiled raster representation of upstream contributing area. This raster is used to assign tile-based flow accumulation to each tile-based vector in the *Stream FC* input dataset.

(iv) Workspace (Input): Workspace in which processing will occur. Please ensure you have read/write-access to this folder location for any intermediate datasets that may be required.

(v) US_ha field (Output): Attribute field defining maximum upstream area (in hectares) associated with each segment in the input *Stream FC* feature class.

(vi) Note: No new datasets are created with this tool, but the *US_ha* field is appended to the input *Stream FC* dataset.

Step 3. Identify Edge Contaminated Links



(i) Stream FC (Input): Vector representation of stream channel locations in Esri Shapefile or Geodatabase Feature Class format. The geometry/locations of these vector networks must be coincident with an available flow accumulation raster dataset for subsequent processing steps.

(ii) Stream ID Field (Input): Attribute field defining a unique identifier for each stream vector segment.

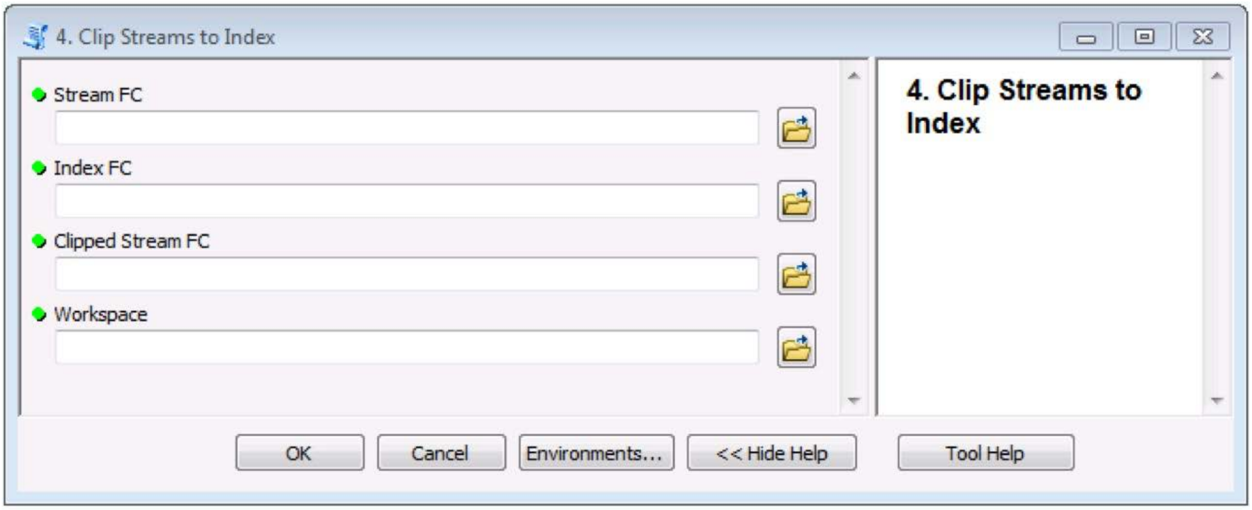
(iii) Flow Direction Raster (Input): Tiled raster representation of D8 flow direction for each raster cell. This raster is used to identify stream segments for which a full upstream watershed (catchment) is not captured entirely within an input flow direction raster.

(iv) Workspace (Input): Workspace in which processing will occur. Please ensure you have read/write-access to this folder location for any intermediate datasets that may be required.

(v) TruFlow field (Output): Attribute field defining stream segments for which upstream area (*US_ha* field) attributes are complete and valid ([TruFlow] = 1) and those for which an incomplete watershed area has been flagged ([TruFlow] = 0).

(vi) Note: No new datasets are created with this tool, but the *TruFlow* field is appended to the input *Stream FC* dataset.

Step 4. Clip Streams to Index



(i) Stream FC (Input): Vector representation of stream channel locations in Esri Shapefile or Geodatabase Feature Class format. The geometry/locations of these vector networks must be coincident with an available flow accumulation raster dataset for subsequent processing steps.

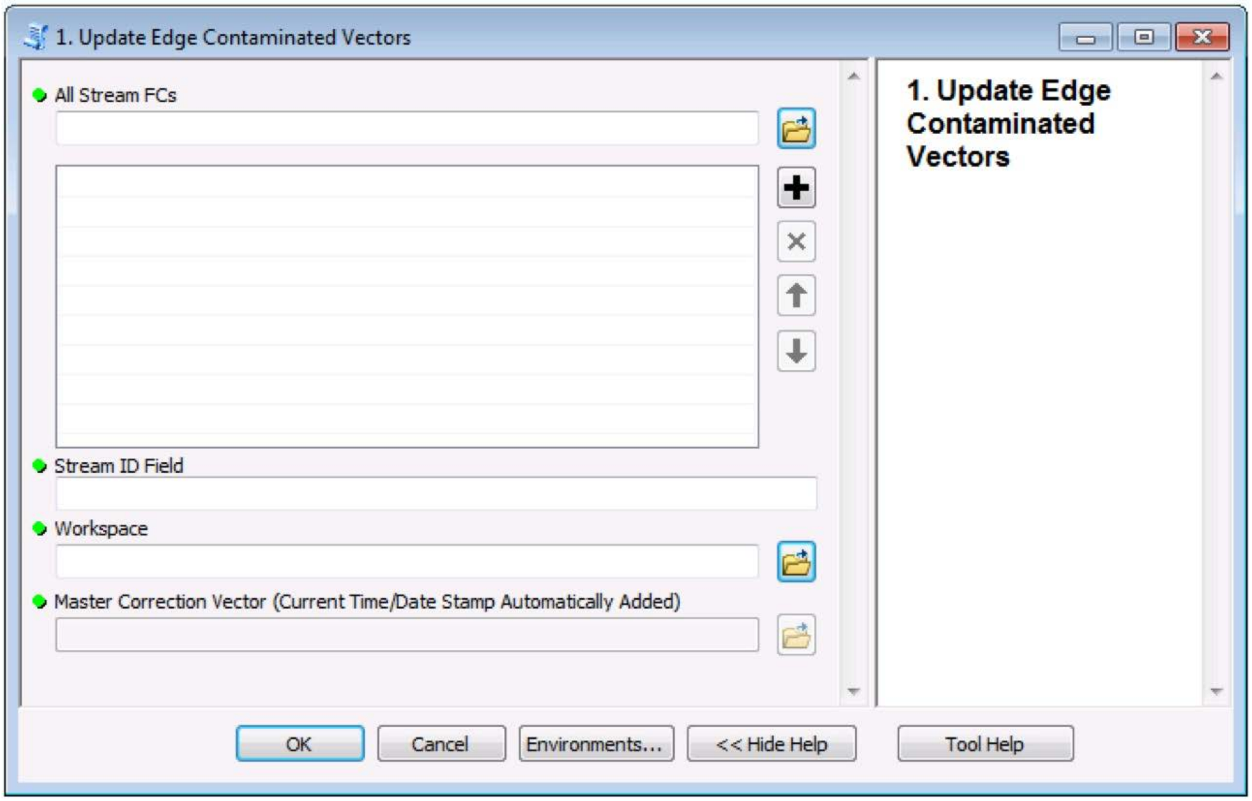
(ii) Index FC (Input): A Vector polygon representation of a topologically-consistent (no overlaps or gaps) tile system used to clip each input *Stream FC* feature class.

(iii) Clipped Stream FC (Output): Required for subsequent processing, a topologically-consistent Stream FC feature class ensures that there are no overlapping or gapped stream vectors across a larger project area.

(iv) Workspace (Input): Workspace in which processing will occur. Please ensure you have read/write-access to this folder location for any intermediate datasets that may be required.

Project-Specific Tools

Step 1. Update Edge Contaminated Vectors



(i) All Streams FCs (Input List): All properly attributed stream feature classes whose upstream contributing area attributes will be updated as necessary by adjacent tiled stream feature classes.

(ii) Stream ID Field (Input): Attribute field defining a unique identifier for each stream vector segment.

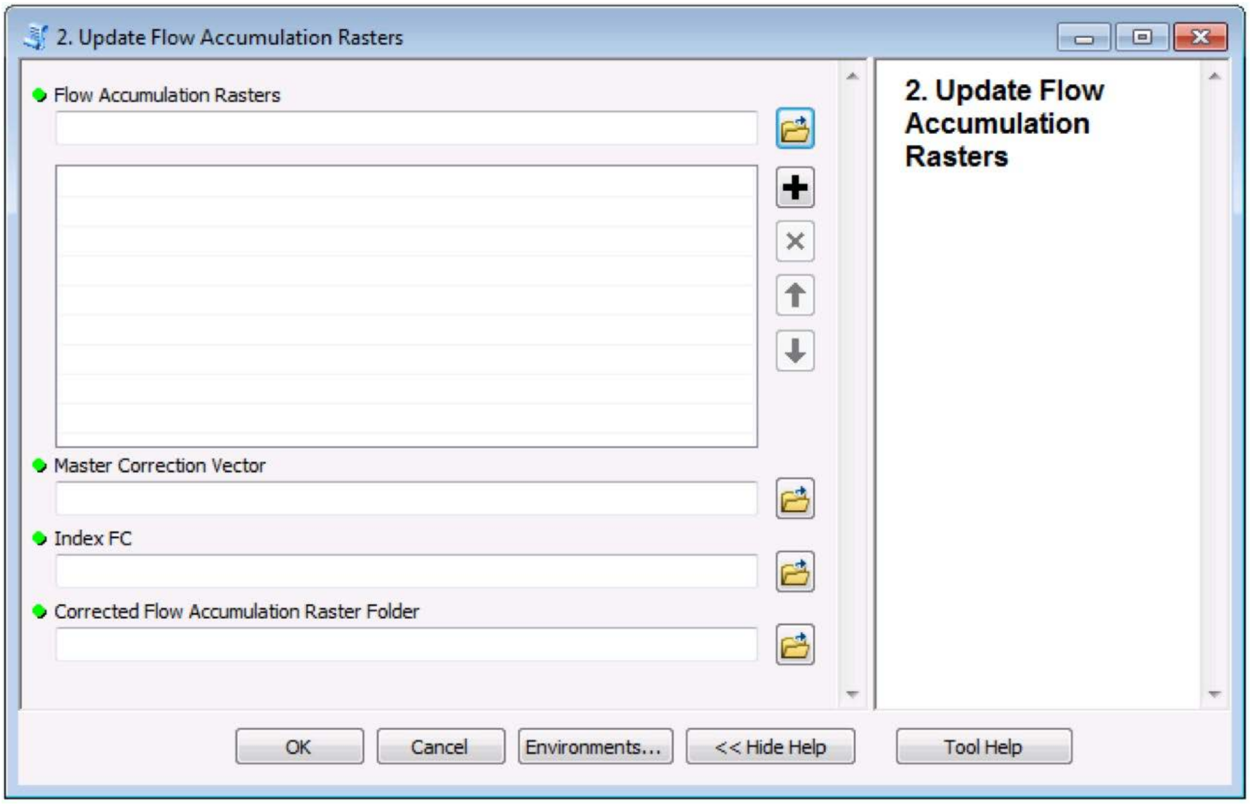
(iii) Workspace (Input): Workspace in which processing will occur. Please ensure you have read/write-access to this folder location for any intermediate datasets that may be required.

(iv) Master Correction Vector (Output): Line vector feature class used to store project-level stream attribute update information for only edge-contaminated stream links.

(v) US_diff field (Output): Attribute field defining the upstream contributing area difference (offset) relative to each original stream vector segment.

(vi) PassNum field (Output): Attribute field identifying the pass (iteration) number at which an upstream vector segment group was corrected.

Step 2. Update Flow Accumulation Rasters



(i) Flow Accumulation Rasters (Input List): All original flow accumulation rasters whose cell values have not been updated to reflect the cross-tile flow from adjacent upstream rasters.

(ii) Master Correction Vector (Input): Line vector feature containing project-level stream attribute update information for only edge-contaminated stream links. The location and attribute information of these vectors will be used to update flow accumulation raster cell values within tile index feature class boundaries.

(iii) Index FC (Input): A Vector polygon representation of a topologically-consistent (no overlaps or gaps) tile system used to clip each input *Stream FC* feature class.

(iv) Corrected Flow Accumulation Folder (Output): Folder containing updated flow accumulation rasters, clipped to the bounds of each tile index feature class boundary.

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