Functional Linkage of Water basins and Streams (FLoWS) v1 User's Guide:

ArcGIS tools for Network-based analysis of freshwater ecosystems

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Abstract

The FLoWS toolbox for ArcGIS v9.1 provides graph theoretic-based analysis tools that functionally links aquatic and terrestrial components of a landscape based on hydrologic processes. This functionality allows for spatial analysis to incorporate metrics such as distance upstream, proportion of flow (discharge) that a site contributes to another site and degree for fragmentation within a drainage network due to dams. FLoWS also allows for terrestrial analysis such as the influence of a city's sewage discharge has on downstream cities, how many acres of agriculture drain into a river and where the accumulated effects might reach some defined threshold. This type of analysis capabilities makes FLoWS useful for regional water planers, wildlife biologists, soil conservation district managers, and aquatic and terrestrial ecosystem modelers. The fundamental backbone behind FLoWS is based on network or graph data structure.

The network data structure implemented in FLoWS is based on simple topological relationships between geographical objects or features, where a set of nodes (or locations) are related through edges (or reaches). A FLoWS Landscape Network represents a geometric network, which stores the geometry of nodes and edges in addition to topological adjacencies. Note that edges are directed, so hydrologic flow can be represented.

The FLoWS toolbox consists of five toolsets: pre-processing, create landscape network, selection, analysis, and export. The *pre-processing* toolset contains miscellaneous tools that are useful in editing and converting raw datasets into appropriate inputs for other FLoWS tools. The *selection* tools allow interactive queries or selections on Landscape Networks within an ArcMap document. This allows users to create new selection sets that represents upstream or downstream topological relationships to be summarized or used in further analysis. The *analysis* tools allow users to perform graph or network-based analyses. These routines typically populate a user-defined field for a defined Landscape Network feature class. The *export* tools evaluate point to point relationships within a Landscape Network and create a comma delimited *n* x *n* matrix of distance values between pairs of locations.

An example dataset is provided so you can become familiar with FLoWS concepts and tools before applying them to your datasets.

TABLE OF CONTENTS

Software Environment

FLoWS version 1.0 is a Geoprocessing toolbox, written in Python (v2.1) for ArcGIS v9.1. Nearly all tools in FLoWS require only ArcGIS desktop (no extensions). Only two tools (***Create RCAs*** *and* ***Create Cost RCAs***) require the Spatial Analyst extension. If you are creating any landscape network (which is a personal Geodatabase), an ArcINFO license is required. The other tools (query, selection, analysis, export, etc.) in FLoWS can function with an ArcView license.

All input data should be in the same projected coordinate system and datum.

Example Dataset Description

The ***mt_hood*** folder provided with FLoWS contains example datasets needed to build a FLoWS Landscape Network and run analyses (Appendix I). These datasets include:

Name	Format	Definition
Dem_fill	raster	The ned_dem_30 filled with a z value of 6 using the ArcMap Fill command
Flow_dir	raster	Flow direction raster using the dem_fill raster
hillshade	raster	Hillshade for the dem_fill raster
Ned_dem_30	raster	Raw NED 30 meter DEM
Str_reach_ras	raster	Rasterized stream reaches (NHD 1:100,000)
Water_bdy_ras	raster	Rasterized water bodies (NHD 1:100,000)
sample_pts	shapefile	sample study points (made up points)
Rcas	shapefile	Reach catchment areas using Create RCAs tool
Cost_rcas	shapefile	Reach catchment areas using Create Cost RCAs tool
Polyline_net.mdb	PGDB	FLoWS Landscape network of stream reaches
Rca_net.mdb	PGDB	FLoWS Landscape Network of stream reaches and RCAs

Typology of waterbasin-stream relationships

There are a variety of ways that space is represented and used to understand the behavior of watersheds and streams: *site*, *watershed*, *distance-base, and network*. Commonly landscape (GIS, remotely-sensed) data are needed to complement field-based at a *site* or location where covariates such as geology, dominant vegetation, elevation, etc. are collected (e.g., EPA EMAP sites). Occasionally nearby covariate data that form the context of a site are needed, such as catchment area, population density, acres of agricultural land use, etc.

A second way is to represent a landscape in terms of *water basins* (or catchments). Co-variates are summed or averaged within watersheds (often called "lumped" models). These hydrologic units are used to compute some landscape indicator variable, for example, average road density, dam density (Jones et al. 1997; Moyle and Randall 1998), connected impervious surface (Wang et al. 2001) or total number of dams within a water basin. These water basins are often conceived of as overlapping, hierarchical areas defined from the "pour-point" or outlet on up to the headwater or watershed boundary. This follows directly from the River Continuum Concept (Vannote 1980), where river systems are conceived as a continuous gradient of physical conditions from headwaters to the mouth of a river. Often in practice, however, typically these are tessellations such as Hydrologic Unit Codes, where only 55% of the 2,150 cataloguing units (so called 8-digit HUCs) are true basins -- the rest are called "adjoint" watersheds or interior basins (Seaber et al. 1987). Moreover, hydrologic flow between true basins and downstream adjoint basins typically is not.

A third way is to explicitly examine the spatial relationships between sites (or locations of interest), which can then be incorporated into a geostatistical model (e.g., Ganio et al. 2005). This is most commonly accomplished by covariates at a site, but also responses measured at other nearby sites. Typically, spatial relationships are measured by simply straightline distance (as the crow flies) between points (e.g., Olden et al. 2001). Increasingly, distance along the hydrological network (as the fish swims).

A fourth way is to conceive and represent river systems and aquatic landscapes as a network. In this sense, relationships between sites can be represented through functional distance measures. For many hydrological processes (not all!) downstream flow direction is an important ecological process, so that distance is not symmetric. Also, including important landscape attributes that modify the degree to which nearby locations are connected is important. This would include topographic considerations such as stream gradient and slope, as well as features that might impede the movement of a species or process such as waterfalls, dams, or certain vegetation types. Representing functional relationships can be done within a network, to recognize that physical conditions along a river are often controlled by the network geometry of the river system (Benda et al. 2004). "One consequence of this interplay [between pattern and process] is the form of functional connectivity found in a landscape. The landscape pattern-process linkage produces spatial dependencies in a variety of ecological phenomena, again mediated by organismal traits (Wiens 2002, pg. 511).

Terminology

Graph: A graph is a data structure comprised of a set of points (nodes) functionally joined by lines (edges). The set of nodes is typically defined as $V(G) = \{v_1, v_2, v_3, \ldots v_p\}$ and the edges as $E(G) = \{e_1, e_2, e_3, \ldots e_q\}$. Therefore, the graph G has p nodes (order) and q edges (value): $G(p,q)$. Edge e_{ij} connects adjacent nodes v_i and v_j. In this application, nodes represent hydrologic breaks and edges represent hydrologic flow paths.

Landscape Network: A Landscape Network is a type of graph that recognizes spatial context and relationships with additional geographic information. The data structure of a

Landscape Network is stored within an ESRI personal geodatabase. Landscape Networks have four distinguishing features (Theobald 2005):

1. The Landscape Network stores both the topology of a graph and the geometry of the nodes, reaches and RCAs.
2. Nodes represent stream topologic breaks such as confluences or outlet points.
3. Edges represent flow paths from node to node.
4. Reach Catchment Areas (RCAs) represent the aerial extent that contributes overland flow to a given edge.

Filled DEM: A Digitial Elevation Model (DEM) with sinks and small imperfection (noise) filled so for surface water movement modeling. This is a pre-processing step for the *Create RCAs* tool and can be executed in ArcMap using the Fill tool in the Spatial Analyst extension.

Flow Direction Raster: A direction raster that represents flow direction from a given cells to neighboring cells. This is a pre-processing step for the *Create RCAs* tool and can be executed in Spatial Analyst using the Flow Direction tool.

Tool: A tool is a Python script found in a toolset.

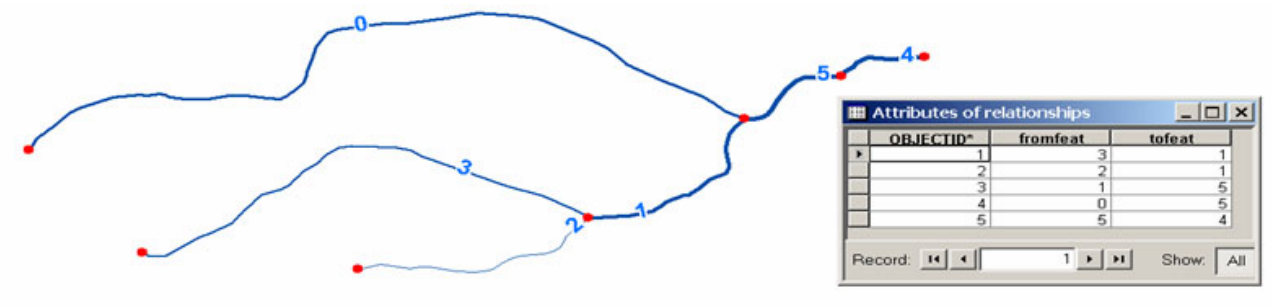
Toolbox: The entire collection of FLoWS toolsets and tools.

Toolset: FLoWS contains five primary toolsets: *pre-processing*, *create landscape network*, *selection*, **analysis**, and *export* toolsets.

HYDROLOGIC RELATIONSHIPS TABLES

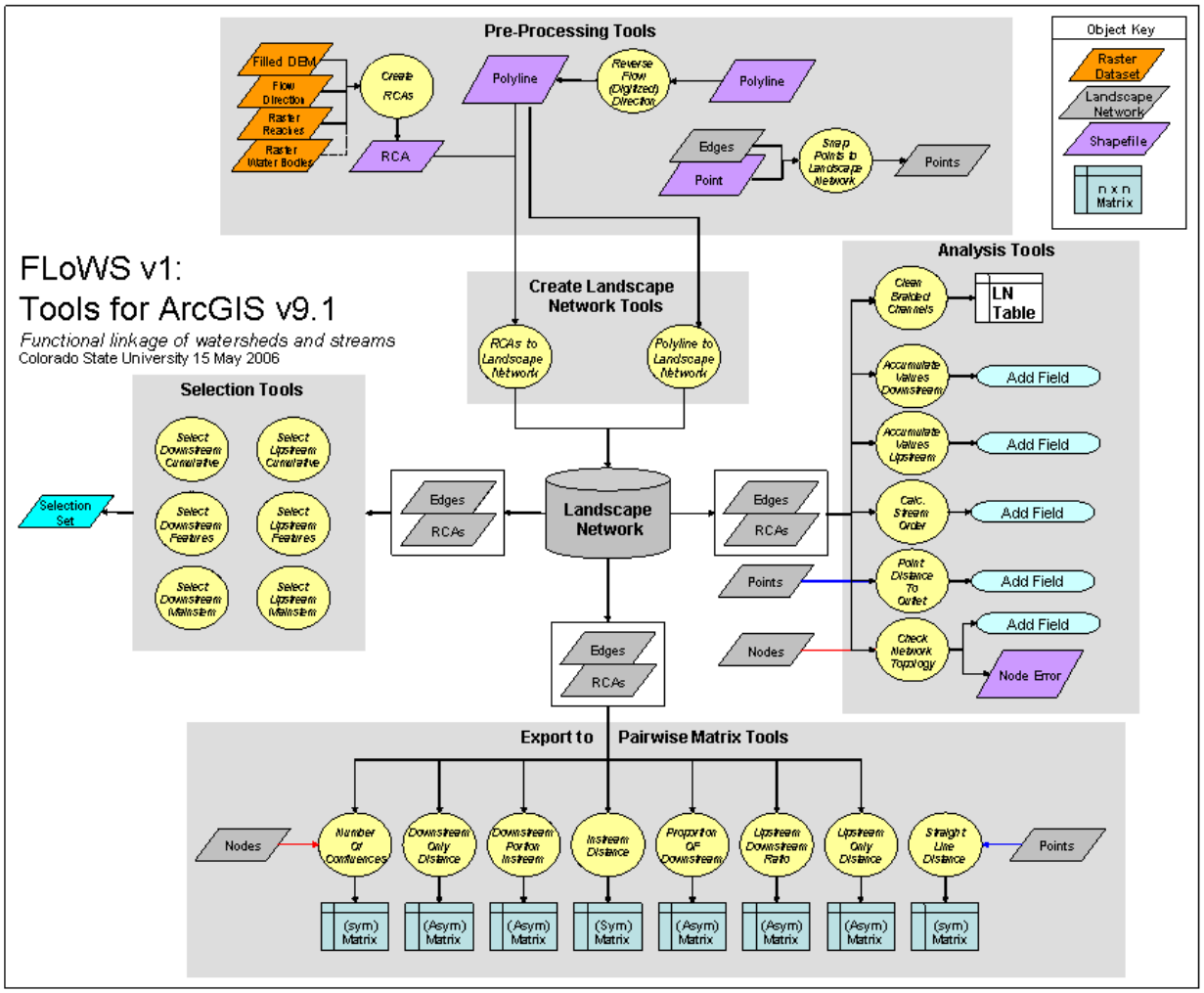
The FLoWS landscape Network relies on two relationship tables (***noderelationships*** and ***relationships***) to functionally link hydrologic features within a drainage network. The ***noderelationships*** table links nodes to their associated edges via the **rid** field. This table is used to count the number of confluences between features and find source or outlet features within a drainage network. The ***relationships*** table links edge and RCA features to each other in downstream order. This table has two key fields **fromfeat** and **tofea**t that relate the edge and RCAs through the **rid** field. The relationship table is sorted downstream, which allows for navigation within the network to be a simple linear process of going up or down within the table.

Features within the relationships table are related (sorted) downstream. This simple example demonstrates this with *fromfeat* 3 flowing into *tofeat* 1 and *fromfeat* 1 flowing into *tofeat* 5.



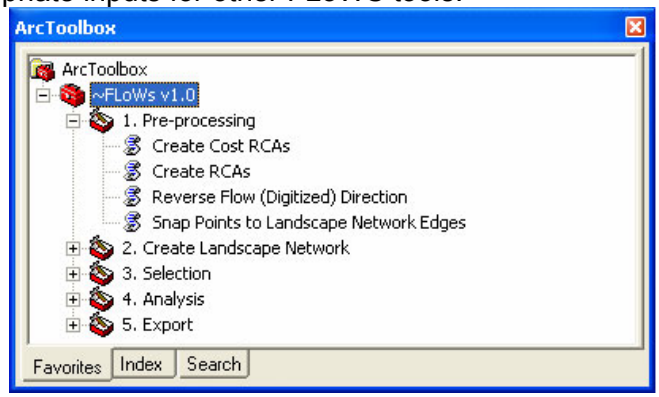
FLoWS v1.0 toolbox and data model diagram

The FLoWS toolbox consists of five toolsets: *pre-processing*, *create landscape network*, *selection*, *analysis*, and *export*. The *pre-processing* toolset contains miscellaneous tools that are useful in editing and converting raw datasets into appropriate inputs for other FLoWS tools. The *selection* tools allow interactive queries or selections on Landscape Networks within an ArcMap document. This allows users to create new selection set that represent upstream or downstream topological relationships that can be summarized or used in further analysis. The *analysis* tools allow users to perform graph or network-based analyses. These routines typically populate a user-defined field for a defined Landscape Network feature class. The *export* tools evaluate point to point relationships within a Landscape Network and create a comma delimited *n* x *n* matrix of distance values between pairs of locations.



PART 1: Pre-processing Tools

The *pre-processing* toolset contains miscellaneous tools that are useful in editing and converting raw datasets into appropriate inputs for other FLoWS tools.

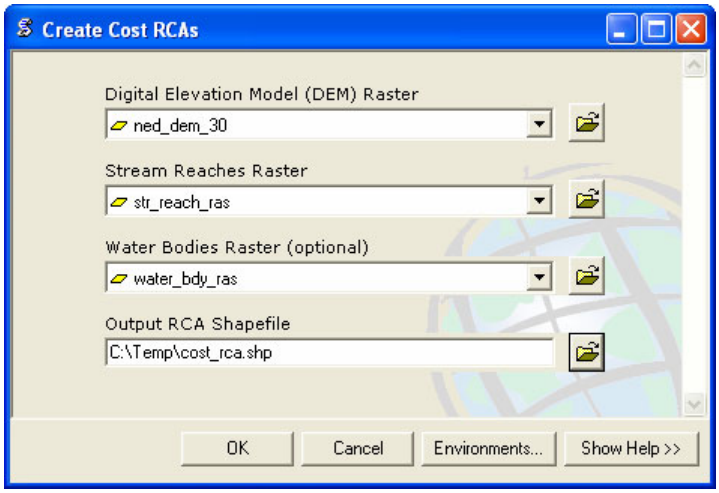


Create Cost RCAs

This tool generates a polygon shapefile of Reach Catchment Areas (RCAs) for every unique reach (polyline) within an input hydrologic network. An RCA represents a sub-component (polygon) of a watershed that drains directly into a given stream segment. This script requires a Digital Elevation Model (DEM), and rasterized hydrologic features (stream reaches and water bodies) to calculate RCAs. The output is a polygon shapefile that represents RCAs. These RCAs can be linked to the input reach features via the unique ID (field) used to generate the reach raster dataset. This linkage is used in the **RCAs to Landscape Network** tool to build the downstream relationships between RCAs and reaches within a given drainage network. This tool uses a Cost Distance analysis to calculate RCAs using topographic information as cost weights.
A surrogate variable for soil moisture, TOPMODEL (aka Topographic Wetness Index), is computed using: *Ln (a / tan(B))*, where a is the length of the uphill flowpath (computed from FlowAccumulation) and B is the local slope (Beven and Kirkby 1979). The inverse index value is used as one of the components of the cost weight. The second component introduces weights so that ridgelines are more clearly delineated. We use the Topographic Position Index, which compares the elevation at a given cell to the mean elevation of a specified neighborhood around that cell (Weiss 2002; Jenness 2005). By default, we use an annulus neighborhood with an inner radius of 7 and outer radius of 12.

Since Cost Distance is used to calculate RCAs, it recommended that the input DEM be clipped to the full watershed extent of the input stream network. This is necessary because the Cost Distance analysis will grow RCAs to the full data extent of the input DEM.

Create Cost RCAs form with example dataset parameters



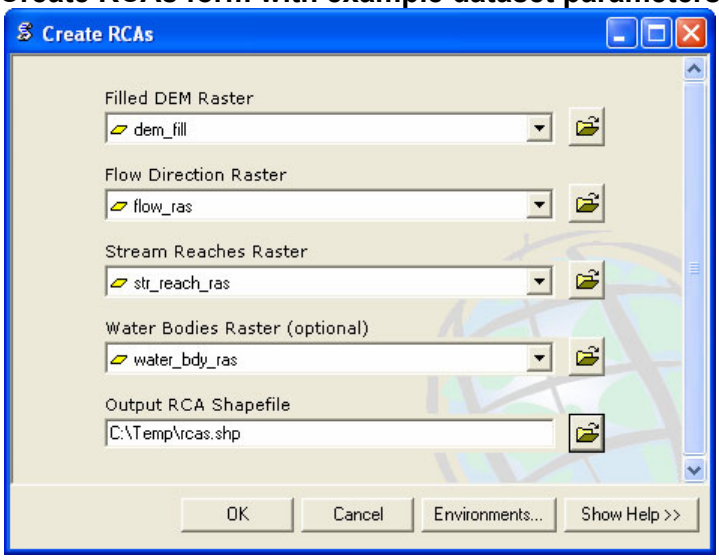
Parameters

- **Digital Elevation Model (DEM) Raster**
  - This can be a filled or raw (unprocessed) DEM.
- **Stream Reaches Raster**
  - This is a raster that represents a stream network as a polyline features class. Typically this is generated by the Spatial Analyst command Convert to Raster, and the GRIDCODE for each reach must be a unique value (typically FID) that represents a unique stream reach. This value is used to join a stream reach to its associated RCA.
- **Water Bodies Raster (optional)**
  - This is a raster that represents water bodies within a given study area. Its GRIDCODE value is not important, because it will be reassigned to its corresponding stream reach GRIDCODE.
- **Output RCA Shapefile**
  - This is the output RCA shapefile name. This shapefile will have an attribute field called GRIDCODE, which is its associated reach identifier.

Create RCAs

This tool generates a polygon shapefile of Reach Catchment Areas (RCAs) for every unique polyline within an input hydrologic network with the Spatial Analyst command *Watershed*. An RCA represents a sub-component (polygon) of a watershed that drains directly into a given stream segment. This script requires a filled DEM, a flow direction raster (output from Fill DEM and BUILD Flow Direction Raster), and rasterized hydrologic features (stream reaches and water bodies) to calculate RCAs. The output is a polygon shapefile that represents RCAs. These RCAs can be linked to the input reach features via the unique ID (field) used to generate the reach raster dataset. This linkage is used in the *RCAs to Landscape Network* tool to build the downstream relationships between RCAs and reaches within a given drainage network.

Create RCAs form with example dataset parameters



Parameters

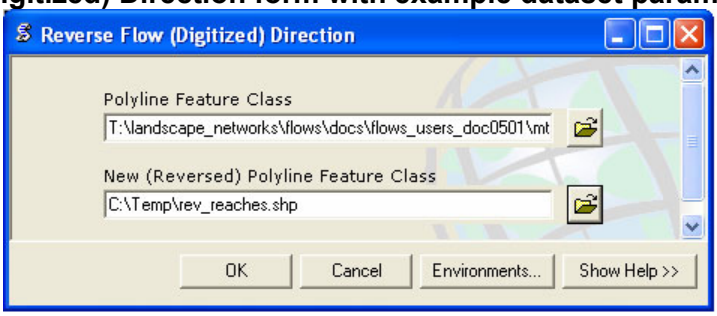
- **Filled DEM**
  - A Digital Elevation Model (DEM) that has been "hydrologically conditioned" by filling artificial pits. This conditioned DEM can be provided by the user, and/or generated by the Spatial Analyst tools *Fill DEM* and *Build Flow Direction*. Note that we do not assume that streams have been "burned in", or that watershed boundaries have been "walled".
- **Flow Direction Raster**
  - A raster of flow direction that has been generated the Fill DEM and Build Flow Direction raster tool in FLoWS.
- **Stream Reaches Raster**
  - This is a raster that represents a stream network represented as polyline features. Typically this is generated by the Spatial Analyst command *Convert to Raster*, and the GRIDCODE for each reach must be a unique value (typically FID) that represents a unique stream reach. This value is used to join a stream reach to its associated RCA.
- **Water Bodies Raster (optional)**
  - This is a raster that represents water bodies within a given study area. Its GRIDCODE value is not important, because it will be reassigned to its corresponding stream reach GRIDCODE.
- **Output RCA Shapefile**
  - This is the output RCA shapefile name. This shapefile will have an attribute field called GRIDCODE, which is its associated stream reach identifier.

Reverse Flow (Digitized) Direction

This tool reverses the digitized direction of the input polyline features that represent a hydrologic network. This tool is useful if a hydrologic network has been digitized upstream (so that the starting point is lower elevation than the ending point) and it needs to be

imported into a Landscape Network that builds feature to feature relationships assuming downstream flow. The Polyline to Landscape Network and the RCAs to Landscape Network tools assume that input reach feature classes are digitized with flow. This tool should be used if the digitized direction is aginst flow. The EPA's National Hydrography Dataset (NHD) polylines are digitized with flow.

Reverse Flow (Digitized) Direction form with example dataset parameters



Parameters

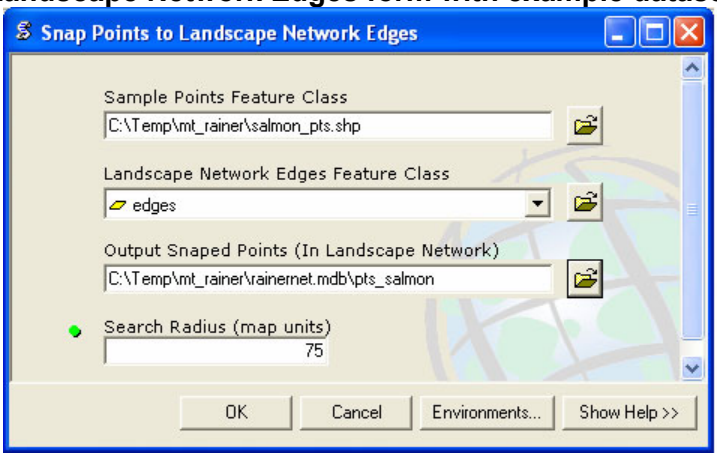
- **Polyline Feature Class**
  - A polyline feature class that is digitized against flow.
- **New (Reversed) Polyline Feature Class**
  - Output polyline feature class (shapefile) with reversed line direction

* The reaches shapefile for the Mt. Hood dataset doesn't need to be reversed it is digitized with flow.

Snap Points to Landscape Network Edges

This tool allows features represented by points (such as dams, stream gages, sample locations, point-source pollution, mines, etc) to be incorporated into the Landscape Network by associating each point to an edge via dynamic segmentation. Dynamic segmentation intersects the point with the closest edge segment, moves the point to that location and calculates a point's distance ratio from the end of an edge. This allows for point to point distances to be calculated along a network without needing to permanently alter the hydrologic reaches by cutting them into two reaches.

Snap Points to Landscape Network Edges form with example dataset parameters

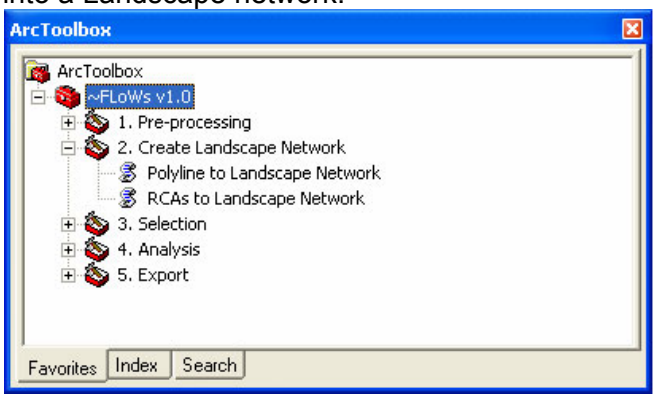


Parameters

- **Sample Point Feature Class**
  - Point feature class that will be snapped to the Landscape Network edges feature class.
- **Landscape Network Feature Class (edges)**
  - A Landscape Network edges feature class
- **Output Snapped Points (In Landscape Network)**
  - Output Landscape Network point feature class with hydrologic relationships established.
- **Search Radius (map units)**
  - The maximum distance in map units between point features and edge features for which distance and rid will be determined. If no edge feature is within the search radius of a given point the internal number and distance output will be 0.

PART 2: Create Landscape Network Tools

The *Create Landscape Network* tools provide two tools that allow for polyline and polygon features to be imported into a Landscape network.

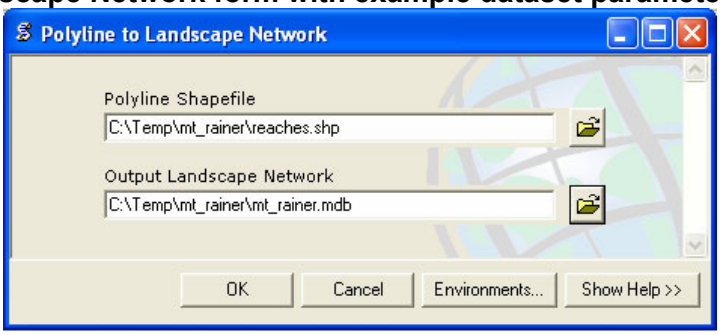


Polyline to Landscape Network

This tool generates a Landscape Network based on geometric coincidence of the input polyline features. The geometric coincidence method is implemented by finding polyline segments nodes and relating them to other polyline segment nodes to compute flow direction and downstream relationships. The output Landscape Network is a personal Geodatabase composed of four elements: an edge feature class, node feature class, relationships table, and a node relationships table. The edge feature class is the input polyline feature class with a relational field **rid**, which relates polyline segments to the relationships table. The node feature class is a point feature class of all the end points (or nodes) within the input polyline feature class. The field **pointid** joins polyline segment nodes to the **noderelationships** table. The relationships table is a sorted table (as a Forward Star structure) that represents flow or movement direction. It has two fields: **fromfeat** (from feature) and **tofeat** (to feature), which indicate feature to feature

relationships within the edge feature class. The **noderelationships** table relates nodes to edges within the Landscape Network.

Polyline to Landscape Network form with example dataset parameters



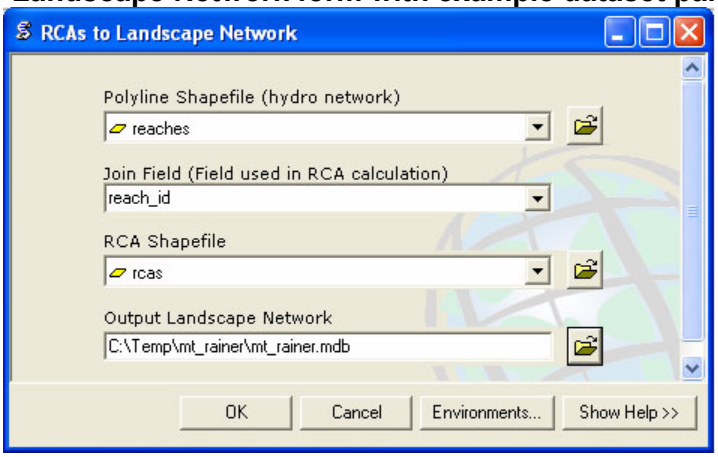
Parameters

- **Polyline Shapefile**
  - A polyline shapefile
- **Output Landscape Network**
  - Output FLoWS Landscape Network with the .mdb extension in the name (e.g., network**.mdb**).

RCAs to Landscape Network

This tool generates a Landscape Network for RCAs based on geometric coincidence of the input polyline (hydrologic network) features. The output Landscape Network is a personal Geodatabase composed of four elements: an edge feature class, node feature class, relationships table, and a node relationships table. The RCA feature class is the input polyline feature class with a relational field **rid**, which relates it to the relationships table. The node feature class is a point feature class of all the end points (or nodes) within the input polyline feature class. The field **pointid** joins it to the **noderelationships** table. The relationships table is a sorted table (as a Forward Star structure) that represents flow or movement direction. It has two fields: **fromfeat** (from feature) and **tofeat** (to feature), which indicate feature to feature relationships within the edge feature class. The **noderelationships** table relates nodes to edges within the Landscape Network.

RCAs to Landscape Network form with example dataset parameters

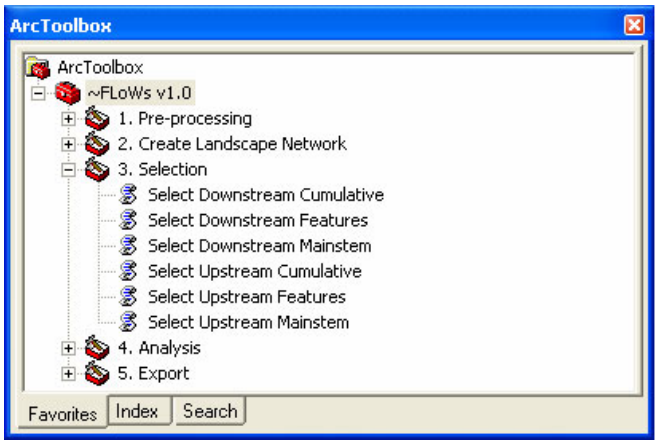


Parameters

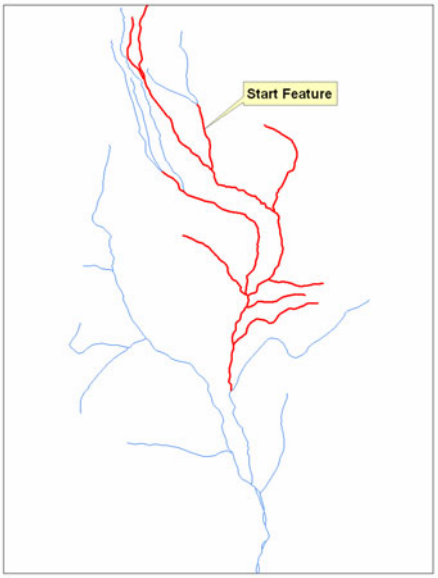
- **Polyline Shapefile (hydro network)**
  - The polyline shapefile used to create the Reach Contributing Areas (RCA) in the input RCA shapefile which defines flow relationships between RCAs.
- **Join Field (field used in Create RCAs tool**
  - Field associated with the input reaches shapefile that links to the GRIDCODE value of the input RCA shapefile.
- **RCA Shapefile**
  - The Reach Contributing Area (RCA) shapefile created by the Create RCAs or Create Cost RCAs tools.
- **Output Landscape Network**
  - A Landscape Network (Personal GeoDataBase) with the .mdb extension

PART 3: Selection Tools

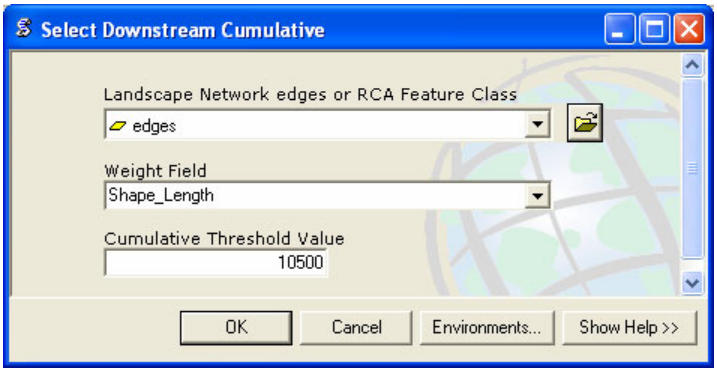
The *selection* tools allow interactive queries or selections on Landscape Networks within an ArcMap document. These tools work on an existing selection set to determine which features will be selected. If there is not an existing selection set, then all features will be evaluated resulting in a new selection set and all features in the network will be selected.



Select Downstream Cumulative



This tool adds features to the selected set that are downstream from the selected features (as defined in ArcMap). The user needs to define a numeric field and a threshold value such that features will be included in the selection if downstream features have a cumulative value less than or equal to the threshold value. This tool it useful in finding features that are downstream or flow into downstream features within a given weight threshold from selected features.



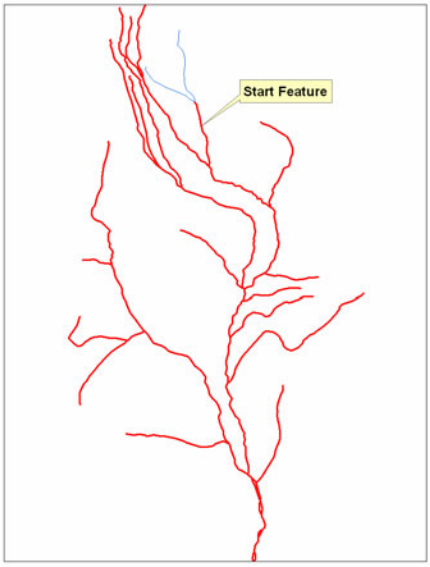
Parameters

- **Landscape Network edges or RCA Feature Class**
  - Landscape Network feature class (edges or RCA) that has selected features
- **Weight Field**

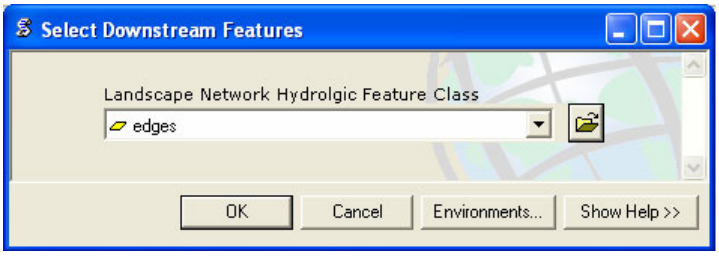
- Numeric field that will be summed upstream until the threshold value is exceeded

- **Cumulative Threshold Value**
  - Threshold value that the sum of downstream features weight value will not be exceeded

Select Downstream Features



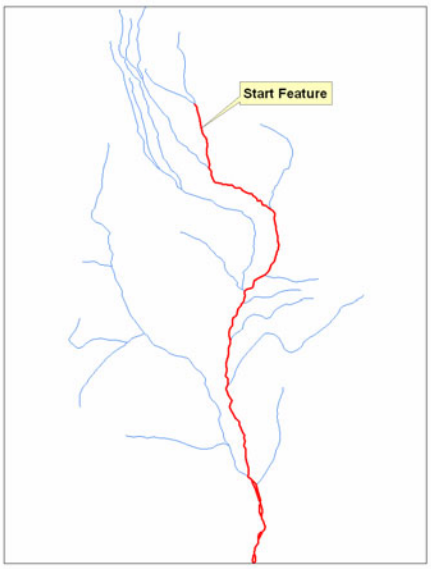
This tool adds features to the selected set that are downstream from the selected features (as defined in ArcMap). Like the *Select Downstream Mainstem* tool, this tool adds features that are directly downstream (along the mainstem), but also features that are upstream of added features. For example, all mainstem and tributary reaches below a dam can be identified (assuming the initial selected feature represents a reach with a dam on it). This tool it useful to find features that flow into or are below selected features within a drainage network.



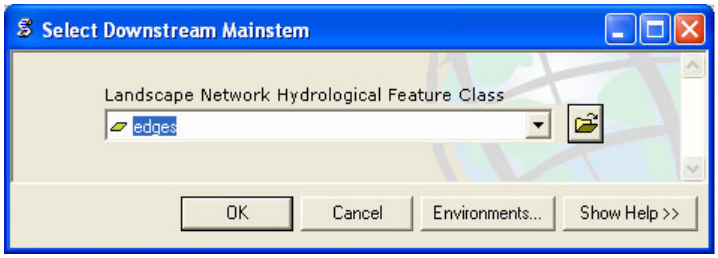
Parameters

- **Landscape Network Hydrologic Feature Class**
  - Landscape Network feature class (edges or rRC)

Select Downstream Mainstem



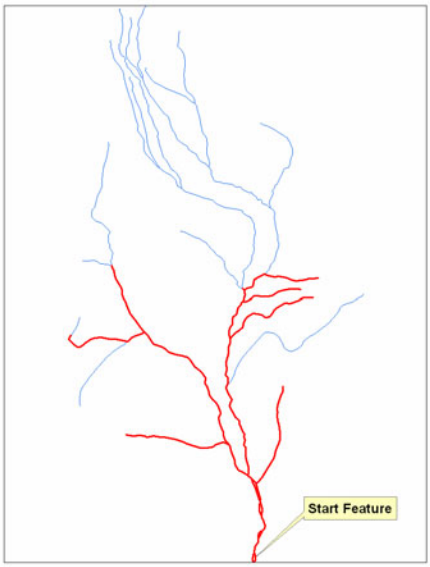
This tool adds features to the selected set that are (strictly) downstream along the mainstem from the selected features (as defined in ArcMap). This tool is useful in finding what features a directly downstream from a selected set. This could be used to find what cities are downstream from a given city or dam.



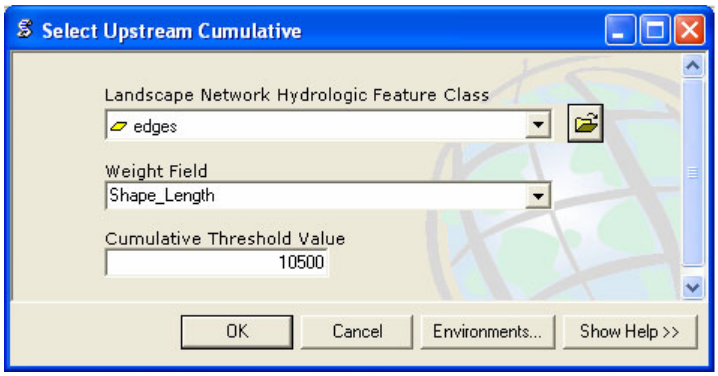
Parameters

- **Landscape Network Hydrologic Feature Class**
  - Landscape Network Feature class (edges or RCA)

Select Upstream Cumulative



This tool adds features to the selected set that are upstream from the selected features (as defined in ArcMap). The user needs to define a numeric field and a threshold value such that features will be included in the selection if upstream features have a cumulative value less than or equal to the threshold value. This tool it useful in finding features that flow into features that are below a dam within a drainage network given a summed weight threshold. This tool is useful in finding what upstream features given a weight threshold are above selected features. For Example, this could be used to find upstream cities within 200 stream miles of a stream reach or dam.



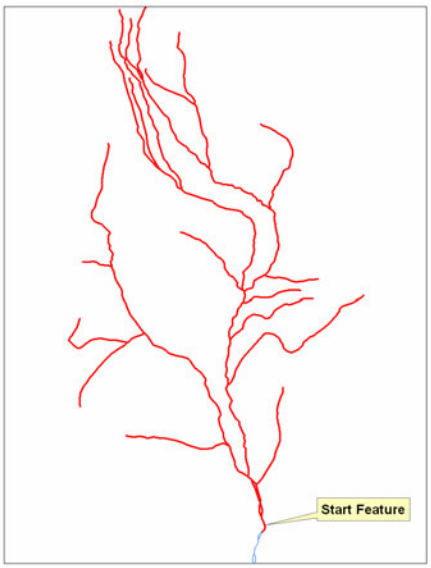
Parameters

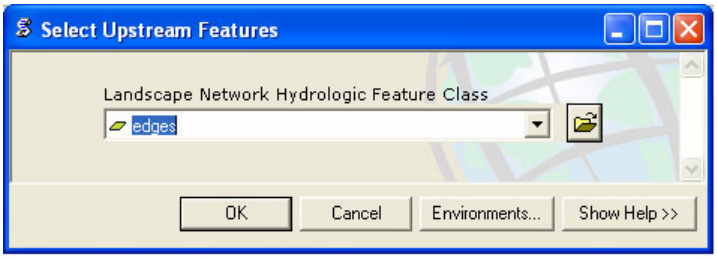
- **Landscape Network Hydrologic Feature Class**
  - Landscape Network Hydrologic feature class (edges or RCA)
- **Weight Field**
  - Numeric field that will be summed upstream until the threshold value is exceeded
- **Cumulative Threshold Value**

- Threshold value that the sum of upstream features weight value will not be exceeded

Select Upstream Features

This tool adds features to the selected set that are upstream from selected features (as defined in ArcMap). This tool is useful to find all features that are above a selected stream reach or RCA. This analysis could be used to generate a new sub-network or used to select other features such as cities or landuse that are upstream from a given selected set.



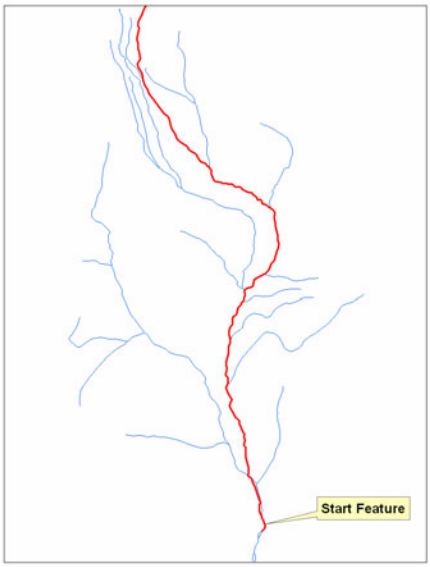


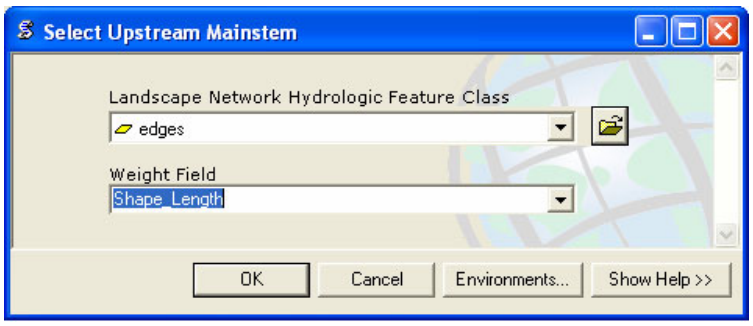
Parameters

- **Landscape Network Hydrologic Feature Class**
  - Landscape Network feature class (edges or RCA)

Select Upstream Mainstem

This tool adds mainstem features to the selected set that are upstream from the selected features (as defined in ArcMap). The user needs to define a numeric field so that mainstem features are defined by finding the largest upstream accumulated value at each confluence upstream from the initial selection. This tool is useful in defining a drainages mainstem based on different criteria, such as stream length, water basin area, or a given land use type.



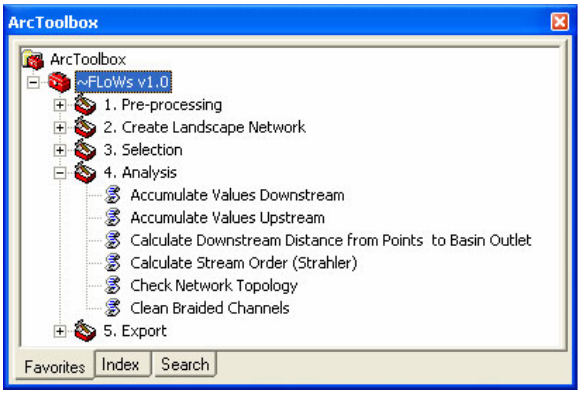


Parameters

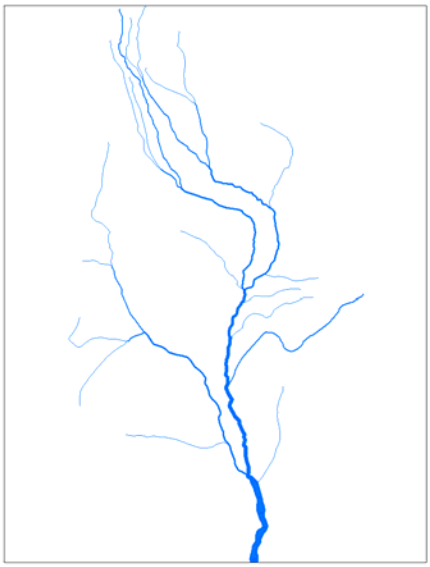
- **Landscape Network Hydrologic Feature Class**
  - Landscape Network feature class (edges or RCA)
- **Weight Field**
  - Numeric field that will be accumulated to calculate the main stem

PART 3: Analysis Tools

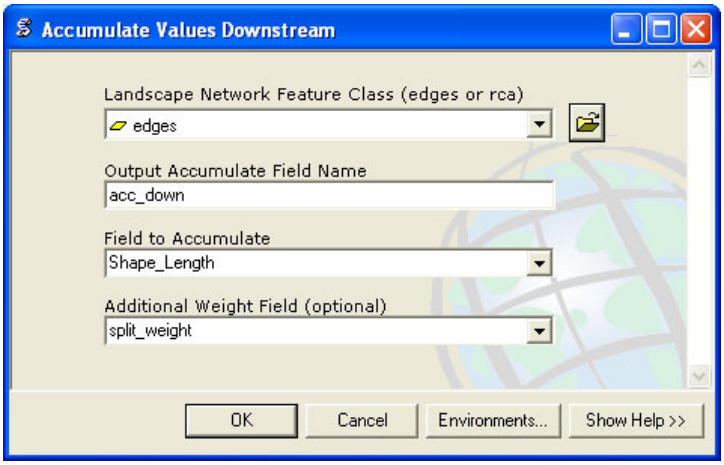
The *analysis* tools allow users to perform graph or network-based analyses. These routines typically populate a user-defined field for a defined Landscape Network feature class. The *analysis* tools also allow for network topology to be checked and to clean braided channels so that the other analysis tools are not compounded by braided stream interactions.



Accumulate Values Downstream



This tool accumulates values from a user-defined field downstream and populates the values of a new field for each feature with its downstream accumulated value. If an additional weight field is supplied, then accumulated values going into a given edge or RCA will be multiplied by the value of the additional weight field.



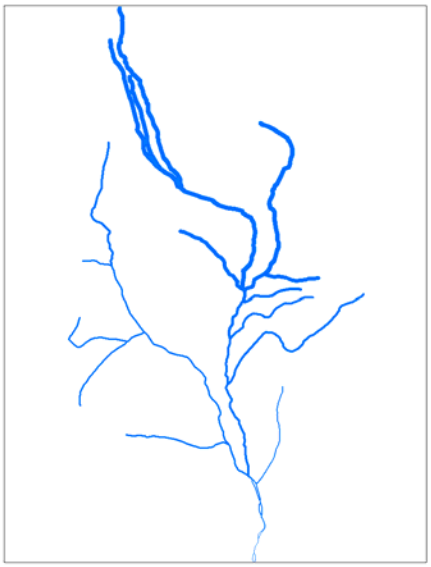
Parameters

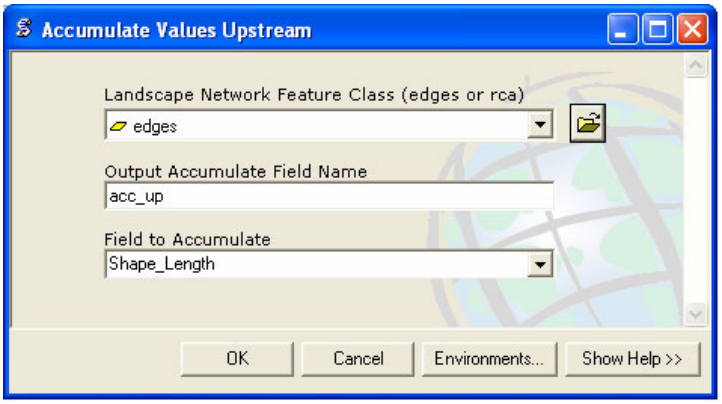
- **Landscape Network Hydrologic Feature Class**
  - A Landscape network feature class that represents a hydrologic system (e.g., edges or RCA).
- **Output Accumulated Field Name**
  - Field that will be populated with accumulated values. Warning: if the output field exists it will be overwritten.

- **Field to Accumulate**
  - Numeric field which values will be accumulated downstream.
- **Additional Weight Field (optional)**
  - Field that will be multiplied against the accumulated value for a given edge. This can be used to weight splits with in the network for braided or divergent stream channels.

Accumulate Values Upstream

This tool accumulates values upstream based on a accumulate field and populates new field the accumulated values. This tool allows for any numeric field associates with edges or RCAs to be accumulated upstream. For example, this tool can be used to find an edge that is the furthest from an outlet by accumulating length upstream and finding the maximum value for all edges.



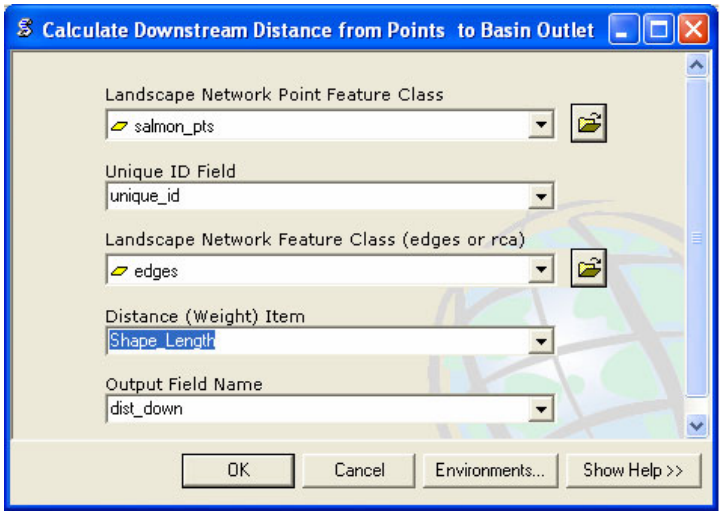


Parameters

- **Landscape Network Hydrologic Feature Class**
  - A Landscape network feature class that represents a hydrologic system (e.g., edges or RCA).
- **Output Accumulated Field Name**
  - Field that will be populated with accumulated values. Warning: if output field exists it will be overwritten.
- **Field to Accumulate**
  - Numeric field that will be accumulated upstream.

Calculate Downstream Distance from Points to Basin Outlet

This tool calculates the distance (along the downstream mainstem) from each point in drainage to the closest downstream outlet node and populates a user-defined field with the summed distance value. The input point features must be a snapped and represented as a point feature class within the Landscape Network geodatabase.

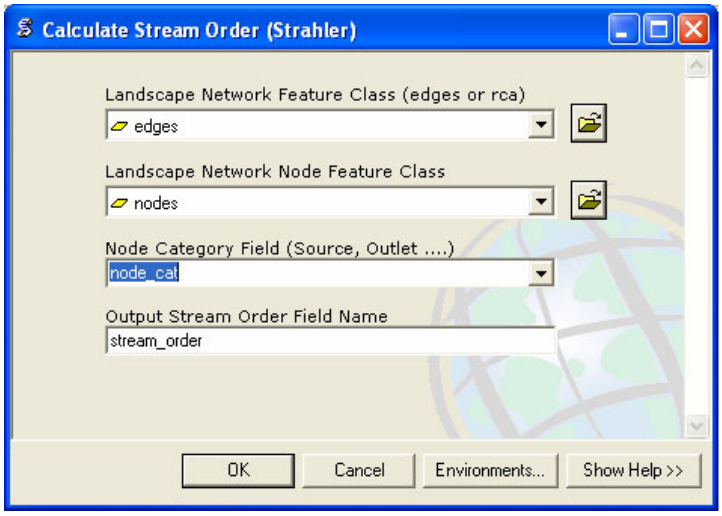


Parameters

- **Landscape Network Point Feature Class**
  - Point feature class that has been snapped and imported into a Landscape Network.
- **Unique ID Field**
  - A field associated with the input point feature class that has a unique value for each point.
- **Landscape Network Feature Class (edges or RCA**
  - A Landscape Network RCA or edges feature class.
- **Distance (Weight) Item**
  - Edge or RCA feature class field that will be used to calculate distance to basin outlet.
- **Output Field Name**
  - A new or existing field associated with the input point feature class that will be populated with distance values. Warning: if an existing field is used it will be overwritten.

Calculate Stream Order (Strahler)

This tool calculates Strahler stream order for each reach within a Landscape Network feature class. It populates a user-defined field with a feature's associated stream order. Before running this tool, be sure to confirm the network topology is correct by using the *Check Network Topology* tool which finds errors and adds a field that describes the node types used to determine stream order in braided channels (also be sure to visually inspecting the network by using various Selections. If the stream network has braided channels, the Strahler order value will be compounded so it is recommended that braided channel relationships be removed first.



Parameters

- **Landscape Network Feature Class (edges or RCA)**
  - A Landscape Network edges feature class
- **Landscape Network Node Feature Class**
  - Landscape Network node feature class
- **Node Category Field (Source, Outlet …)**
  - Field associated with the node feature class that has node topologic relationships (e.g., Source, Outlet.....). This field should be the output of the Check Network Topology tool.
- **Output Stream order Field Name**
  - Field name that will be populated with Strahler stream orders

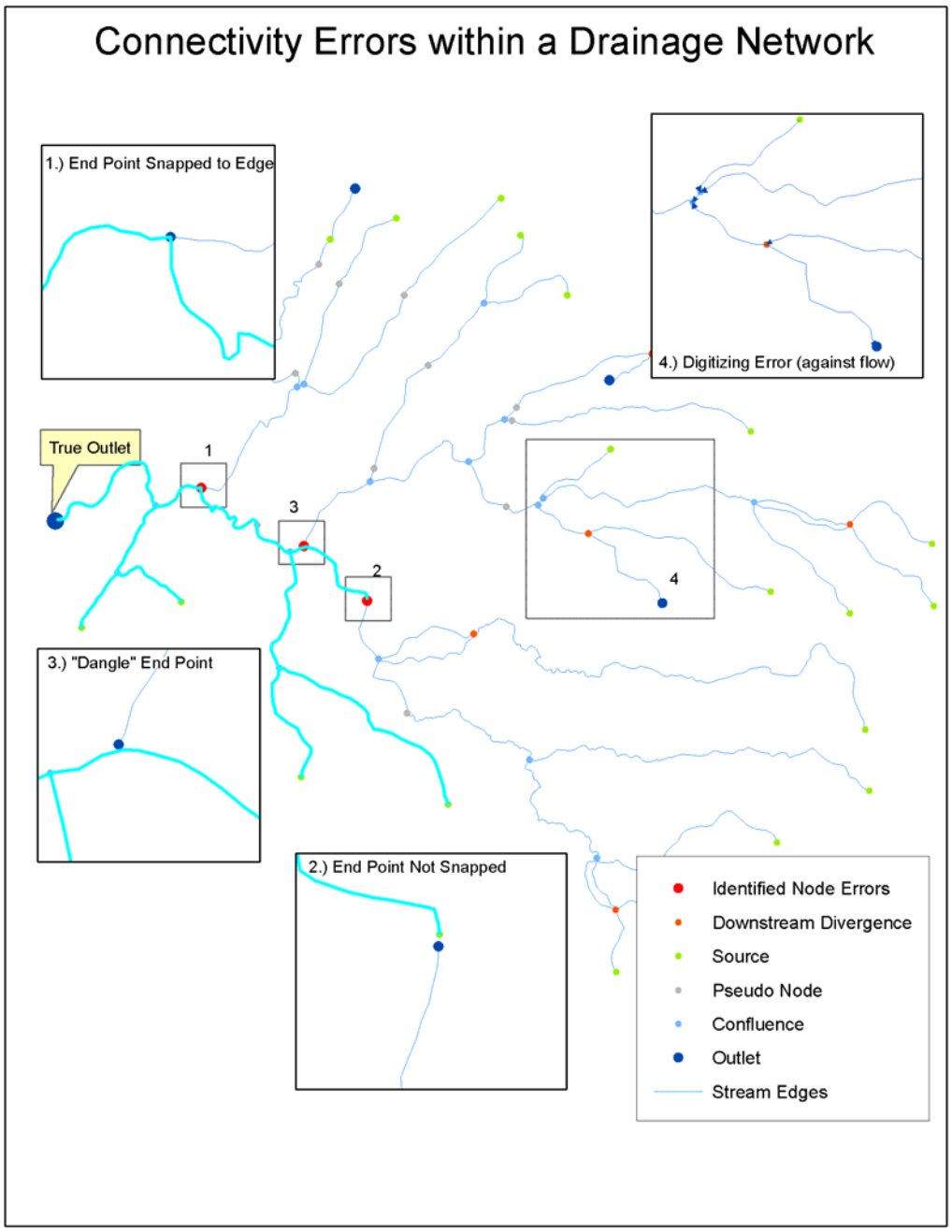
Check Network Topology

This tool searches the node and edge feature classes in a Landscape Network for topological errors based on geometric coincidence. It attributes a user-defined field in the node feature class with node categories or types, which include: source, outlet, pseudo node, downstream divergence, converging stream, and confluence. *Source nodes* occur at the starting point of an edge if there is not an adjacent edge with its to_node coincident (i.e. does not have an upstream input). *Outlet nodes* occur at the from_node of an edge that does not have an adjacent edge with a starting point coincident (i.e. does not have a downstream output). *Pseudo nodes* are locations where a starting point of an edge is coincident with the two node of only one other edge. *Confluence nodes* occur where two or more edges (ending points) are coincident with exactly one other edge (starting point). *Downstream divergence nodes* represent locations where an edge's ending point is coincident with two or more edges' starting points. Converging nodes occur when two or more edges' ending points are coincident (with no starting point coincidence).

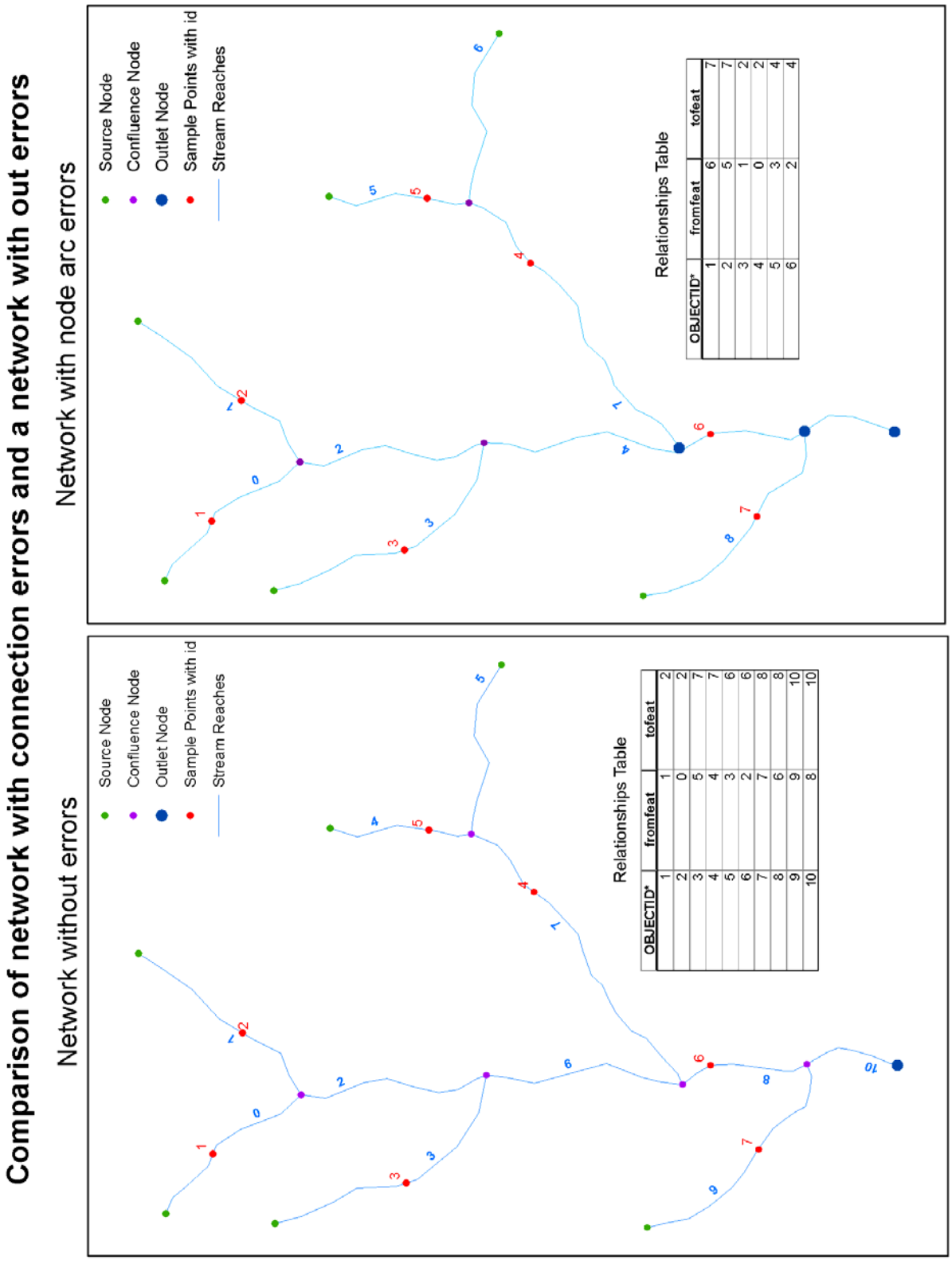
Possible topological errors are computed and stored in a shapefile called node_errors.shp located in the same directory as the input Landscape Network. Topological node and edge errors include outlet nodes that are within a user-specified search tolerance distance of source nodes, and nodes that are snapped to an edge without a coincident node (i.e. an edge is connected to another edge at its middle). Note that it is also important to visually display node errors (especially to identify erroneous outlets at headwater streams if they are digitized in the wrong

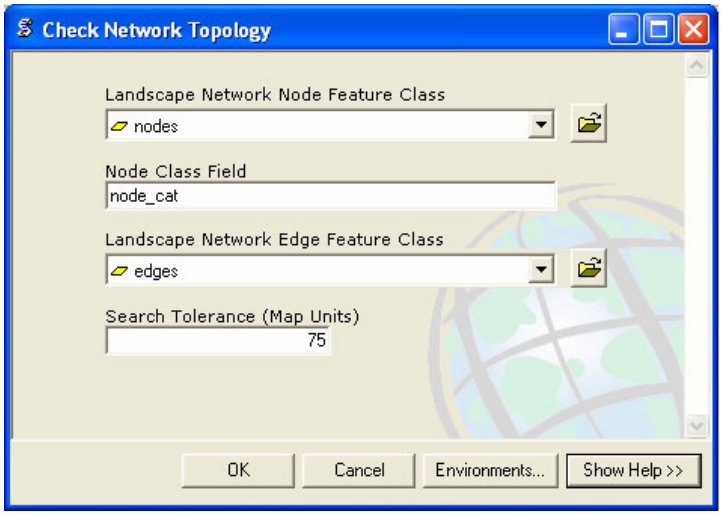
direction) and accumulated flow. Also, selections up and downstream often identify possible topological errors. It must be stressed that the quality of an analysis rests on the topological correctness of the hydrologic network, which is not readily apparent (nor required) for typical GIS analyses.

Four common types of topology errors within a FLoWS landscape Network



The effects of topology errors within the relationships table





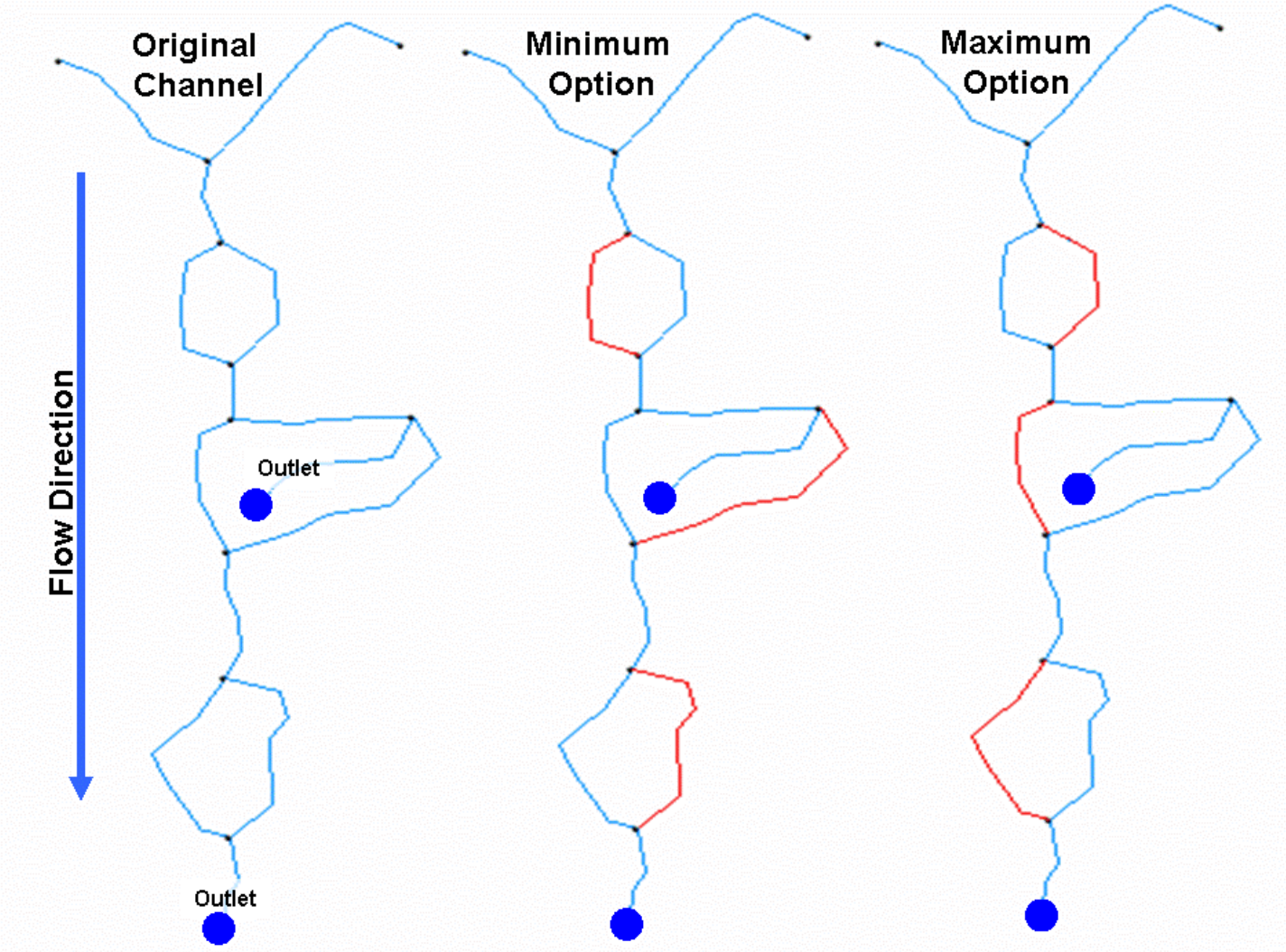
Parameters

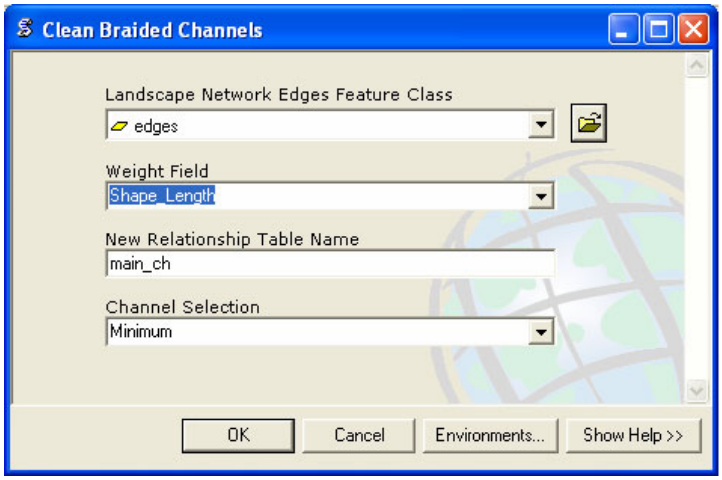
- **Landscape Network Node Feature Class**
  - Landscape Network node feature class
- **Node Class Field**
  - Name of field that will contain the node designation categories
- **Landscape Network Edge Feature Class**
  - Landscape Network edge feature class
- **Search Tolerance (Map Units)**
  - Search radius in map units. The search tolerance will be used to determine if outlet and source nodes are disconnects (breaks) within the network.

Clean Braided Channels

This tool generates a new relationships table within the input Landscape Network with braided from/to relationships removed. The new table within the Landscape Network can be renamed to relationships to allow braided stream channels to be bypassed through the defined main channel. To display what from/to relationships within braided channels refresh ArcMap display. When viewing the removed relationships selection set, remember that it displays from/to relationships and not edge removal. The example shows features with removed from/to relationships from the new relationships table (in red). The minimum and maximum functions choose different paths because the minimum function is minimizing *shape_length* and maximum is maximizing *shape_length* through braided channels. The example includes two outlet points to demonstrate that this tool retains network connectivity for multiple output points with in a drainage network.

This figure demonstrates how the two different channel selection functions select the mainstem through braided stream channels. The channel selection functions maximize or minimize globally to prevent multiple outlets or other network features from losing connectivity from upstream features.



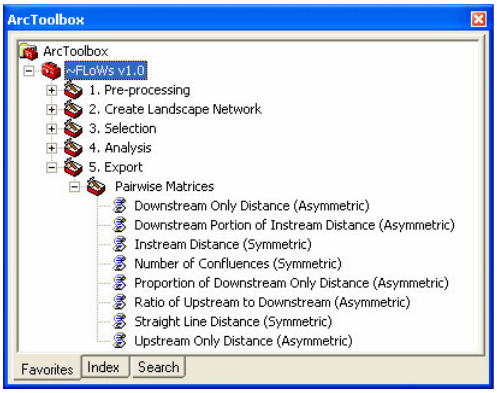


Parameters

- **Landscape Network Edges Feature Class**
  - A Landscape Network edge or RCA feature class
- **Weight Field**
  - Numeric field that will be used to determine main channel
- **New Relationships Table Name**
  - New relationships table name within the input Landscape Network
- **Channel Selection**
  - How the main channel through braided areas will be calculated. Minimum will minimize the user-defined weight field and maximum will maximize the user-defined weight field in finding the main channel through braided stream channels.

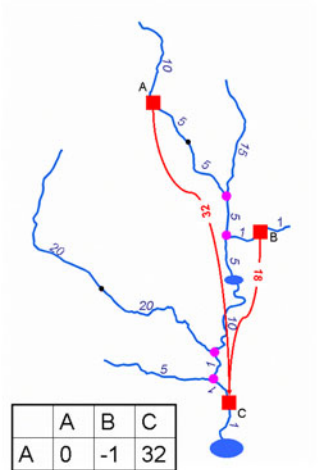
PART 3: Export / Pair-wise Matrices Tools

The *export* tools evaluate point to point relationships within a Landscape Network and create a comma delimited *n* x *n* matrix of distance values between pairs of locations. These tools are useful in generating *n* x *n* matrices as input to statistical models that incorporate network wide weight relationships.

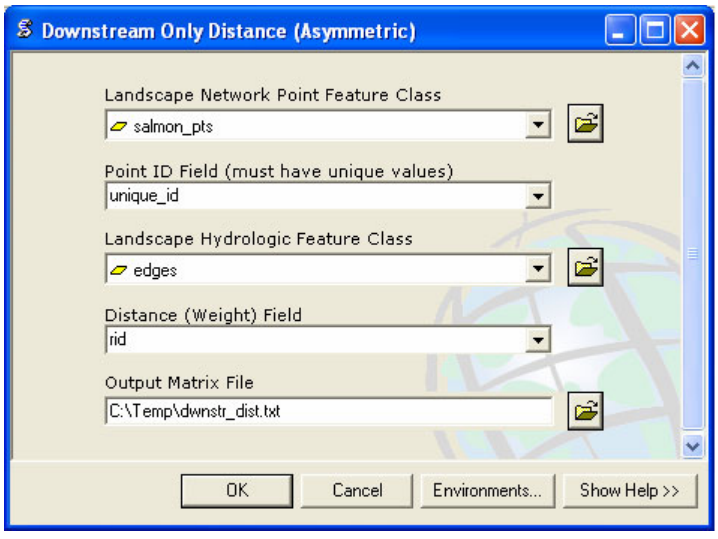


Downstream only Distance (Asymmetric)

This tool creates an asymmetric matrix of downstream-only distances from all or selected pairs of points in the input feature class based on a Landscape Network feature class (e.g., edges or RCAs distances are computed using values from the user-defined field and are output as a comma delimited text file. If a pair of points is not connected, their distance value is -1.



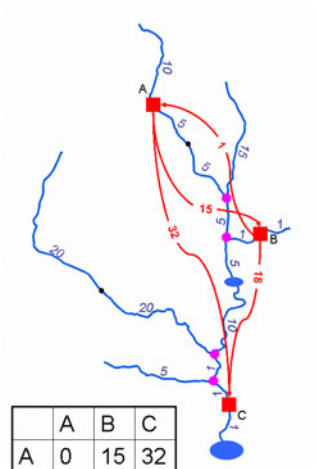
	A	B	C
A	0	-1	32
B	-1	0	18
C	-1	-1	0



Parameters

- **Landscape Network Point Feature Class**

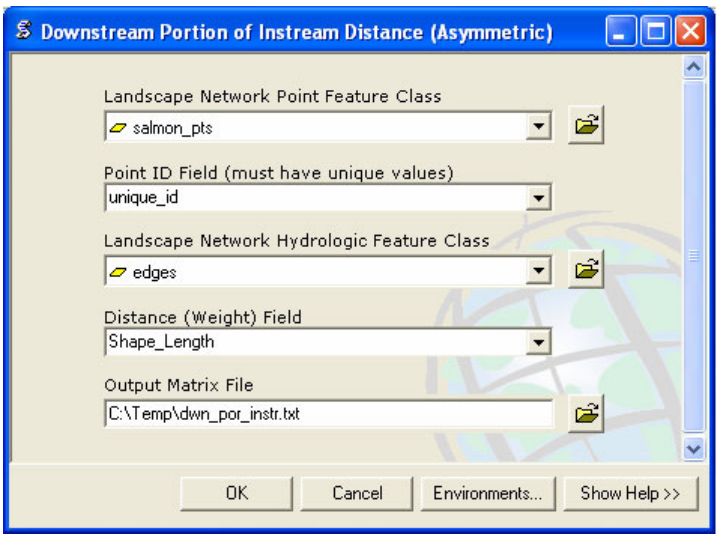
  - Point feature class that has been snapped and imported into a Landscape Network.
- **Point ID Field (must have unique values)**
  - A field associated with the input point feature class that has a unique value for each point. This field will be used as the point identifier within the output matrix.
- **Landscape Hydrologic Feature Class**
  - A Landscape Network edge or RCA feature class
- **Distance (Weight) Field**
  - A numeric field associated with the input Landscape Network Hydrologic feature class that will be used to calculate point to point distances.
- **Output Matrix File**
  - A comma delimited text file representing a nxn distance matrix.



	A	B	C
A	0	15	32
B	1	0	18
C	-1	-1	0

Downstream Portion of Instream Distance (Asymmetric)

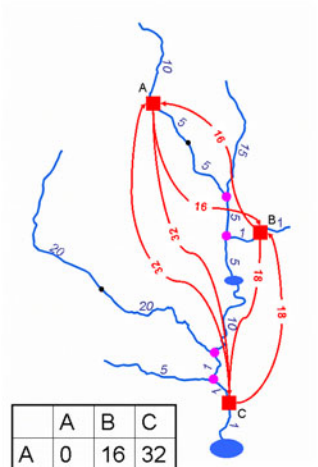
This tool creates an asymmetric matrix that provides only the downstream portion of the instream distance between all or selected pairs of points in the input feature class based on a Landscape Network feature class (e.g., edges or RCAs). Distances are computed using values from the user-defined field and are output as a comma delimited text file. Points that are not connected will have a -1 value in the matrix file.



Parameters

- **Landscape Network Point Feature Class**

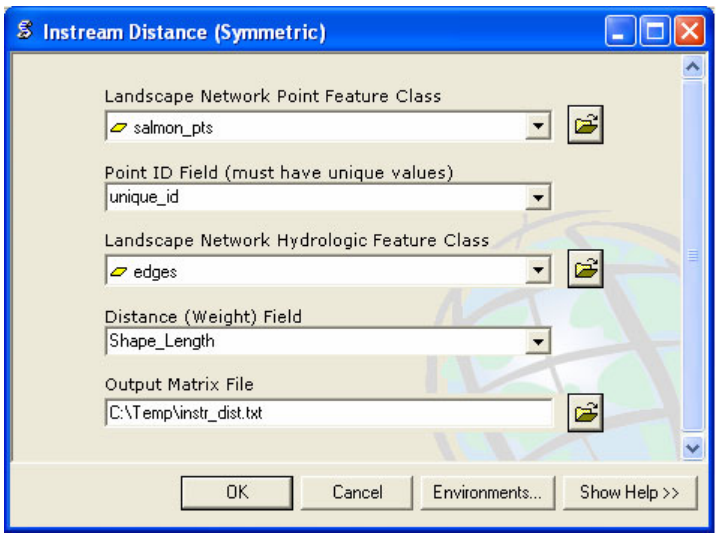
  - Point feature class that has been snapped and imported into a Landscape Network.
- **Point ID Field (must have unique values)**
  - A field associated with the input point feature class that has a unique value for each point. This field will be used as the point identifier within the output matrix.
- **Landscape Hydrologic Feature Class**
  - A Landscape Network edge or RCA feature class
- **Distance (Weight) Field**
  - A numeric field associated with the input Landscape Network Hydrologic feature class that will be used to calculate point to point distances.
- **Output Matrix File**
  - A comma delimited text file representing a *n* x *n* distance matrix.



	A	B	C
A	0	16	32
B	16	0	18
C	32	18	0

Instream Distance (Symmetric)

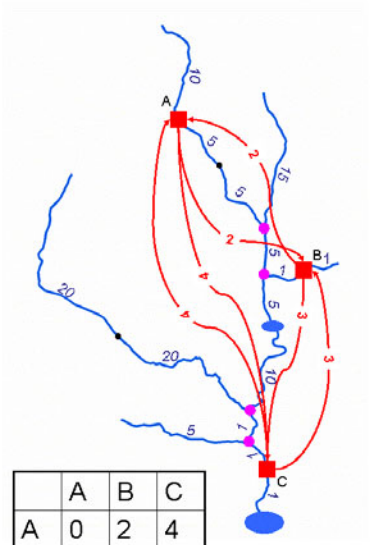
This tool creates a symmetric matrix of instream distances from all pairs of points in the input feature class based on a Landscape Network feature class (e.g., edges or RCAs). Distances are computed using values from the user-defined field and are output as a comma delimited text file. Points that are not connected will have a -1 value in the matrix file.



Parameters

- **Landscape Network Point Feature Class**

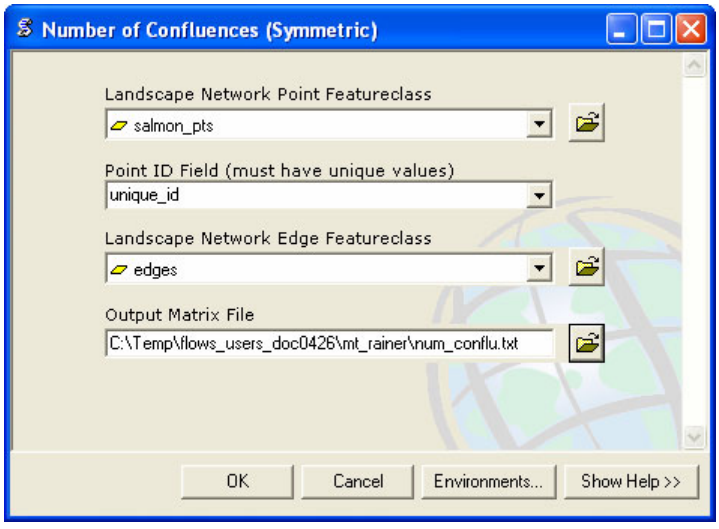
  - Point feature class that has been snapped and imported into a Landscape Network.
- **Point ID Field (must have unique values)**
  - A field associated with the input point feature class that has a unique value for each point. This field will be used as the point identifier within the output matrix.
- **Landscape Hydrologic Feature Class**
  - A Landscape Network edge or RCA feature class
- **Distance (Weight) Field**
  - A numeric field associated with the input Landscape Network Hydrologic feature class that will be used to calculate point to point distances.
- **Output Matrix File**
  - A comma delimited text file representing a nxn distance matrix.



	A	B	C
A	0	2	4
B	2	0	3
C	4	3	0

Number of Confluences (Symmetric)

This tool creates a symmetric matrix that is the number of confluences between all or selected pairs of points (upstream and downstream). A confluence is defined as a junction where two or more edges coincident into one edge. Points that are not connected will have a -1 value in the matrix file.



Parameters

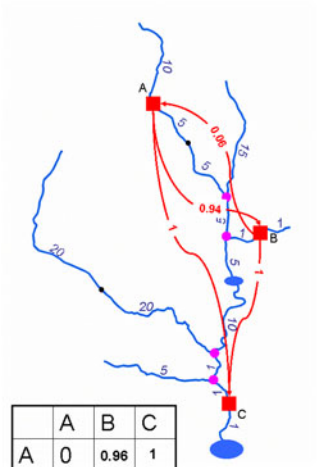
- **Landscape Network Point Feature Class**

- Point feature class that has been snapped and imported into a Landscape Network.

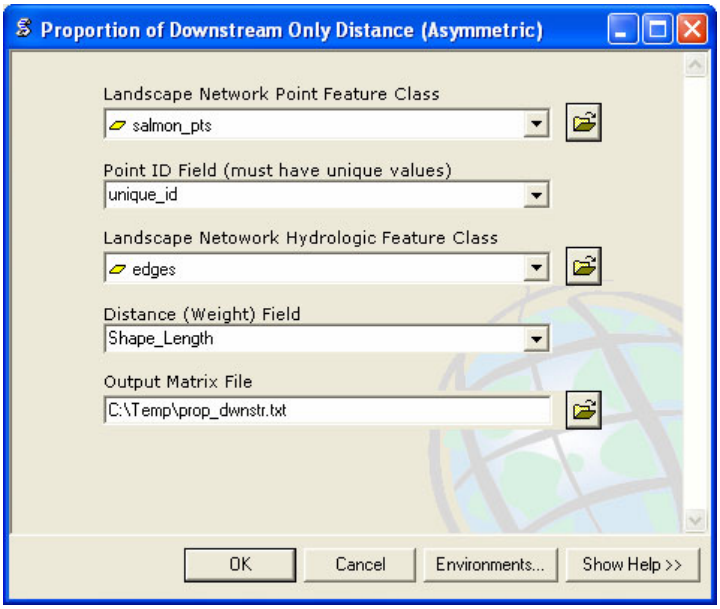
- **Point ID Field (must have unique values)**
  - A field associated with the input point feature class that has a unique value for each point. This field will be used as the point identifier within the output matrix.
- **Landscape Hydrologic Feature Class**
  - A Landscape Network edge or RCA feature class
- **Output Matrix File**
  - A comma delimited text file representing a nxn distance matrix.

Proportion of Downstream Only Distance (Asymmetric)

This tool creates an asymmetric matrix file, comma delimited, with values representing the downstream proportion (or percent) of the total instream distance between all or selected pairs of points. Proportions are based on a summation of a user-defined field associated with a edge or RCA Landscape Network feature class. Points that are not connected will have a -1 value in the matrix file.



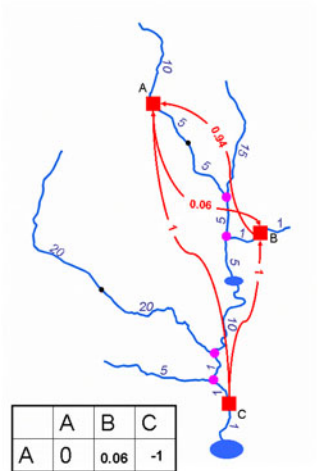
	A	B	C
A	0	0.96	1
B	0.06	0	1
C	-1	-1	0



Parameters

- **Landscape Network Point Feature Class**

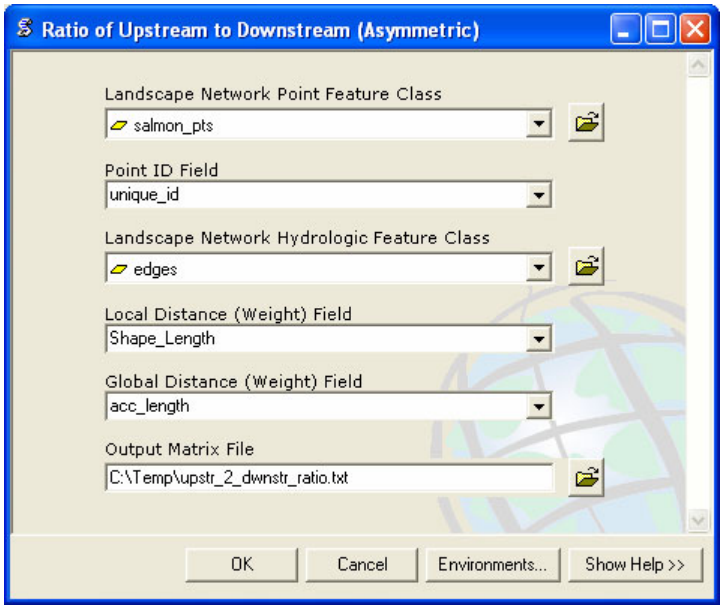
  - Point feature class that has been snapped and imported into a Landscape Network.
- **Point ID Field (must have unique values)**
  - A field associated with the input point feature class that has a unique value for each point. This field will be used as the point identifier within the output matrix.
- **Landscape Hydrologic Feature Class**
  - A Landscape Network edge or RCA feature class
- **Distance (Weight) Field**
  - A numeric field associated with the input Landscape Network Hydrologic feature class that will be used to calculate point to point distances.
- **Output Matrix File**
  - A comma delimited text file representing a nxn distance matrix.



	A	B	C
A	0	0.06	-1
B	0.94	0	-1
C	1	1	0

Ratio of Upstream to Downstream (Asymmetric)

This tool creates an asymmetric matrix file, comma delimited, that provides the ratio of the upstream to downstream weights between all or selected pairs of points in the input feature class based on a Landscape Network feature class (e.g., edges or RCAs). This tool uses a local and a global weight fields to calculate ratios. The local field contains values that are relative to a given feature (e.g., Shape_Length). The global weight field values in cooperate accumulated values which means that the accumulation tools should be ran before using this tool. Points that are not connected will have a -1 value in the matrix file



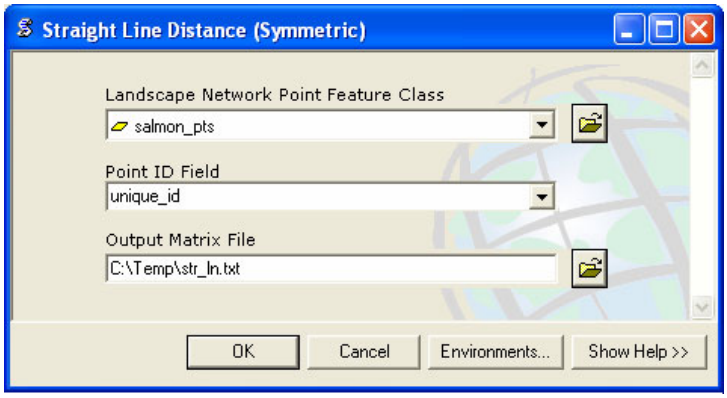
Parameters

- **Landscape Network Point Feature Class**
  - Point feature class that has been snapped and imported into a Landscape Network.
- **Point ID Field (must have unique values)**
  - A field associated with the input point feature class that has a unique value for each point. This field will be used as the point identifier within the output matrix.
- **Landscape Hydrologic Feature Class**
  - A Landscape Network edge or RCA feature class
- **Local Distance (Weight) Field**
  - A numeric field associated with the input Landscape Network Hydrologic feature class that is local value to be used in calculating ratios between upstream and downstream points.
- **Global Distance (Weight) field**
  - A numeric field associated with the input Landscape Network Hydrologic feature class that will be used to calculate a ratio between the upstream point and downstream point. This filed is usually the result of the accumulation tools.
- **Output Matrix File**
  - A comma delimited text file representing a nxn distance matrix.

Straight Line Distance (Symmetric)

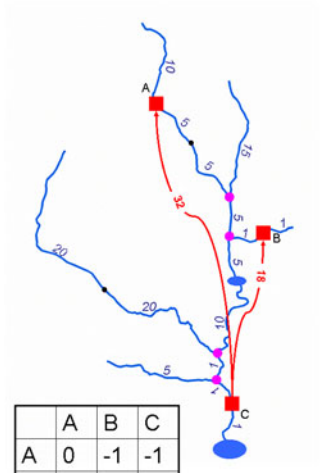
This tool creates a symmetric matrix that provides the straight line distance (computed in map units) between all or selected pairs of points in the input feature class based on a Landscape Network feature class (e.g., edges or RCAs).

	A	B	C
A	0	12	26
B	12	0	13
C	26	13	0



Parameters

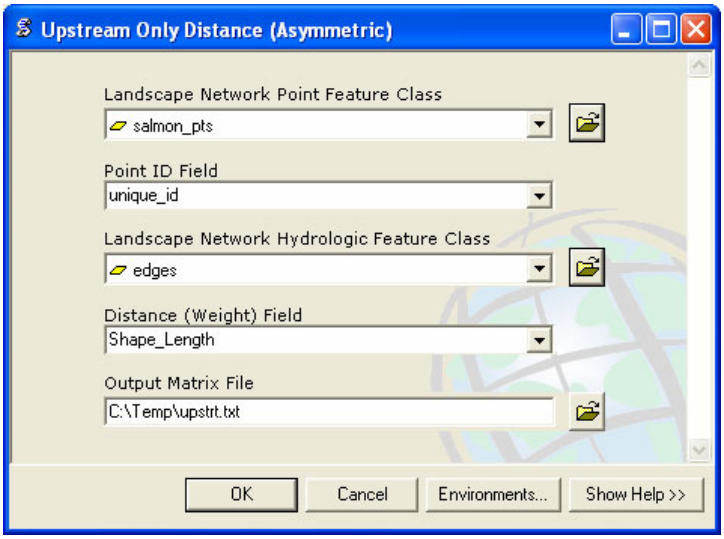
- **Landscape Network Point Feature Class**
  - Point feature class that has been snapped and imported into a Landscape Network.
- **Point ID Field (must have unique values)**
  - A field associated with the input point feature class that has a unique value for each point. This field will be used as the point identifier within the output matrix.
- **Output Matrix File**
  - A comma delimited text file representing a nxn distance matrix.



	A	B	C
A	0	-1	-1
B	-1	0	-1
C	32	18	0

Upstream Only Distance (Asymmetric)

This tool creates an asymmetric matrix of upstream-only distances from all or selected pairs of points in the input feature class based on a Landscape Network feature class (e.g., edges or RCAs). Distances are computed using values from the user-defined weight field and are output as a comma delimited text file. If a pair of points is not connected, their distance value is -1.



Parameters

- **Landscape Network Point Feature Class**
  - Point feature class that has been snapped and imported into a Landscape Network.
- **Point ID Field (must have unique values)**

  - A field associated with the input point feature class that has a unique value for each point. This field will be used as the point identifier within the output matrix.
- **Landscape Network Hydrologic Feature Class**
  - A Landscape Network edge or RCA feature class
- **Distance (Weight) Field**
  - A numeric field associated with the input Landscape Network Hydrologic feature class that will be used to calculate point to point distances.
- **Output Matrix File**
  - A comma delimited text file representing a nxn distance matrix.

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APPENDIX 1:
Mt. Hood Example Dataset and Processing Steps

1. Primary Mt. Hood datasets:

a. **nhd_dem_30:**
   i. Digitial Elevation Model (DEM) downloaded from the National Elevation Dataset (NED) web site http://ned.usgs.gov/ at a resolution of 30 x 30 meters.

b. **reaches.shp:**
   i. Medium resolution (1:100,000) stream reaches (polylines) downloaded from the National Hydrologic Dataset (NHD) website http://nhd.usgs.gov/data.html. The NHD hydrologic data is downloaded as an ESRI personal GeoDatabase with feature classes and feature datasets. It is intended to be used in ESRI's Geometric network data structure. The reaches.shp shapefile is a subset of the NHD flowline feature class within the downloaded NHD personal GeoDatabase. This shapefile will be rasterized and used as seeds to grow Reach Catchment Areas (RCA) in conjunction with the DEM and a flow direction raster.

c. **water_bdy.shp:**
   i. Medium resolution (1:100,000) water bodies (polygons) downloaded from the National Hydrologic Dataset (NHD) website http://nhd.usgs.gov/data.html. The water_bdy.shp shapefile is a subset of the NHD Waterbody feature class within the downloaded NHD personal GeoDatabase.

d. **sample_pts.shp :**
   i. This is a point shapefile of points collected in the field that will be imported into a Landscape Network and connected to their associated stream reaches.

2. Processing NHD personal GeoDatabase to extract stream reaches and water bodies.

a. **Extracting stream reaches form the NHD personal GeoDatabase Hydrography feature dataset.**
   i. In ArcMap, add the NHDFlowlines feature class in the Hydrography feature dataset and the NHDFCode table at the root of the Geodatabase.
   ii. Join the NHDFCode table to NHDFlowlines feature class using FCode as the join item.
   iii. Use the ***Select By Attribute*** tool to select features that are natural water bodies this excludes canels, ditches, and piplenes. Features with artificial path and connector attributes should be retained because they connect streams that flow through water bodies and other hydrological features.

iv. Export the selected features to a shapefile and rasterize on a unique 8-bit identification field. The unique identifier code used to create the streams raster will be used in the RCA's to Landscape Network tool to link up RCA's and their associated stream segment (reach).

b. **Extract water bodies from the NHD personal Geodatabase Hydrography feature dataset.**
   i. In ArcMap add the NHD Waterbodies feature class in the Hydrograhpy feature dataset.
   ii. Use the ***Select By Location*** tool to select water bodies that touch stream reaches
   iii. Export the selected features to a shapefile and rasterize on the FID field within the exported shapefile. The grid code of the water bodies does not have to be unique because the Create RCA's tool joins the streams and water bodies raster to create the source seeds with the gridcode of the streams raster that touch the water body being used as the identifier code.

3. Adding the FLoWS version 1 toolbox into the ArcToolBox Viewer:

a. Must Have ArcGIS 9.1 with service pack two
b. Open the ArcToolBox viewer in ArcMap or ArcCatalog
c. Right Mouse click on the ArcToolBox object at the top of the tools list
d. Select Add Toolbox and navigate to the unzipped directory of flows_v1_public.zip and select the tool box FLOWS v1 public.
e. If the FLOWS v1 public toolbox is added in ArcCatalog, it will always appear in ArcMap and ArcCatalog when ArcToolBox is opened.

4. Generating Reach Catchment Areas (RCAs):

a. The Preprocessing tool ***Create RCAs*** will generate a shapefile that contains chatchment areas for each seed reach. The GRIDCODE value in the attribute table is the reach ID that was used to generate the input stream reach raster. This ID linkage between the RCAs and the input stream reach ID will be important when building a Landscape Network. If the output RCA shapefile has nodata (blank) polygons, it can be rasterized on the GRIDCODE value and used in place of the stream reach raster in the ***Create RCAs*** tool to fill in the nodata areas.
   i. Example input parameters:
      1. dem_fill_4 the filled DEM using a z-limit of 4.
      2. flow_ras flow direction raster.
      3. str_reach_ras the rasterized version of the shapefile reaches.shp using reach_id as the GRIDCODE value.
      4. water_bdy_ras the rasterized version of the shapefile water_bdy.shp using water_id as the GRIDCODE value.
   ii. Example output parameters:
      1. rca.shp polygon shapefile has a RCA for each unique value in the str_reach_ras raster. The GRIDCODE field links the RCA

features to the stream reach features based on the reach_id field, which was used as the GRIDCODE values in the str_reach_ras raster.

b. The Preprocessing tool ***Create Cost RCAs*** will generate a shapefile that contains chatchment areas for each seed reach. The GRIDCODE value in the attribute table is the reach ID that was used to generate the input stream reach raster. This ID linkage between the RCAs and the input stream reach ID will be important when building a Landscape Network. If the output RCA shapefile has island nodata polygons, it can be rasterized on the GRIDCODE value and used in place of the stream reach raster in the ***Create Cost RCAs*** tool to fill in the nodata areas. This tool uses the Cost Allocation tool in conjunction with topographic weight to create RCAs. This speeds up the processing time and generates a fully tessellated RCA shapefile. The draw backs are that it will grow RCA features to the full extent of the input DEM, which may extent further than the input stream reach raster. To prevent this from occurring clip the input DEM to the largest watershed boundary of the input stream network.
    i. Example input parameters:
        1. dem_fill_4 a filled DEM. A filled DEM is not necessary for this tool.
        2. str_reach_ras the rasterized version of the shapefile reaches.shp using reach_id as the GRIDCODE value.
        3. water_bdy_ras the rasterized version of the shapefile water_bdy.shp using water_id as the GRIDCODE value.
    ii. Example output parameters:
        1. rca.shp polygon shapefile has a RCA for each unique value in the str_reach_ras raster. The GRIDCODE field links the RCA features to the stream reach features based on the reach_id field, which was used as the GRIDCODE values in the str_reach_ras raster.

5. Generating Landscape Networks:

Generating Landscape Networks using stream reach polylines and RCA polygons or using stream reach polylines only. The basic elements of a FLoWS Landscape Network consists of two feature classes nodes and edges and two relational tables that link the features classes together within an ESRI personal GeoDatabse. The nodes feature class represents confluences, sources, outlets or other break point features within the input stream reach polyline feature class. The edges feature class is an exact copy of the input stream reach feature class with an extra attribute field rid, which links it to the node feature class via the relational tables. If a RCA shapefile is used in the creation of a Landscape Network, then it will be added to the Landscape Network and linked to the nodes and edges feature classes.

The input stream reach polyline shapefile's flow direction should be checked to make sure that the digitized flow of the line segments flows down stream. This can be checked by using a line symbology that shows flow or digitized

direction. If the flow of the lines is upstream use the Pre-Processing tool ***Reverse Flow (Digitized) Direction***, which creates a new shapefile that has line segments with their topology reversed.

a. The Create Landscape Network tool ***RCAs to Landscape Network*** creates a Landscape Network with three feature classes (nodes, edges, and RCAs) and two relational tables that link the features within each feature class so that their ordering is sorted downstream.
    i. Example input parameters:
        1. reaches.shp the NHDFlowline feature class exported to a shapefile.
        2. reaches_id the field used to create the str_reaches_ras raster.
        3. rca.shp the output shapefile from the Create RCAs tool.
    ii. Example output parameters:
        1. rca_network.mdb the name of the output Landscape Network (personal GeoDatabase) the name entered should contain the .mdb extension. This Landscape Network will have three feature classes (nodes, edges, and rca).
b. The Create Landscape Network tool ***Polyline to Landscape Network*** creates a Landscape Network with two feature classes (nodes and edges) and two relational tables that link the features within each feature class so that their ordering is sorted downstream.
    i. Example input parameters:
        1. reaches.shp the NHDFlowline feature class exported to a shapefile.
    ii. Example output parameters:
        1. polyline_network.mdb the name of the output Landscape Network (personal GeoDatabase) the name entered should contain the .mdb extension. This Landscape Network will have two feature classes (nodes and edges).

6. Checking a Landscape Network for connectivity problems:

Using the ***Check Network Topology*** in the Analysis tool set of FLoWS, enter the node and edge feature classes, within the Landscape Network, and define a field for the node feature class that will hold node designation classes (e.g., source, outlet …) and a search radius (in map units). The search radius is used to find features for a given outlet feature that it may be connected to. This tool will generate a shapefile called node_errors in the same directory as the Landscape Network containing points or nodes where there are potential connectivity problems.

This tool will add and populate a field within the node feature class with node designations and create a node_errors point shape file that identifies potential node errors. The node error points in the node_errors shapefile

should be evaluated in conjunction with other analysis techniques to find true connectivity errors.

Other analysis methods effective in finding network connectivity problems include using the selection set tools to select up or down stream features to visually find connectivity breaks, accumulate values up or down stream and look for accumulation value breaks, use the node designation field to look for outlet nodes that should be confluence or source nodes, and using line symbology with arrow endpoints to visually see stream direction.

i. Example input parameters:
   1. nodes feature class from the polyline_network.mdb
   2. edges feature class from the polyline_network.mdb
   3. 75 meters (map units) as the search radius

ii. Example output parameters:
   1. node_cat is the name of the output field that will be added to the nodes' attribute table it will hold node designation values (e.g., source, confluence, Outlet ….)
   2. node_errors a shapefile stored in the same directory as the input Landscape Network feature classes.

a. Fixing Network connectivity problems entails digitizing or editing the original input polyline shapefile (reaches.shp) that was used to create the original landscape network. It is recommended using the original network feature classes and the node_errors shapefile as a back ground to find areas that need to be edited.

7. Importing point data into a Landscape Network:

Using the ***Snap Points to Landscape Network Edges*** tool in the Pre-processing tool set of FLoWS enter the point shapefile that will be imported into the Landscape Network, the edge feature class to snap the points to, the output name of the new snapped feature class located in the same Landscape Network that the input edge feature class is located, and the maximum distance that a point can be from an edge for it to be snapped. Points that didn't snap to an edge can be found out by looking at the near_FID field in the input point shapefile's attribute table. Points that didn't snap to an edge will have a value of -1. Snapping distance statistics can be investigated by running summary statistics on the field near_dist in the attribute table of the new point Landscape Network feature class.

i. Example input parameters:
   1. sample_pts.shp this is a shape file of sampling locations done on stream reaches within the Mt. Hood region.
   2. edges feature class the polyline_network Landscape Network.
   3. 55 meters (map units) as a search raidus to find the closes edge in.

ii. Example output parameters:
   1. sample_pts a new feature class in the polyline_network Landscape Network.

8. Using FLoWS Selection Set tools

The FLoWS selection set tools are geared to be used in conjunction within an ArcMap session. The selection set tools allows features upstream or downstream of already selected features to be selected the same as an attribute or spatial query tools do. The selection set tools work on edges and RCA feature classes. To view the new selection set refresh the data viewing window.

a. Select upstream features from a selection set that are within 3000 meters of the original selected features using the ***Select Upstream Cumulative*** tool.
    i. Example Input parameters:
        1. edges with feature(s) selected within an ArcMap document.
        2. Shape_Length a field associated with edges, which is the length (meters) of each line segment.
        3. 3000 meters the threshold distance
        4. Refresh view

9. Creating pair-wise distance (weight) matrices with a Landscape Network

The Export to Pair-wise Matrix tools user interface are pretty self explanatory and easy to use once any network connectivity problems have been fixed. The Export to Pair-wise Matrix tools can be ran on an entire Landscape Network point feature class or on a selection set in ArcMap. The Point ID Field input of the tools requires a field that has a unique value for each point in the feature class. The unique value of the field will be the values that show up in the n x n output matrix.