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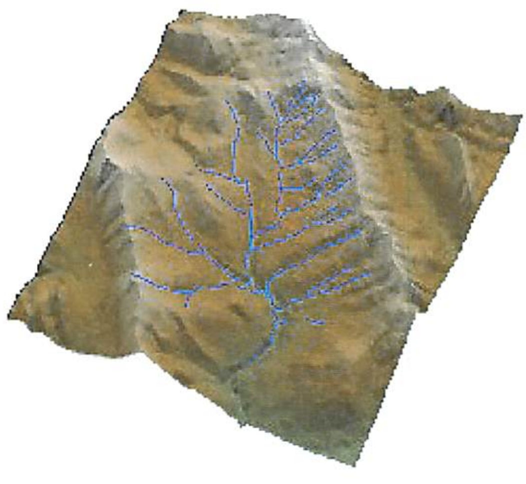
Watershed Delineation and Stream Classification for the Northern East Slopes Region including the Foothills Model Forest

September 17th, 2003



Time To Decide

FMF Watershed Delineation and Stream Classification

Foothills Model Forest Publication Disclaimer

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Authors:	Keith Duhaime *kduhaime@facet.com* Toll Free Direct: 1.800.665.3959
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Facet Decision Systems, Inc.
Suite 300 – 1060 West 8th Avenue
Vancouver, BC V6H 3Y4 Canada

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Introduction

The Goal

The goal of this project is to provide the Foothills Model Forest and its partners the best possible watershed data set for both current research applications, and for future land management applications.

Why Watersheds?

"The belief that watersheds make a sound basis for water resource planning and management is not new, as evidenced by waves of scientific, policy, and public interest going back as far as the 1930's. Yet after many years of high expectations, the nation is still struggling to find ways to implement integrated management at the watershed level. Much of the science and technology needed to provide the underpinnings necessary for integrated water management already exists. Numerous scholarly reports have highlighted the potential benefits to be gained from a watershed approach. But we have fallen short in turning our understanding of watersheds and the benefits of integrated management into action."[1]

The Challenges

Developing a good model of land drainage so that water, land, and forestry resources can be managed according to best management practices. To fulfil its leadership role in developing strategies for managing forest lands, the Foothills Model Forest needs the best possible base data.

The Solution – Facet Watersheds Data

To achieve the objectives of the watershed delineation and stream classification project, Facet proposed its watersheds dataset solution. ***Facet Watersheds Data*** provides a critical *missing link* in achieving an integrated approach to water resource management. It is an *integrated data product* that links the land and water features of the watershed together. With this cross-linked data, the movement of water, and all of its contents, across the land and throughout the stream network can be analyzed. As a result, effects like non-point source loadings, sedimentation and

[1] *New Strategies for America's Watersheds, National Academy Press (1999), Page 13* http://books.nap.edu/books/0309064171/html/13.html#pagetop

other critical measures can be calculated using standard tools and readily available data.

Facet Watersheds Data is designed for use with other current data, like soils, roads and vegetation, and with common technology tools such as GIS (Geographic Information Systems), spreadsheet and database programs.

Facet has been actively involved in water and watershed projects for nearly a decade. Facet has researched and developed a powerful tool set and highly automated processes. These data products, and the ability to produce them, are the culmination of many years of effort on behalf of clients like Southern California Edison[2], The Department of the Interior – Bureau of Reclamation[3], Department of Fisheries and Oceans Canada[4] and the British Columbia Ministry of Sustainable Resource Management[5].

The watershed delineation and stream classification results are intended to promoteintegrated watersheds management within the region.

The ***Facet Watersheds Data*** solution consists of six GIS layers, an additional data table defining relationships in the stream hierarchy, and a hydrologically corrected DEM. These deliverables can be summarized as follows:

- A polygon layer which breaks the terrain into a set of triangles.
- A polyline layer consisting of all the reach segments in the watersheds.
- A polyline layer that shows the flow-path of water from each of the terrain triangles to their receiving reaches. The flow-paths are connected to both the receiving reach and the originating triangle with ID attribute columns.
- A polymarker layer that shows the break points between reach segments and tabulates the reason for each particular reach break.
- A polygon layer that shows the local drainage area for each reach segment.
- A polygon layer that shows the total drainage area, both local and upstream, for each reach segment.
- A relational table that describes the reach network. This table contains a tabular description of the reach hierarchy.
- A hydrologically corrected digital elevation model (DEM) for each watershed.

The GIS layers contain over 100 attributes that will allow the Foothills Model Forest to model a whole new set of potential land/water interactions. These layers, when combined, will provide a much more complete description of stream morphology than is possible with the reach-level summary data set originally requested by Foothills Model Forest.

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2 http://www.facet.com/projects/CS_Hydrobasin.html

3 http://www.facet.com/projects/CS_SnakeRiver.html

4 http://www.facet.com/projects/CS_FraserSalmon.html

5 http://www.facet.com/projects/CS_WatershedRanking.html

Study Area and Project Data

Study Area Boundaries

The classification was completed for the vast majority of streams within the Northern East Slopes Region, which includes the entire Foothills Model Forest. It includes all streams within the Weldwood FMA, as well as headwater areas of smaller streams and rivers that are outside the FMA (Figure 1).

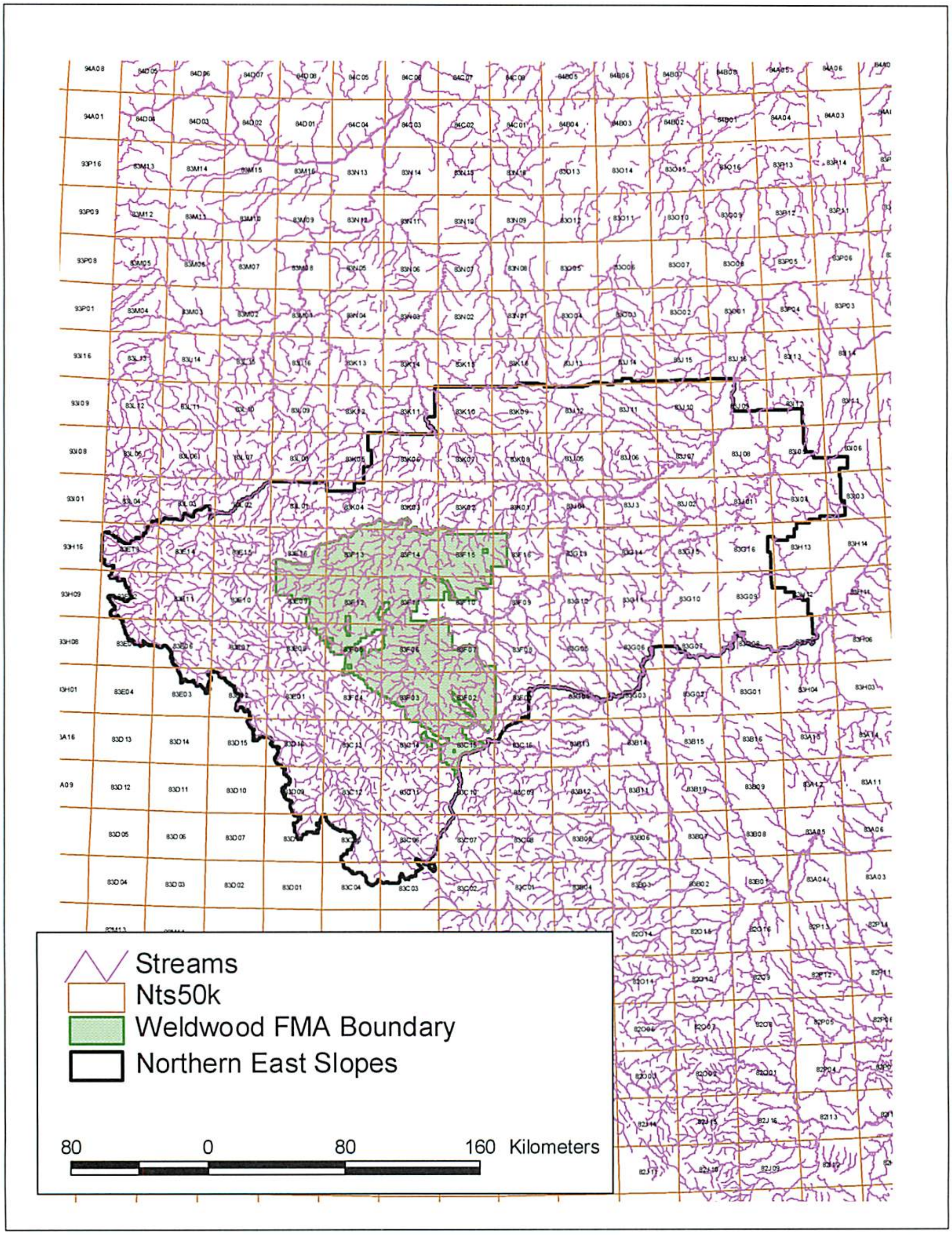

Figure 1. Boundary of Northern East Slopes Region.

Project Data

The Foothills Model Forest (FMF) provided the following digital data for the project, including:

1. Digital elevation model (DEM) covering the entire study area.
2. Stream information including the Alberta single line hydrography with Strahler stream order. Full network topology will be present in this dataset.
3. Other hydro information including the seamless hydro-polygons and hydro-points.

Creating the Solution

Physical Model

When water flows across land and into streams, mountains are eroded, and river deltas are built. Water flow creates a physical link between the land and streams. The component pieces of a watershed are all linked by water flow, and are all part of a geological unit that was shaped by water flow.

Water is an erosive force, a solvent for nutrients, a carrier of poisons and a key component of natural habitats. If we want to understand our natural environment, we need to know how water gets from land to stream and what it does in the stream. To understand and manage our natural environment, it is necessary to answer detailed questions about erosion, sediment transport, stream morphology, non-point source (NPS) pollutants, impacts of human activities, and any number of physical processes.

There are well-understood measurements from field projects that answer these questions, but surveying even a small watershed is expensive. This means that a typical project only surveys a few key locations over a short time.

We used digital elevation data (DEM) and water features from topographic data to model how water flows over the land and through the streams. In the case of the FMF watershed delineation and stream classification project, the standard Alberta Environmental Protection DEM and hydrographic data were used.

Figure 2 – Upstream reaches (red) & downstream reaches (white) from a selected point in the watershed.

Virtual water flowing over standard data sets

Facet's approach is based on advanced science, but in essence, is very simple. We have a computer model that pours "virtual water" onto "virtual land" and records where it flows:

- We build a three-dimensional computer model of the landscape using elevation data.
- We embed the map graphics that depict water features. These water features "show the flow" through the valleys of the computer model.
- We drip "virtual water drops" onto the computer model and track how they flow over land until they hit a stream.
- We model flow through the streams, from tributaries to larger rivers.
- As the virtual water flows, we measure numerous attributes, from how steep the path is, to the amount of land drained by a segment of stream.
- The water flow measurements are stored in a data table and are linked to a map.

Our computer model acts as a factory that makes new water flow data. Once the model has been run once there is no need to rerun it except when a large-scale change in the geography occurs, as in the case of an earthquake or a significant shift in course of a waterway.

Answering detailed questions about erosion, sediment transport, stream morphology, NPS pollutants, impacts of human activity and many other physical processes can be accomplished by intersecting data layers like soil maps, land use, and ground cover with ***Facet Watersheds Data*** triangles. These intersections, and the consequent analysis, can be made using standard GIS tools. Watershed-based management is indeed possible with standard GIS tools and with the simple addition of ***Facet Watersheds Data***.

Editing and Building a Hydrology Network

Our first step is creating a simple network from GIS hydrology data: rivers, lakes, two-line rivers, islands, and related features such as sandbars, dams, waterfalls, and ditches. Significant editing is sometimes required to prepare data from GIS sources, including:

- reversing the order of digitization, e.g. streams not digitized downslope, lakes not clockwise.
- assigning new feature codes to mislabeled features, e.g. river segments labeled as lakes.
- adding missing features, e.g. construction lines to separate lakes from two-line rivers.
- snapping features to be contiguous, especially across map sheet boundaries.

In the case of the data supplied by Foothills Model Forest, very few errors were found in the stream network data. A separate production database was built to divide the study area into a number of small watersheds for processing. Very high throughputs were achieved using this process. The production database was then used to re-assemble the small watersheds into study area.

3D Rivers and Homogeneous-Slope Reaches

While modern digitizing techniques produce 3D rivers directly from air photos, older data produces only 2D rivers. With attention to quality control routines, 2D rivers can be applied to gridded DEM data to create 3D rivers. Despite careful interpolation routines, errors in the raw DEM data initially produce rivers with "noisy" slopes, including positive slopes. These were corrected with numerical filters to yield corrected slopes that met the project requirement for removal of all positive stream slope values. The main filter to do this is an ordinal filter which uses an heuristic approach. Water is forced to flow down the reach network. The elevation is checked along the reach, and where spikes or pits occur, an appropriate value is reassigned to the grid cell from the reach network.

Creation of Reach Breaks

In processing the data, the stream network was divided into a series of homogenous reaches, based on topologic (stream network) and topographic (slope) criteria. The target was an average reach length in the range of 300m based on a set of topographic criteria. This 300m average distance is desired in order to provide an accurate measure of channel sinuosity for the small streams of interest.

Topologic Criteria for Reach Breaks

Based on topology, reach breaks were placed at all topological breaks including waterfall points (Alberta hydro-points layer), lake boundaries and intersections with all other Alberta hydro-polygon features. All hydro-point and hydro-poly feature information is tagged to each reach break point and reach segment. Reach breaks are placed at all stream confluences.

In processing the data, a series of topographic reach breaks were placed every 100m in an upstream direction from each topologic reach break. Proceeding in an upstream direction from each topologic reach break, the topographic breaks were amalgamated based on slope (Table 1). All topologic reach breaks (breaks at hydro-poly features and selected confluences) are permanent features and were not dissolved during the aggregation process.

Table 1. Reach Aggregation Rules

Slope Class of Downstream Segment	*Slope Range of Downstream Segment*	*Amalgamate if Difference with Upstream Segment is less than:*
-1	*<0 (all segments with a negative slope value)*	*Amalgamate all segments with negative slope with next segment upstream*
1	*0-1%*	*0.5 %*
2	*1-2%*	*1.0*
3	*3-4%*	*1.5*
4	*4-6%*	*2.0*
5	*6-10%*	*3.0*
6	*10-20%*	*5.0*
7	*20-40%*	*10*
8	*>40%*	*20*

If good predictability is found between reaches from field sampling and reaches derived from DEMs, great savings in field work could result.

Quality control plots including river profiles (Figure 3) and histograms of river slope are used to assess the river slope results.

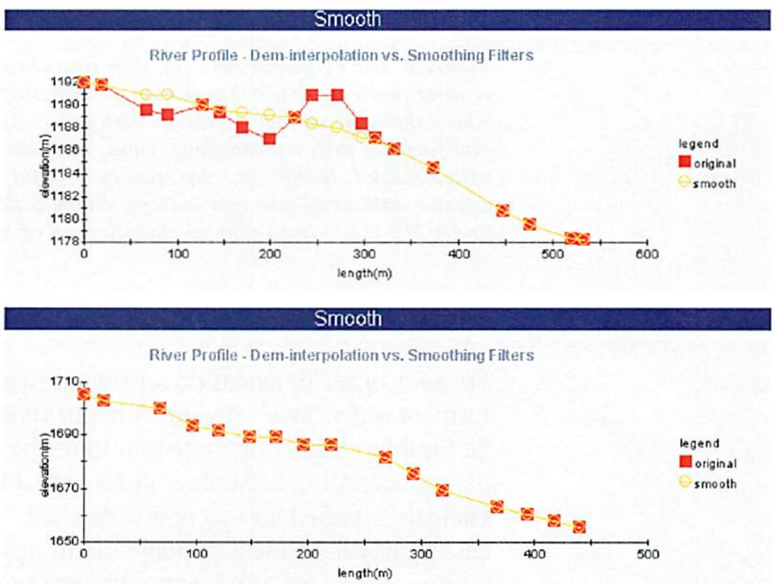

Figure 3. River profiles (plots of elevation vs. horizontal distance) are used in a quality control step to assess the results of assigning river elevations from a DEM. The upper panel shows, a river where the original DEM information, the red line, was particularly noisy, to the point where positive slopes resulted; an appropriate filter produces the yellow line. The lower panel shows the more common case where the derived elevations are acceptable, and moreover shows that the filtering did not introduce undesirable artifacts.

The result for each watershed is a list of reach polylines and a list of reaches, exported as GIS files in SHAPE and DBF formats. Slope is the most informative single characteristic of a river reach, and many of the reach attributes that one would like to know, e.g. substrate type, can be related to slope, and therefore predicted from slope.

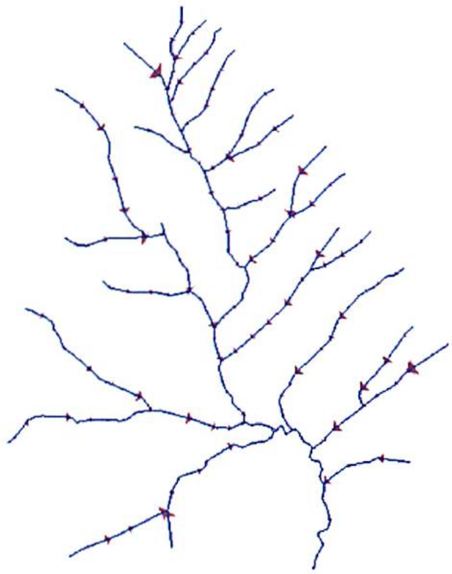

Figure 4. The hydrology network, with rivers broken into new polylines called reaches. Each reach is determined so that it has a homogenous slope within itself, and reach breaks are established where the slope changes. Reaches also reflect hydrologic features, particularly river convergences and features such as waterfalls, dams, and lakes. Typically, the tolerance for variability in slope with a reach is higher for steep reaches than for reaches with low slope. With suitable analysis and suitable data, small changes in slope, on the order of 0.2%, can be determined in rivers with slopes under 2%; this is important for classification of rivers by biologists.

Strahler Order of Rivers

Strahler order proceeds downstream: two primary streams of order "one", join to form an order "two" stream. A major river such as the Columbia or the Nile might be Strahler order 7 or 8 where it joins the ocean. Watersheds can be identified and nested according to Strahler order with a third order watershed completely enclosing its first and second watersheds. Third order watersheds can be identified easily, they have the advantage of "tiling" the landscape at a convenient scale without gaps, and group naturally into fourth order watersheds or manually into convenient watershed groups.

Land Forms as a Triangulated Irregular Network

Next we build a model of the shape of the terrain. We do this by dividing the land into triangles. Each triangle defines a piece of land with a common slope and aspect. (Aspect measures the direction the slope faces). The triangles cover the whole landscape.

Each landscape triangle is a different size depending on the terrain it covers. In rough terrain, each triangle is about the size of a city lot, in smooth terrain the triangles cover a few city blocks. Triangle-based terrain models like this are called Triangular Irregular Networks (TIN).

There are some advantages to describing the land forms (terrain) as a pattern of triangles of different sizes and shapes (a TIN). Although most DEM datasets are provided as regular grids, these grids are derived from irregularly scattered elevation data and from break lines that define noticeable ridges, cliffs, and gullies. Elevation points on lake shores and river banks go into DEM grids. This original data is discarded after interpolating a grid from it. This data is not lost in a TIN surface, so one ends up working closer to the actual data. As well, ridges are represented correctly as sharp edges in a TIN, but in a grid they typically appear as "zig-zags" and are likely to have spurious flat spots. Gridding obscures watershed boundaries, but they are unambiguous in a TIN; this is especially important in relatively flat terrain (prairie, tundra, wetlands).

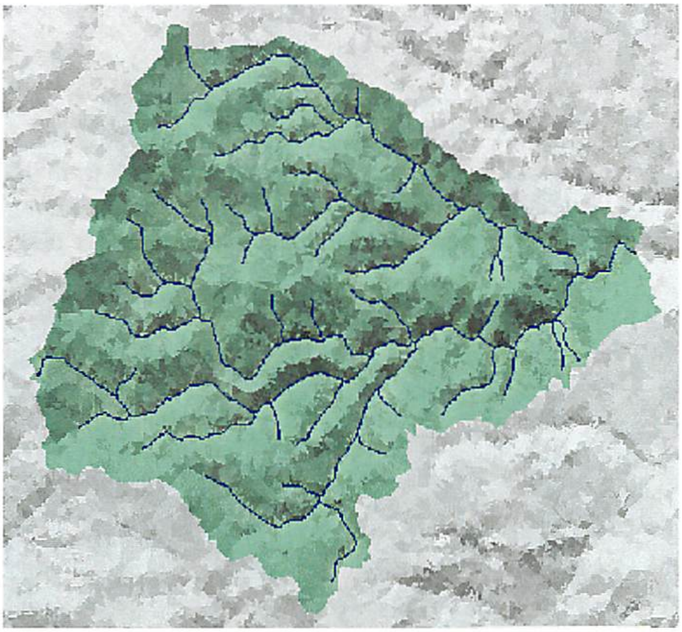

Figure 5 – The Triangles that drain into the highlighted stream are colored green.

What We Measure

Once we have built the triangles we measure them. How big they are. Which direction they face. What their slope is. What their elevation is. We put these measurements, with the triangle coordinates, into a simple table (see Appendix 1.2). Once the information from our terrain model is thus captured, it can be analyzed using standard database and/or GIS tools.

Drainage Paths Across Land

Conventional algorithms determine flow paths across land using grid cells, but this can be very ambiguous. Drainage across a triangle is unambiguous. Our algorithms drop virtual water on the triangles and trickle them downhill and record their paths. Each triangle is flat, so water drops that flow across it will have parallel paths. When the drop crosses into a new triangle, its path takes a new direction. We follow the flow paths until they hit a water body.

The result is the most accurate and reliable representation of surface flows available for drainage from any point, or feature, in the landscape to the receiving point within a river reach (Figure 6). It should be noted that in areas of very low slope, the raw data may be ambiguous as to which direction a flow path should flow. In these instances, the expected result exceeds the precision of the raw data.

Flow Paths

We can measure many things about the flow paths. How steep they are. Which direction they flow. How far the drop travels from its source to its destination. We typically measure a single path for each triangle because this gives us sufficient detail. Each triangle knows its destination stream and how the water got there. We store this information in a table (Appendix 1.3).

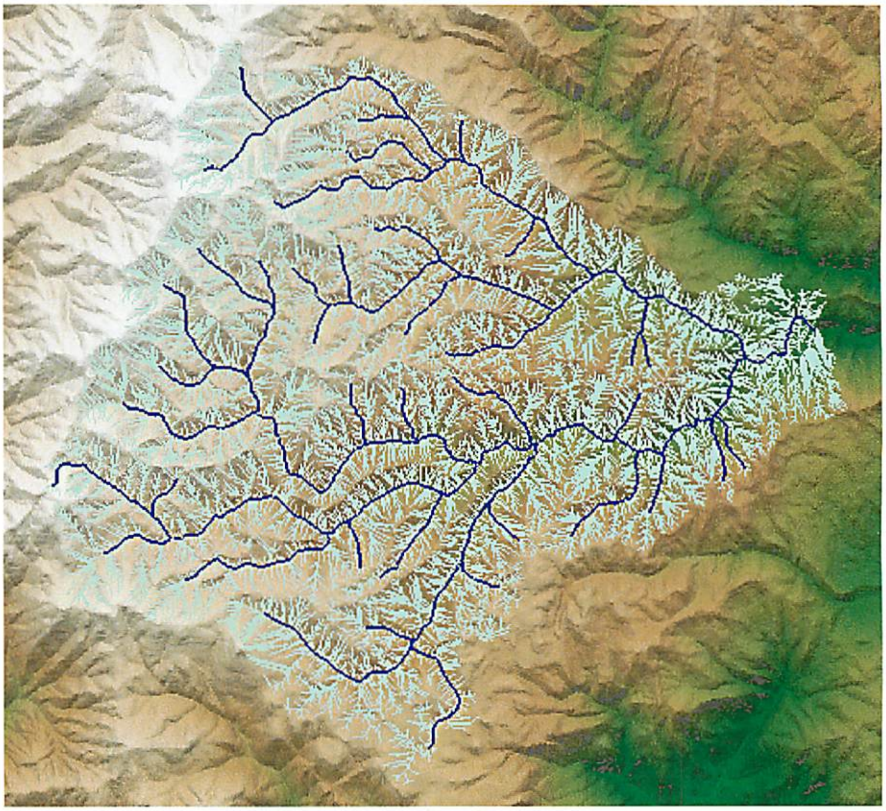

Figure 6 – Flow paths (light green) on a landscape.

River Network Integrated with TIN (NetTIN)

To model flow through the streams we embed the stream graphics into the terrain model. Rivers in valleys always flow downhill but "noisy" data means that this is not always the case with the embedded streams. We use automated quality control procedures to reconcile differences between elevation measurements and the river locations. We add triangles to the terrain model so that rivers and streams always flow along the edges of triangles. Then we break each stream into "reaches" using one of several possible reach schemas. These schemas are designed to meet the needs of various types of users including scientists, engineers and water licensing boards. In this case the specific criteria were defined by the Foothills Model Forest The resulting data structure is called a NetTIN.

This integration of land and water information is possible because the quad edges in the TIN triangles and the river network are exactly the same data structure – a *quad edge*. The quad edge has some mathematical and computational advantages to the older *winged edge* used, for instance, in ESRI ArcInfo polygon coverages. The same quad edge used for polylines and polygons in our system, greatly improves the ability to integrate and manipulate GIS features that are disparate data structures in older GIS systems.

Each reach is measured in several ways. How long it is. How steep it is. Whether it is sinuous or straight. What elevation it starts at, and where it ends. In addition to the obvious measurements about the stream itself, we also summarize the measurements for the flow paths and the triangles that drain into the reach. This, in addition to many other measurements, gives us data such as average valley width and slope, and the area of land drained by this stream reach. We add these measurements and many others to the reach data table (Appendix 2.1).

Drainage Network

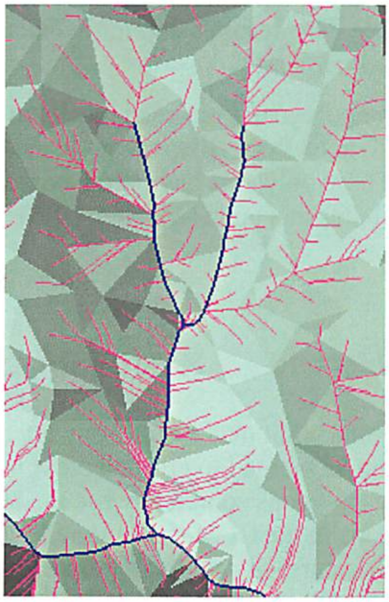

Figure 7 – Water flows in a network.

The Network opens up many more measurement possibilities. What the reach stream order (tributary or main stem) is. What other reaches this reach drains through. Once all the measurements are completed and put into the data table, we have a very complete model with all of the links needed to reconstruct how water flows over the landscape and through the drainage hierarchy of streams; a dynamic three dimensional representation of the watershed.

Indices Useful for Reach Classification

The NetTIN provides information on the valley that contains the river. There are several ways to extract a series of indices to characterize a *horizontal cross-section* of the land surrounding each reach. The conventional way is to interpolate elevations along a cross section normal to some line segments in a river reach polyline (*normal* means perpendicular in this context, at right angles). The heights at specific distances, say 10, 20 and 40 m, are used to calculate indices of containment, confinement, and slope stability. Alternatively, we have *profiles* for every drainage path into the reach, which can be used in similar ways, with care to be representative of the entire reach. As well as the shape of surrounding channel, floodplain, and valley, each reach has data to calculate overall slope, fall, and sinuosity.

Local Drainage for Each Reach

To the list of reach attributes we add the local drainage area because we know all of the triangles that drain to this reach, and their areas. Valuable in itself, this result produces some surprising advantages (see automatic integration of new information). These polygons have also been stored in a local drainage layer with appropriate attributes in a table (Appendix 1.5).

Total Upstream Area

The total area upstream is easily obtained from the watershed cross-links system. The network provides every upstream reach and we can add up the local drainage area for all of these. This result is explicitly included in the Reaches table because it is likely to be used frequently.

The local drainage polygons from each reach have also been amalgamated with the local drainage polygons from all upstream reaches to create total drainage polygons for each reach. These polygons have been stored in a upstream drainage layer with appropriates attributes in a table (Appendix 1.6).

Automatic Integration of New Information

There is an important additional result from determining the local drainage triangles. They can be merged to create a polygon that represents the local drainage for a reach. These polygons completely tile the landscape without gaps (unless there are undrained basins in the DEM, and normally those are corrected). This means that any new GIS feature, say a polygon representing a proposed new use for land, can be intersected with the local drainage polygons to determine which river reaches are directly affected and which downstream reaches are indirectly affected. Moreover, the total area of the new land use polygons can be assigned proportionally to each reach according to how much it overlaps with each drainage polygons. Please note that this applies to satellite and air photo information as well, each pixel in the image can be assigned according to which reach it drains into.

Figure 8. Land use information, typically polygons such as these in red, are cross-linked to the rivers that land use will influence by determining the drainage paths from the polygons. Here the original polygon points are used to calculate the paths (yellow) to streams or a lakeshore that is part of the hydrology network. To correctly weight the contribution of a polygon that drains to several different reaches, the land-use polygon can be intersected with the underlying triangles, and then drainage from the resulting small polygons will sum the correct area contributions.

Watershed Boundaries

As mentioned above, ridge lines are clarified in TINs, and obscured in DEM grids. We established above that we can easily determine every triangle that drains, eventually, through any river segment. By merging those triangles into a single polygon, we have the watershed boundary for everything upstream and upslope of that river segment.

Note again, that in some instances, there were minor anomalies in watershed boundaries due to limitations of the precision of the original DEM data.

Watershed Characterization

Simple rules for characterizing watersheds can be applied to the watershed boundaries and the statistics of the land triangles in the watershed. Some of the characteristics we have been asked for recently include: *contributing and non-contributing drainage area, basin perimeter, basin shape factors, effective basin width, compactness and elongation ratios, basin or valley length,* and *mean elevation. Relief* and *ruggedness numbers, basin slope, basin relative relief,* and similar information can be calculated directly from the *Paths* attributes for land triangles, and we think that *histograms of slope frequency* (area in each slope class; cumulative area by slope) are informative about watershed sensitivity. The *length, mean slope, profile,* and *sinuosity* of the main channel also falls out of the Reaches table, as does *drainage density, number of first order streams*. Processing watershed information is simpler after establishing *Reaches* and *Paths* attributes, therefore, many watersheds (thousands) can be analyzed statistically to predict characteristics that are measured in some watersheds, but needed in many. Predicting the 5, 20, 50, and *100-year maximum flows*, for example, typically uses the total upstream drainage area (in *Reaches* table) to fit a log-log regression model.

Watershed Hierarchy and Codes

A *tree walk algorithm* is a methodical way of proceeding through every segment of a river network, typically by starting at the most downstream point, and always taking the first available right hand turn. If we create watershed boundaries (as above) for each river segment that we encounter in a tree walk, we will create the entire set of nested watershed boundaries. By noting existing river codes as we proceed (they are assigned everywhere upstream), and noting stream order, the hierarchical watershed codes for each boundary polygon are generated automatically.

Order of Processing Operations

Figure 1 shows some of the possible results from the watershed cross-links processing and their dependencies on source data or previous products. Some of the processing by-products, such as the nested watershed boundaries or the river center-line network without elevation data, may be useful and are produced economically.

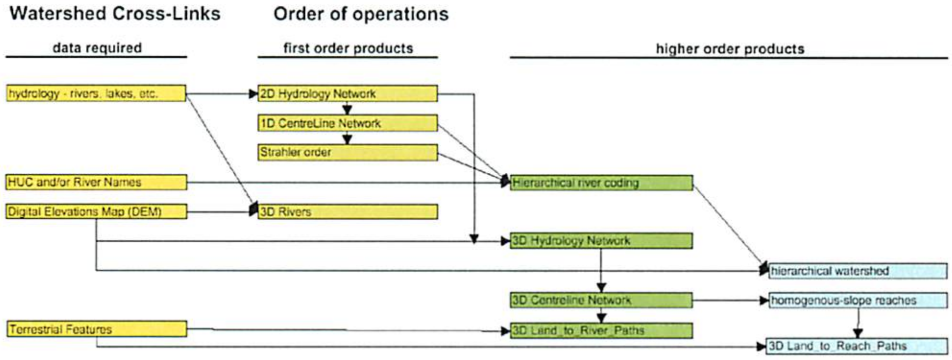

Figure 1. Processing of the hydrology, DEM, feature names, and other source data proceeds with some intermediate products that may be valuable for specific applications. Individual agencies may insert their own results at any stage, such as a set of reach-breaks derived from field sampling.

Future Applications and Opportunities

By capturing as many physical measurements as possible in a GIS data set, we have eliminated the need to ever run the model again. We have completed a suite of physical measurements from the current terrain model. If you make any physical measurements or do detailed surveys, these results can be used to calibrate the data table without rerunning the model. The changes and edits can be done using standard GIS techniques.

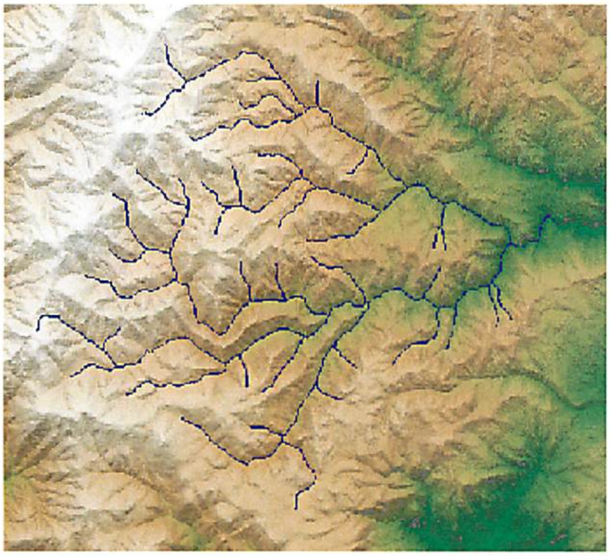

Figure 2 – Stream reaches on a DEM.

Managing the natural environment means being able to answer many detailed questions about that environment and the impact of human activity on the landscape. Over the past couple of decades we've come to understand that watersheds are nature's boundaries and that they are far more relevant in managing the environment than the geopolitical boundaries created by man. As such we've started to ask our questions in relation to these natural physical features. Unfortunately, until now, developing answers and building management plans has been far more difficult. The problem has been the lack of a reliable integrated data set that describes these features and makes it possible to ask and answer important questions about them.

Facet Watersheds Data products are designed to overcome this problem. Our physical model makes new watersheds data, which makes watershed-based management possible using standard GIS tools. The answers to many of the questions are now available by intersecting already available GIS data layers like land use, soil maps, vegetation maps or ground cover with the triangles in our data products.

Appendix 1 – Layer Attribute Tables

2.1 Reach Table

2.2 Triangle Table

2.3 Flow-path Table

2.4 Reach Points Table

2.5 Local Drainage Table

2.6 Upstream Drainage Table

Appendix 2 – Relational Table

Appendix

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Appendix 1 - Layer Attribute Tables

This Appendix describes the attribute tables attached to the Terrain Triangle, Flow-path, and reach GIS layers.

1.1 Reach Table

This is a polyline layer of all the reach segments in the watershed with the following attributes for each segment.

Column Name	*Derived*	*Comment*
Wsdkey	this reach segment has a unique ID	reaches are within river polylines.
Len2d	calculated when created	corresponds to 2D GIS; shorter than actual length.
Len3d	calculated when created	This is the 3D length, greater than 2D map length.
Fall	vertical distance of first point in the reach above the last point	Habitat suitability index for salmon spawning based on reachSlope values.
Lowelev	derived from the minimum z-value.	Lowest elevation on the reach.
Strtlen	3D separation as a straight line between first and last point in the reach.	
Slope	Fall /Len2d.	ratio, dimensionless, as a proportion not a percent.
Slpperc	Fall /Len2d *100	Slope as a percentage .
Sinuosity	Len3d/Strtlen	ratio, dimensionless, as a proportion not a percent.
Rchorder	calculated from centre-line network	Strahler order: order-1 streams join to make an order-2 stream
Pthmxlen	length of the longest cross land flow path draining into this reach	Distance to the centroid of the furthest triangle draining into the reach
Pthmxstlen	maximum straight length from flow origin to reach	Origins are at triangle centroids.
Pthmnlen	mean length of the list of cross-land paths	A list of polylines represents the cross-land paths for drainage into this reach id.
Pthmnstlen	mean straight length from flow origin to reach	Origins are at triangle centroids.
Pthmnslp	mean slope of the list of cross-land paths	Paths are from the centroid of each land triangle
Locmnelev	mean elevation of centroids of land triangles with this reachID	important for snow melt, insolation, vegetation

	reachID	vegetation
Locarea	local area calculated from land triangles with this reachID	feature has same id as this reach
Locdomasp	mean aspect of drainage: N, NW, W, etc. Calculated from area-weighted aspects land triangles with this reachID	Calculation considers that the mean aspect of two triangles facing 359 degrees and 1 degree is 0 degrees.
Locdomarea		
Locmnslp	Mean slope of drainage. Calculated from aspects land triangles with this reachID	combine with soil and vegetation information to calculate erosivity (erosion rate).
Locslp3	Area in meters squared of local drainage directly into this reach that has slope from 0 to 3 percent.	0 to 2.999, etc.
Locslp8	Area in meters squared of local drainage directly into this reach that has slope from 3 to 8 percent.	slope classes are those of the BC Ministry of Sustainable Resource Management, and can be replaced with your slope categories.
Locslp15	Area in meters squared of local drainage directly into this reach that has slope from 8 to 15 percent.	determine fate of erosion - does it become sediment load in this reach?
Locslp30	Area in meters squared of local drainage directly into this reach that has slope from 15 to 30 percent.	
Locslp50	Area in meters squared of local drainage directly into this reach that has slope from 30 to 50 percent.	
Locslp60	Area in meters squared of local drainage directly into this reach that has slope from 50 to 60 percent.	
Locslp70	Area in meters squared of local drainage directly into this reach that has slope from 60 to 70 percent.	
Locslp100	Area in meters squared of local drainage directly into this reach that has slope greater than >70 percent.	
Locslpstp		Steepest slope in local drainage.
Locareaflt	Area in meters squared of Flat aspect land. Has a slope less than 2%	
Locaspn	Area in meters squared of N aspect land. Has a slope greater than 2% and an aspect between 337.6 and 22.5 degrees.	
Locaspne	Area in meters squared of NE aspect land. Has a slope greater than 2% and an aspect between 22.6 and 67.5 degrees.	
Locaspe	Area in meters squared of E aspect land. Has a slope greater than 2% and an aspect between 67.6 and 112.5 degrees.	
Locaspse	Area in meters squared of SE aspect land. Has a slope greater than 2% and an aspect between 112.6 and 157.5 degrees.	
Locasps	Area in meters squared of SE aspect land. Has a slope greater than 2% and an aspect between 157.6 and 202.5	

	degrees.	
Locaspsw	Area in meters squared of SW aspect land. Has a slope greater than 2% and an aspect between 202.6 and 247.5 degrees.	
Locaspw	Area in meters squared of W aspect land. Has a slope greater than 2% and an aspect between 247.6 and 292.5 degrees.	
Locaspnw	Area in meters squared of NW aspect land. Has a slope greater than 2% and an aspect between 292.6 and 337.5 degrees.	
Chnll10	mean elevation above river of left bank at 10 m	
Chnll20	mean elevation above river of left bank at 20 m	mean calculated from many points along reach
Chnll30	mean elevation above river of left bank at 30 m	containment, slope stability, etc.
Chnll40	mean elevation above river of left bank at 40 m	
Chnll50	mean elevation above river of left bank at 50 m	
Chnll60	mean elevation above river of left bank at 60 m	
Chnll70	mean elevation above river of left bank at 70 m	
Chnll80	mean elevation above river of left bank at 80 m	
Chnll90	mean elevation above river of left bank at 90 m	
Chnll100	mean elevation above river of left bank at 100 m	
Chnlr10	mean elevation above river of right bank at 10 m	based on normals to reach centreline.
Chnlr20	mean elevation above river of right bank at 20 m	these values used to calculate confinement,
Chnlr30	mean elevation above river of right bank at 30 m	
Chnlr40	mean elevation above river of right bank at 40 m	
Chnlr50	mean elevation above river of right bank at 50 m	
Chnlr60	mean elevation above river of right bank at 60 m	
Chnlr70	mean elevation above river of right bank at 70 m	
Chnlr80	mean elevation above river of right bank at 80 m	
Chnlr90	mean elevation above river of right bank at 90 m	
Chnlr100	mean elevation above river of right bank at 100 m	
Totmnelev		Mean elevation of the drainage through the reach.
Totarea	drainage area upstream and upslope of this reach	
Totdomasp		Dominant aspect class for the total drainage.

Totdomarea		Area of the dominant aspect class for the total drainage.
Totmnslp		Mean slope for the total drainage.
Totslp3	Area in meters squared of total upstream and upslope land that drains through this reach and has slope from 0 to 3 percent.	
Totslp8	Area in meters squared of total upstream and upslope land that drains through this reach and has slope from 3 to 8 percent.	
Totslp15	Area in meters squared of total upstream and upslope land that drains through this reach and has slope from 8 to 15 percent.	
Totslp30	Area in meters squared of total upstream and upslope land that drains through this reach and has slope from 15 to 30 percent.	
Totslp50	Area in meters squared of total upstream and upslope land that drains through this reach and has slope from 30 to 50 percent.	
Totslp60	Area in meters squared of total upstream and upslope land that drains through this reach and has slope from 50 to 60 percent.	
Totslp70	Area in meters squared of total upstream and upslope land that drains through this reach and has slope from 60 to 70 percent.	
Totslp100	Area in meters squared of total upstream and upslope land that drains through this reach and has slope >70 percent.	
Totslpstp		Steepest slope for the total drainage.
Totareaflt	Area in meters squared of Flat aspect land upstream and upslope with a slope less than 2%	
Totaspn	Area in meters squared of N aspect land upstream and upslope a slope greater than 2% and an aspect between 337.6 and 22.5 degrees.	
Totaspne	Area in meters squared of NE aspect land upstream and upslope a slope greater than 2% and an aspect between 22.6 and 67.5 degrees.	
Totaspe	Area in meters squared of E aspect land upstream and upslope a slope greater than 2% and an aspect between 67.6 and 112.5 degrees.	
Totaspse	Area in meters squared of SE aspect land upstream and upslope a slope greater than 2% and an aspect between 112.6 and 157.5 degrees.	

Totasps	Area in meters squared of SE aspect land upstream and upslope a slope greater than 2% and an aspect between 157.6 and 202.5 degrees.	
Totaspsw	Area in meters squared of SW aspect land upstream and upslope a slope greater than 2% and an aspect between 202.6 and 247.5 degrees.	
Totaspw	Area in meters squared of W aspect land upstream and upslope a slope greater than 2% and an aspect between 247.6 and 292.5 degrees.	
Totaspnw	Area in meters squared of NW aspect land upstream and upslope a slope greater than 2% and an aspect between 292.6 and 337.5 degrees.	
Fnode_		Attribute from Foothills Model Forest raw data for this stream reach.
Tnode_		Attribute from Foothills Model Forest raw data for this stream reach.
Lpoly_		Attribute from Foothills Model Forest raw data for this stream reach.
Rpoly_		Attribute from Foothills Model Forest raw data for this stream reach.
Length		Attribute from Foothills Model Forest raw data for this stream reach.
Streams_di		Attribute from Foothills Model Forest raw data for this stream reach.
Order_		Attribute from Foothills Model Forest raw data for this stream reach.
Streams_1		Attribute from Foothills Model Forest raw data for this stream reach.
Break		This field indicates the reason for the reach break and is coded as follows. 0 - break from original input stream dataset 1 – lakes 2 – falls or dam 3 – 1+2 (i.e. Lakes and (falls or dam)) 4 – morphology change 5 – 1+4 6 – 2+4 7 – 1+2+4

1.2 Triangle Table

This is a polygon layer of all the triangles in the watershed with the following attributes for each triangle.

Column Name	Derived	Comment
Reachid	which reach this triangle centroid drains to by following this path	a triangle centroid has one path to get to this reach
Wsdkey	which reach segment this triangle centroid drains to by following this path	a triangle centroid has one path to get to this reach segment
Slope	slope of this triangle	
Slpperc	Percent slope of the triangle.	
Aspbrng	azimuth bearing (steepest direction) of this triangle	Given in exact degrees
Aspclass	compass direction (steepest direction) of this triangle	N, NE, E, SE, S, SW, W, NW
Area2d	area of this triangle projected to xy plane	as seen in map view – appropriate for catchment analysis
Area3d	area of this triangle in 3 dimensions	
Elev	elevation of centroid of this triangle	

1.3 Flow-path Table

This is a polyline layer of all the flow-paths in the watershed with the following attributes for each flow-path. There is one flow-path for every triangle in the watershed.

Column Name	Derived	Comment
Wsdkey	which reach segment this triangle centroid drains to by following this path	a triangle centroid has one path to get to this reach
Totlen3d	total length of this path	
Totfall	starts at triangle centroid elevation, ends at intersection with a stream reach.	
Totrun	total 2D length of this path	
Totslp	overall mean slope of the path, as totFall over totRun	
Lenslp3	Length in meters of drainage path from this triangle that is across land that has slope from 0 to 3 percent.	
Lenslp8	Length in meters of drainage path from this triangle that is across land that has slope from 3 to 8 percent.	
Lenslp15	Length in meters of drainage path from this triangle that is across land that has slope from 8 to 15 percent.	
Lenslp30	Length in meters of drainage path from this triangle that is across land that has slope from 15 to 30 percent.	

Lenslp50	Length in meters of drainage path from this triangle that is across land that has slope from 30 to 50 percent.	
Lenslp60	Length in meters of drainage path from this triangle that is across land that has slope from 50 to 60 percent.	
Lenslp70	Length in meters of drainage path from this triangle that is across land that has slope from 60 to 70 percent.	
Lenslp100	Length in meters of drainage path from this triangle that is across land that has slope greater than >70 percent.	

1.4 Reach Points Table

This is a polymarker layer of all the points in the watershed where the reach segments are terminated with the following attributes for each point. There is one point for every reach segment in the watershed.

Column Name	*Derived*	*Comment*
Wsdkey	which reach segment	
Breakskind		This field indicates the reason for the reach break and is coded as follows. 0 - break from original input stream dataset 1 – lakes 2 – falls or dam 3 – 1+2 (i.e. Lakes and (falls or dam)) 4 – morphology change 5 – 1+4 6 – 2+4 7 – 1+2+4

1.5 Local Drainage Table

This is a polygon layer of all the local drainages in the watershed for each reach segment with the following attributes for each polygon. There is one polygon for every reach segment in the watershed. The land represented by each polygon drains directly into the associated reach.

Column Name	*Derived*	*Comment*
Wsdkey	which reach segment is this polygon draining into	This polygon represents only land flowing into this reach segment.
Locare	Area of the polygon projected into xy – plane.	

1.6 Upstream Drainage Table

This is a polygon layer of all the total or upstream drainages in the watershed for each reach segment with the following attributes for each polygon. There is one polygon for every reach segment in the watershed. The land represented by each polygon drains directly into the associated reach or into a reach segment upstream of the respective reach.

Column Name	*Derived*	*Comment*
Wsdkey	which reach segment is this polygon draining into	This polygon represents all land flowing into this reach segment, both locally and all land flowing into reach segments upstream of this segment.
Uparea	Area of the polygon projected into xy – plane.	

Appendix 2 - Relational Table

This Appendix describes the Relational Table, its construction, and how it is used.

Relational Table

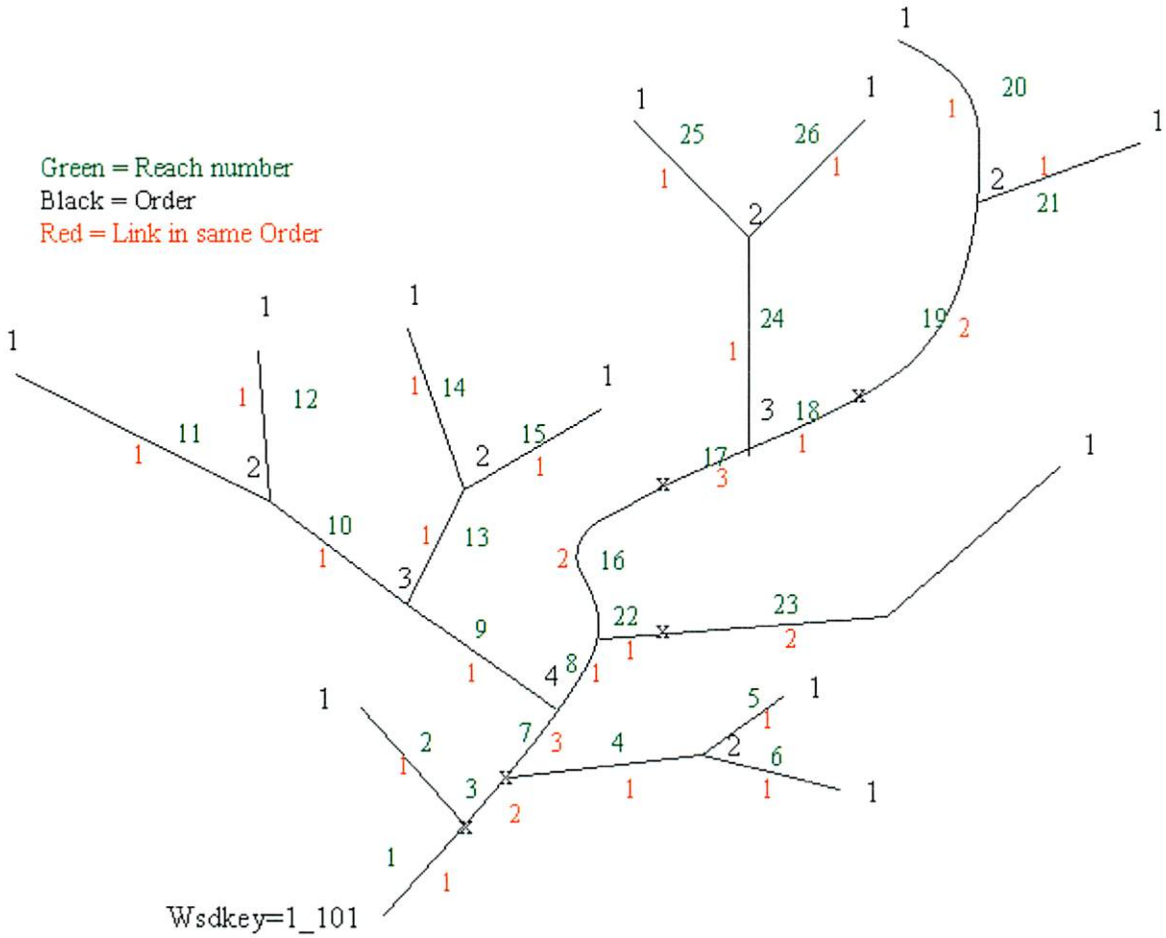
Column Name	*Derived*	*Comment*
Wsdkey	Unique ID for each reach segment	
Reach	An index to the row in the relational table	
Order	The Strahler order of the reach segment	
Mycount	The position in a string of consecutive reach segments of the same order.*	
Drain1	Which row in the table (Reach) contains the Wsdkey of the 1st order reach segment furthest downstream that drains this reach segment.	
Count1	Where in the sequence of 1st order reach segments that drains this reach does this one flow.	
Drain2	Which row in the table (Reach) contains the Wsdkey of the 2nd order reach segment furthest downstream that drains this reach segment.	
Count2	Where in the sequence of 2nd order reach segments that drains this reach does this one flow.	
Drain3	Which row in the table (Reach) contains the Wsdkey of the 3rd order reach segment furthest downstream that drains this reach segment.	
Count3	Where in the sequence of 3rd order reach segments that drains this reach does this one flow.	
Drain4	Which row in the table (Reach) contains the Wsdkey of the 4th order reach segment furthest downstream that drains this reach segment.	
Count4	Where in the sequence of 4th order reach segments that drains this reach does this one flow.	
Drain5	Which row in the table (Reach) contains the Wsdkey of the 5th order reach segment furthest downstream that drains this reach segment.	

Count5	Where in the sequence of 5th order reach segments that drains this reach does this one flow.
Drain6	Which row in the table (Reach) contains the Wsdkey of the 6th order reach segment furthest downstream that drains this reach segment.
Count6	Where in the sequence of 6th order reach segments that drains this reach does this one flow.
Drain7	Which row in the table (Reach) contains the Wsdkey of the 7th order reach segment furthest downstream that drains this reach segment.
Count7	Where in the sequence of 7th order reach segments that drains this reach does this one flow.
Drain8	Which row in the table (Reach) contains the Wsdkey of the 8th order reach segment furthest downstream that drains this reach segment..
Count8	Where in the sequence of 8th order reach segments that drains this reach does this one flow.

* Note: Where Mycount is equal to 1 indicates a change in the reach order.

How is the Relational Table constructed?

Below is a hypothetical fourth order watershed and associated relational table that will illustrate how the relational table is constructed. In this watershed, reach breaks exist at each confluence and where designated with an "x".



Each reach segment is designated with a number in green. The green number correlates with the row in the table which describes its relationships. The reach order of each reach is designated in black.

The red numbers indicate where in a string of reach segments <u>with the same reach order</u>, the particular segment is located going upstream. For example, reach segments 1, 3, and 7 (in green) are all order 4 in a string of order 4 segments. Reach segment 1 is number 1 in the string, segment 3 is number 2 in the string, and segment 7 is number 3 in the string. A second example is reach segments 18 and 19. Both are order 2. Segment 18 is number 1 and segment 19 is number 2.

Wsdkey	Reach	Order	Mycount	Drain1	Count1	Drain2	Count2	Drain3	Count3	Drain4	Count4
1_101	1	4	1	0	0	0	0	0	0	1	1
1_102	2	1	1	2	1	0	0	0	0	1	1
1_103	3	4	2	0	0	0	0	0	0	1	2
1_104	4	2	1	0	0	1	1	0	0	1	2
1_105	5	1	1	1	1	4	1	0	0	1	2
1_106	6	1	1	1	1	4	1	0	0	1	2
2_202	7	4	3	0	0	0	0	0	0	1	3
2_203	8	3	1	0	0	0	0	8	1	1	3
2_204	9	3	1	0	0	0	0	9	1	1	3
7_674	10	2	1	0	0	10	1	9	1	1	3
7_677	11	1	1	11	1	10	1	9	1	1	3
7_678	12	1	1	12	1	10	1	9	1	1	3
12_009	13	2	1	0	0	13	1	9	1	1	3
12_010	14	1	1	14	1	13	1	9	1	1	3
13_075	15	1	1	15	1	13	1	9	1	1	3
13_089	16	3	2	0	0	0	0	8	2	1	3
27_001	17	3	3	0	0	0	0	8	3	1	3
28_001	18	2	1	0	0	18	1	8	3	1	3
28_007	19	2	2	0	0	18	2	8	3	1	3
28_013	20	1	1	20	1	18	2	8	3	1	3
30_003	21	1	1	21	1	18	2	8	3	1	3
31_003	22	1	1	22	1	0	0	8	1	1	3
67_098	23	1	2	22	2	0	0	8	1	1	3
67_100	24	2	1	0	0	24	1	8	3	1	3
76_009	25	1	1	25	1	24	1	8	3	1	3
81_001	26	1	1	26	1	24	1	8	3	1	3

The table is constructed by examining each reach segment. Each segment has its own Wsdkey that is unique. The objective is to derive all of the appropriate Wsdkeys that flow through a particular reach segment. These can then be used to query the triangle table to pull out all the triangles that drain though the particular reach segment. These can then either be dissolved into the drainage polygon for this reach segment or the attributes from these triangles can be used to query and summarize the information about the drainage through the reach of interest.

To show how the table is constructed, consider the following four examples.

Example 1

To begin, consider the case of reach segment 1. It has order 4. It is the first in a string of 3 segments with order 4. Therefore its value for Drain4 is row 1 of the table (equivalent to reach 1). Since it is the first in the string of order 4, its Count4 is 1. It does not flow though any reaches of orders 1, 2, or 3, therefore its values for Count1, Drain1, Count2, Drain2, Count3, Drain3 are all 0.

Example 2

Now consider the case of reach segment 2. It is order 1, and it is the first (and only) in a string of order 1 reaches. Hence its value for Drain1 is row 2 (reach =2) and its value for Count1 is 1. It does not flow through any order 2 or order 3 reaches. Hence its values for Count2, Drain2, Count3, Drain3 are all 0. In the case of order 4, it drains out through reach 1, and reach 1 is number 1 in the string of order 4 reaches comprised of 1,3,7, so Drain4 is 1 and Count4 is 1.

Example 3

In the case of reach 3, it is order 4. It is the second in a string of order 4, and the last reach it flows out in that string is reach 1. Hence its value for Drain4 is 1, and its value for Count4 is 2. It does not flow through any order 1,2, or 3 reaches, and hence its values for Count1, Drain1, Count2, Drain2, Count3, Drain3 are all 0.

Example 4

Finally, consider the case of reach 22. It is order 1, and it is the first in a string of 2 consecutive order 1 reaches. Hence its value for Drain1 is 22, and its value for Count1 is 1. It flows though no order 2 reaches, so its values for Drain2 and Count2 are both 0. It flows into reach 8, which is the first order 3 in a string of order 3 reaches. So its value for Drain3 is 8 and for Count3 is 1. Next consider where it flows out through order 4. In this instance, following the network down, it flows into reach 7 which is number 3 in a string of order 4 reaches. Therefore its value for Count4 is 3. The outlet for order 4 flow though is reach 1, so its value for Drain4 is 1.

How to use the relational table to define and query upstream drainage areas?

The following examples will demonstrate how to determine everything that belongs to the upstream drainage area from a reach.

Example 1

Assume that it is required to determine everything that flows through the reach with Wsdkey = 2_203.

1) First determine which reach or row this is in the table and which order and Mycount it is. In this case it is row 8 and it is order 3, and it is Mycount 1.

2) Look at Drain3 to determine where it flows out of order 3. In this instance it is also row 8 which is to be expected with a Mycount =1.

3) To determine all the reaches that flow through this reach, use the Drain3 column since it is order 3. Query the table for all rows in Drain3 with a value of 8. In this case, the query will return rows (Reach) 17, 18, 19, 20, 21, 22, 23, 24, 25, 26 as well as 8.

4) Next, in the string of order 3 reaches to which 2_203 belongs, we only want reaches resulting in step 2 that flow through 2_203. This means we only want those rows where Count3 is greater than or equal to the number of reach 8 (aka 2_203). In this instance, the Mycount is 1, and hence all (rows 8, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26) are the result.

5) The next step is to look at the Wsdkeys for rows 8, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26. In this case, the result is 2_203, 27_001, 28_001, 28_007, 28_013, 30_003, 31_003, 67_098, 67_100, 76_009, 81_001.

6) The Wsdkeys can now be linked back to the triangle attributes to pull out all the triangles that flow through Wsdkey= 2_203. It can also pull out all the respective flow paths, reaches, and breakpoints upstream of 2_203.

Example 2

Let us look at a second example. In this case we will choose Wsdkey = 2_202.

1) From the table, Wsdkey 2_202 is reach 7 with order = 4 and Mycount =3.

2) Therefore use the Drain4 column where it is equal to 7 to determine that it flows out through reach 1.

3) Next query the table for all Drain4 values =1. In this case it returns the entire table, rows (Reach) 1 to 26.

4) Then look for the values of Count4 for greater than or equal to the Mycount for 2_202, which is 3. This returns us only the rows where Drain4=1, and Count4 =3.

5) From the results of step 4 are the Wsdkeys of all reach segments flowing through 2_202.

6) These Wsdkeys can now be used to respectively query the triangles, flow paths, reaches, and reach breakpoints tables.