CSDMS TauDEM Clinic "Hands On" Exercise

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Goal

Be able to use TauDEM tools to derive hydrologically useful information from Digital Elevation Models (DEMs)

Purpose

The purpose of this exercise is to introduce Hydrologic Terrain Analysis using TauDEM and to guide you through the steps of running some of the more important functions required to delineate a stream network. Comprehensive documentation on the use of each TauDEM function is given in the online help that is part of the program.

TauDEM (Terrain Analysis Using Digital Elevation Models) is a set of Digital Elevation Model (DEM) tools for the extraction and analysis of hydrologic information from topography as represented by a DEM. This is software developed at Utah State University (USU) for hydrologic digital elevation model analysis and watershed delineation and may be obtained from http://hydrology.usu.edu/taudem/taudem5.0/.

In this exercise, you will perform the following tasks:

- Basic Grid Analysis using TauDEM functions, including.
 - Pit Remove
 - D8 Flow Directions
 - D8 Contributing Area
 - Grid Network
 - D-Infinity flow direction
 - D-infinity Contributing Area
- Stream Network Analysis using TauDEM functions, including
 - Stream Definition by threshold
 - Move Outlets to Streams
 - Stream Reach and Watershed
 - Peuker Douglas
 - Peuker Douglas Stream Definition
- Specialized Grid Analysis using TauDEM functions, including
 - Wetness index derived from slope to area ratio
 - D-Infinity Distance Down

The Logan River watershed is used as an example.

Computer Setup

To complete this exercise, you will need to use the TauDEM 5.0 software as well as MPICH2 software from http://www.mcs.anl.gov/research/projects/mpich2/. You will also need to use visualization

software such as ArcGIS or R. Refer to CSDMS Workshop setup instructions at http://hydrology.usu.edu/taudem/taudem5.0/documentation.html for computer setup details.

Basic Grid Analysis using TauDEM functions

In this section we illustrate the TauDEM basic grid analysis functions.

 Download the Logan River example data zip file from <u>http://hydrology.usu.edu/taudem/taudem5.0/LoganDemo.zip</u>. Extract all files from the zip file. Look at the data.

This data was obtained originally from the National Elevation Dataset seamless data server. See appendix 1 for how to obtain US DEM data from the USGS seamless data server and project it to a spatial reference system for the area of interest. Projected data should be used when working with TauDEM because TauDEM uses grid dimensions (cell size) in its length and slope calculations and these will be incorrect if they are not consistent in E-W and N-S directions and in the same units as the vertical units of the DEM.

ArcMAP. Add data and adjust the symbology.



R

```
z=raster("logan.tif")
```

plot(z)



- 2. The first TauDEM function used is **Pit Remove**. Pits are grid cells surrounded by higher terrain that do not drain. Pit Remove creates a hydrologically correct DEM by raising the elevation of pits to the point where they overflow their confining pour point and can drain to the edge of the domain.
- ArcMap. Open (by double clicking on) the TauDEM Pit Remove Tool (in the Basic Grid Analysis set)



Select **logan.tif** for the Input Elevation Grid. Note that the Output Pit Removed Elevation Grid name is automatically filled with loganfel.tif following the file naming convention. Select the Input Number of Processes (I used 8 for a dual quad core PC).

🎤 Pit Remove	
Input Elevation Grid	Input Elevation Grid
logan.tif 🗾 🖆	A disited elevation model (DEM) addressing as
Input Number of Processes	the base input for the terrain analysis and
Output Pit Removed Elevation Grid	stream delineation.
E:\Users\dtarb\Scratch\Logan\loganfel.tif	
	digitation process that interfere with the
	processing of flow across DEMs, and so are
OK Cancel Environments << Hide Help	Tool Help

The parallel approach used by TauDEM is illustrated below. The domain is subdivided into row oriented partitions that are each processed independently by separate processes. When the algorithms reach a point where they can proceed no further within the partitions there is a swap step that exchanges information along the boundaries. The algorithms then proceed working within the partitions using new boundary information. This process is iterated until completion. The strategies for sharing information across boundaries and iterating are specific to each algorithm.

TauDEM parallel scheme



The number of processes does not have to be the same as the number of processors on your computer, although generally should be the same order of magnitude. The operating system (and MPICH2) takes care of time sharing between processes, so in cases where some processes are likely to be waiting for other processes to complete there may be a benefit in selecting more processes than physical processors on the computer. However then message passing across the borders is increased. For large datasets, some experimentation as to the number of processes that works best (fastest) is suggested.

Click OK on the Pit Remove tool to run the Pit Remove function for the Logan River DEM. The output dialog reports run statistics that include timing, as well as any error or warning messages.

^b it Remove
Completed
<< Details
Close this dialog when completed successfully
Executing: PitRemove logan.tif 8 E:\Users\dtarb\Scratch\Logan\loganfel.tif
Start Time: Sat Oct 29 10:18:25 2011
Executing: CalculateStatistics E:\Users\dtarb\Scratch\Logan\loganfel.tif 1 1 # E:\Users\dtarb\Scratch\Logan
loganfel.tli Stort Time, Sot Oct 20 10:18:25 2011
Start lime: Sat Oct 29 10:16:20 2011 Fractured (CalulateStatistics) successfully
End Time: Sat Oct 29 10:18:27 2011 (Elapsed Time: 1.00 seconds)
Shell Command: mpiexec -np 8 "E:\Program Files (x86)\Taudem\TauDEM5Exe\PitRemove" -z "E:\Users\dtarb\Scratch\Logan
\logan.tif" -fel "E:\Users\dtarb\Scratch\Logan\loganfel.tif" > "E:\Users\dtarb\Scratch\Logan\cmsgtmp.txt"
PitRemove version 5.0.6
Processes: 8
Header read time: 0.079126
Data read time: 0.004965
Compute time: 0.238526
Write time: 0.124965
Total time: 0.447582
Executed (PitRemove) successfully.
End Time: Sat Oct 29 10:18:27 2011 (Elapsed Time: 2.00 seconds)

R

```
# Pitremove
system("mpiexec -n 8 pitremove -z logan.tif -fel loganfel.tif")
fel=raster("loganfel.tif")
plot(fel)
```

Command Line

Open a command prompt. Select Start -> All Programs -> Accessories -> Command Prompt



In the command prompt type the equivalent on your computer to

cd C:\Users\dtarb\Scratch\Demo

This changes directory to the folder where you are working

Type (or cut and paste from here) into the command prompt

mpiexec -n 8 pitremove -z logan.tif -fel loganfel.tif

Note. Command line commands, are exactly the same as the string argument in R system calls so are not repeated in what follows. You can learn more about running TauDEM from the command line at: http://hydrology.usu.edu/taudem/taudem5.0/TauDEM5LineGuide.pdf

3. The next function to run is **D8 Flow Direction**. This takes as input the hydrologically correct elevation grid and outputs D8 flow direction and slope for each grid cell.

> D8 Flow Direction	
Input Pit Filled Elevation Grid	D8 Flow Direction
Input Number of Processes 8	Calculates 2 grids. The first contains the D8 flow directions which are defined, for each cell, as the direction of the one of its eight adjacent or
E://Users/tab/Scratch/Logan/loganp.tif	diagonal neighbors with the steepest downward slope. Flow Direction Coding: 1 - East, 2 - North
Output D8 Slope Grid E:\Users\dtarb\Scratch\Logan\logansd8.tlf	East, 3 - North, 4 - North West, 5 - West, 6 - South West, 7 - South, 8 - South East. The
	direction of steepest descent and is reported as
OK Cancel Environments << Hide Help	

The resulting D8 flow direction grid (grid has suffix p) is illustrated. This is an encoding of the direction of steepest descent from each grid cell using the numbers 1 to 8 per the embedded help above. This is the simplest model of the direction water would flow over the terrain.

ArcMap



R

```
# D8 flow directions
system("mpiexec -n 8 D8Flowdir -p loganp.tif -sd8 logansd8.tif -fel
loganfel.tif",show.output.on.console=F,invisible=F)
p=raster("loganp.tif")
plot(p)
sd8=raster("logansd8.tif")
plot(sd8)
```

Note that on the R system calls there is the option to include "show.output.on.console=F", and "invisible=F" in the arguments. TauDEM functions write to stderr and stdout. This output gives progress information and an indication of how long each program may take. For long tasks it is helpful to see this to get a sense of progress and get reassurance that the program has not crashed. These arguments enable this, rather than this output being held by R for display only when the task completes. These arguments may be included in any R system call, although this was for expedience not done in many of the calls below.

4. The next function to run is **D8 Contributing Area**. This counts the number of grid cells draining through (out of) each grid cell based on D8 flow directions.

ArcMap

n D8 Contributing Area	
Input D8 Flow Direction Grid	D8 Contributing Area
loganp	Calculates a grid of contributing areas using the
	single direction D8 flow model. The contribution
Input Weight Grid (optional)	optional weight grid is used, the value from the
Check for edge contamination Input Number of Processes	cell is taken as its own contributing area to each gird contribution from upslope neighbors that drain in to it according to the D8 flow model. If the
8 Output D8 Contributing Area Grid	optional outlet point shapefile is used, only the outlet cells and the cells upslope (by the D8 flow model) of them are in the domain to be
E:\Users\dtarb\Scratch\Logan\loganad8.tif	evaluated. By default, the tool checks for edge contamination. This is defined as the possibility that a contributing area value may be
OK Cancel Environments << Hide Help	Tool Help

There are options to specify outlets and an input weight grid that were not used here. These are detailed in the tool help and allow calculations to be restricted to the area upstream of designated outlets (specified as a shapefile) and to accumulate an input weight field, rather than just counting contributing area as a number of grid cells.

There is also an option to check for **edge contamination**. Edge contamination is a problem that can occur in the calculation of contributing area when flow is inwards from the boundary of the terrain. The computer does not know what the inflowing contributing area at the edge is, so evaluates the contributing area that may be impacted by this unknown area as no data. The result is streaks that enter the domain along flow paths. This is a desired result as it guards against missing parts of the watershed, but it can and should be turned off if the DEM has been clipped to a watershed boundary. Red has been used to display no data to illustrate edge contamination.

A logarithmic scale is often best to render contributing area values as in the illustration below.



R

```
# Contributing area
system("mpiexec -n 8 AreaD8 -p loganp.tif -ad8 loganad8.tif")
ad8=raster("loganad8.tif")
plot(log(ad8)) # Use log scale for plotting
zoom(log(ad8))
```

5. The **Grid Network** function outputs three grids: (1) the longest flow path along D8 flow directions to each grid cell, (2) the total length of all flow paths that end at each grid cell, and (3) the grid network order. This is obtained by applying the Strahler stream ordering system to the network defined starting at each grid cell.

ArcMap

➢ Grid Network	
Input D8 Flow Direction Grid	Grid Network
loganp 🗾 🖻	
Input Number of Processes	Creates 3 grids that contain for each grid cell: 1)
8	the longest path, 2) the total path, and 3) the
Input Outlets Shapefile (optional)	from the network defined by the D8 flow model
	nom ale network defined by the bollow model.
Input Mask Grid (optional)	The longest upslope length is the length of the
🔹 🖻	flow path from the furthest cell that drains to
Input Mask Threshold Value (optional)	each cell. The total upslope path length is the
	length of the entire grid network upslope of each
Output Strahler Network Order Grid	grid cell. Lengths are measured between cell
E:\Users\dtarb\Scratch\Logan\logangord.tif	whether the direction is adjacent or diagonal
Output Longest Upslope Length Grid	whether the direction is adjacent of diagonal.
E:\Users\dtarb\Scratch\Logan\loganplen.tif	Strahler order is defined as follows: A network of
Output Total Upslope Length Grid	flow paths is defined by the D8 Flow Direction
E:\Users\dtarb\Scratch\Logan\logantlen.tif	grid. Source flow paths have a Strahler order
OK Cancel Environments << Hide Help	Ip Tool Help

R

```
# Grid Network
system("mpiexec -n 8 Gridnet -p loganp.tif -gord logangord.tif -plen
loganplen.tif -tlen logantlen.tif")
gord=raster("logangord.tif")
plot(gord)
zoom(gord)
```

Grid Network Order (file name suffix gord) output from Grid Network is illustrated:



The functions above used the D8 flow model that represents flow from each grid cell to one neighbor. TauDEM also uses the $D\infty$ (D-Infinity) flow model that calculates the steepest outwards flow direction using triangular facets centered on each grid cell and apportions flow between neighboring grid cells based on flow direction angles.

6. The **D-Infinity Flow Direction** function is the starting point for all D-Infinity work. It calculates the D-Infinity flow directions for use in other TauDEM functions requiring D-infinity flow direction input.

D-Infinity Flow Direction	
Input Pit Filled Elevation Grid	D-Infinity Flow Direction
loganfel 🔽 🚅	
Input Number of Processes	Assigns a flow direction based on the steepest
8	slope of a triangular facet (Tarboton, 1997). Flow
Output D-Infinity Flow Directions Grid	on planar triangular facets on a block centered
E:\Users\dtarb\Scratch\Logan\loganang.tif	arid Elow direction is encoded as an angle in
Output D-Infinity Slope Grid	radians counter-clockwise from east as a
E:\Users\dtarb\Scratch\Logan\loganslp.tif	continuous (floating point) quantity between 0
·	and 2 pi. The flow direction angle is determined
	as the direction of the steepest downward slope
OK Cancel Environments << Hide Help	Tool Help
Carcer Environments Contraction	

R

```
# DInf flow directions
system("mpiexec -n 8 DinfFlowdir -ang loganang.tif -slp loganslp.tif
-fel loganfel.tif", show.output.on.console=F, invisible=F)
ang=raster("loganang.tif")
plot(ang)
slp=raster("loganslp.tif")
plot(slp)
```

D-Infinity flow directions are encoded as angles counter clockwise from East in Radians as illustrated in the help.

ArcMan



D-Infinity flow directions render similar to a hillshading.



7. **The D-Infinity Contributing Area** function evaluates contributing area using the D-Infinity model based on flow being shared between grid cells proportional to the angle to the steepest downslope direction. This is designed to represent specific catchment area within dispersed flow over a smooth topographic surface.

D-Infinity Contributing Area	
Input D-Infinity Flow Direction Grid	D-Infinity Contributing Area
loganang 💌 🚅	
Input Outlets Shapefile (optional)	Calculates a grid of contributing area using the multiple flow direction Drinfinity approach. Dr
	infinity flow direction is defined as steepest
Input Weight Grid (optional)	downward slope on planar triangular facets on a
N 🖾 🖉	block centered grid. The contribution at each
Check for edge contamination	(or when the optional weight grid is used, from
Input Number of Processes	the weight grid). The contributing area of each
8	grid cell is then taken as its own contribution
Output D-Infinity Specific Catchment Area Grid	that have some fraction draining to it according
	to the D-infinity flow model. The flow from each
	cell either all drains to one neighbor, if the angle
OK Cancel Environments << Hide Help	Tool Help

ArcMap

R

```
# Grid Network
system("mpiexec -n 8 AreaDinf -ang loganang.tif -sca logansca.tif")
sca=raster("logansca.tif")
plot(log(sca))
zoom(log(sca))
```

The result from running this is specific catchment area obtained from the D-Infinity contributing area function (with edge contamination) as illustrated below.



Stream Network Analysis using TauDEM functions

TauDEM provides a number of methods for delineating and analyzing stream networks and watersheds. The simplest stream network delineation method uses a threshold on contributing area.

8. Stream Definition by Threshold. This function defines a stream raster grid (src suffix) by applying a threshold to the input. In this case the input is a D8 contributing area grid and a threshold of 100 grid cells has been used.

ArcMap	
A Stream Definition by Threshold	
Input Accumulated Stream Source Grid	Stream Definition by Threshold Operates on any grid and outputs an indicator (1,0) grid identifing cells with input values >= the threshold value. The standard use is to use an accumulated source area grid to as the input grid to generate a stream raster grid as the output. If you use the optional input mask grid, it limits the domain being evaluated to cells with mask values >= 0. When you use a D-infinity contributing area grid (*sca) as the mask grid, it functions as an edge contamination mask. The threshold logic is: src = ((ssa >= thresh) & (mask >=0)) ? 1:0.
OK Cancel Environments << Hide Help	Tool Help

R

```
# Threshold
system("mpiexec -n 8 Threshold -ssa loganad8.tif -src logansrc.tif -
thresh 100")
src=raster("logansrc.tif")
plot(src)
zoom(src)
```

The result depicts the stream network as a binary grid (but is not logically connected as a network shapefile yet).



9. Identify a watershed outlet. It is common to want to delineate watersheds upstream of an outlet, say a USGS stream gauge. This requires that gauge locations be precisely located on streams as rendered from the DEM. Due to inaccuracies in gauge locations and DEM stream delineation it is common for gauge locations not to be precisely on streams delineated from the DEM. The move Outlets to streams function slides gauge locations downslope following D8 flow directions until a stream (as defined by a stream raster grid) is encountered. An outlet shapefile can be created by clicking on or near a stream. I did this using the R function below.

```
R
# a quick R function to write a shapefile
makeshape.r=function(sname="shape",n=1)
{
    xy=locator(n=n)
    points(xy)

    #Point
    dd <- data.frame(Id=1:n,X=xy$x,Y=xy$y)
    ddTable <- data.frame(Id=c(1),Name=paste("Outlet",1:n,sep=""))
    ddShapefile <- convert.to.shapefile(dd, ddTable, "Id", 1)
    write.shapefile(ddShapefile, sname, arcgis=T)
    }
    makeshape.r("ApproxOutlets")</pre>
```



This can also be done in ArcGIS using standard shape editing functionality.

ArcMap

Add the **ApproxOutlets.shp** file to ArcMap and zoom in to the area around it. Change the symbology if necessary.



10. The Move Outlets to Streams function is used to move the outlets to the streams.

ArcMap

➢ Move Outlets to Streams	
Input D8 Flow Direction Grid	Move Outlets to Streams
loganp 🗾 🖆	
Input Stream Raster Grid	This tool moves outlet points that are off a
E:\Users\dtarb\Scratch\Logan\logansrc.tif	stream raster grid, downslope along the D8 flow
Input Outlets Shapefile	encountered. Input is a flow direction grid. a
ApproxOutlets 💽 🗃	stream raster grid and an outlets shapefile.
Input Maximum Distance	Output is a new outlets shapefile where each
50	point has been moved to coincide with the
Input Number of Processes	'dist moved' is added to the new outlets
Output Outlet Shapefile	shapefile to indicate the changes made to each
E:\Users\dtarb\Scratch\Logan\outlet.shp	raster (src) grid are not moved and their
	'dist_moved' field is assigned a value 0. Points 🗨
OK Cancel Environments << Hide Help	Tool Help

R

```
# Move Outlets
system("mpiexec -n 8 moveoutletstostreams -p loganp.tif -src
logansrc.tif -o approxoutlets.shp -om Outlet.shp")
outpt=read.shp("outlet.shp")
```

```
plot(src)
points(outpt$shp[2],outpt$shp[3],pch=19,col=2)
```

😫 Untitled - ArcMap - ArcInfo <u>File Edit View Bookmarks Insert Selection Tools Window Help</u> 🗋 🚅 🛃 🎒 🕺 🖻 📸 🗙 🗠 🗠 🤠 🛟 1:8,245 💽 📝 🔌 🚳 🗖 🍉 🕅 💌 🎆 🗽 🛛 Editor 💌 🕨 🖉 💌 Task: 🛛 Create New Feature $\times \odot$ Spatial Analyst 💌 Layer: logan.tif Target: ٠ ۲ 🎤 D-Infinity Flow Directi 🔺 💋 Layers ٠ Θ D8 Contributing Area
 D8 Flow Directions
 Grid Network 🖃 🗹 outlet žŔ •1 53 🎤 Pit Remove E 🗹 ApproxOutlets Ð Specialized Grid Analysis \odot 🎤 D-Infinity Avalanche F ۲ 🖃 🔲 LoganOutlet D-Infinity Concentrati 4 D-Infinity Decaying Ac \odot D-Infinity Distance Do D-Infinity Distance Up 🖃 🗹 logansrc Ŋ<mark>⊠</mark> Ťη 🎤 D-Infinity Reverse Ac 🎤 D-Infinity Transport Li 1 🗆 🗌 logansca 🎤 D-Infinity Upslope Der k D8 Distance to Stream <VALUE> Slope Average Down
Slope Over Area Ratic 30 - 100 0 100.0000001 - 30 楢 ار1 - 300.0000001 - 1 Stream Network Analysis 1,000.000001 - 3 🎤 D8 Extreme Upslope V 3,000.000001 - 1 🎤 Length Area Stream S ÷ E 🗌 loganslp Move Outlets to Strea Peuker Douglas . Value High : 2.48592 圖 Slope Area Combinatio Ð 🎤 Slope Area Stream De Low : 0 Stream Definition By T.
 Stream Definition with 🗆 🗌 loganang Stream Definition By T_ Value 🎤 Stream Drop Analysis 👻 High : 6.28319 Þĺ Favorites Index Search Results Display Source Selection 9 🗈 I 😌 II 🔳 F Drawing 🗸 💺 💿 🥥 🗖 🗖 🗸 🖌 🗹 🖉 Arial ▼ 10 ▼ B Z U <u>A</u> ▼ <u>→</u> ▼ <u>→</u> ▼ 436316.426 4622028.624 Meters

Visualize the **outlet.shp** shapefile. Notice (below) how the outlet has been moved to coincide with the stream.

It is somewhat overkill to use 8 processors to move one outlet point, but this is illustrative of how this could be used for many more points. Upon adding the moved outlet you may have received an ArcMAP unknown spatial reference warning. Be aware in using TauDEM that TauDEM does not do any spatial reference (projection) conversions. Therefore all data needs to be in the same spatial reference system. TauDEM does copy the spatial reference information from input grids to output grids, but does not do this for shapefiles.

With the outlet positioned on the stream the stream network upstream of the outlet can be delineated.

11. Once the outlet has been placed exactly on the stream paths, the D8 Contributing Area function is run again, but specifying an outlet shapefile to evaluate contributing area and effectively identify the watershed upstream of the outlet point (or points for multiple outlets).

	A	
Input D8 Flow Direction Grid		D8 Contributing Area
loganp	- 🖻	Coloulates a grid of contributing grass using the
Input Outlets Shapefile (optional)	_	single direction D8 flow model. The contribution
outlet	⊻ 🛎 👘	of each grid cell is taken as one (or when the
Input Weight Grid (optional)		optional weight grid is used, the value from the
	- 🖻	weight grid). The contributing area for each grid
Check for edge contamination		cell is taken as its own contribution plus the contribution from upslope neighbors that drain in
Input Number of Processes		to it according to the D8 flow model. If the
	8	optional outlet point shapefile is used, only the
Output D8 Contributing Area Grid		model) of them are in the domain to be
E:\Users\dtarb\Scratch\Logan\loganssa.tif	<u> </u>	evaluated. By default, the tool checks for edge
	_	contamination. This is defined as the possibility
	*	that a contributing area value may be
OK Cancel Environments	< Hide Help	Tool Help

R

```
# Contributing area upstream of outlet
system("mpiexec -n 8 Aread8 -p loganp.tif -o Outlet.shp -ad8
loganssa.tif")
ssa=raster("loganssa.tif")
plot(ssa)
```

The result is contributing area only for the watershed upstream of the outlet.



ArcMan

12. The next step is to use the **Stream Definition By Threshold** function to define streams using a specified contributing area threshold. Here a threshold of 2000 grid cells is arbitrarily chosen

Stream Definition by Threshold	
Input Accumulated Stream Source Grid	Stream Definition by Threshold
loganssa 💌 🖻	
Input Mask Grid (optional)	Operates on any grid and outputs an indicator (1,0) grid identifing cells with input values >= the threshold value. The standard use is to use an
Threshold 2000	accumulated source area grid to as the input grid to generate a stream raster grid as the
Input Number of Processes 8	output. If you use the optional input mask grid, it limits the domain being evaluated to cells with
Output Stream Raster Grid	mask values >= 0 . When you use a D-infinity
E:\Users\dtarb\Scratch\Logan\logansrc1.tif	contributing area grid (*sca) as the mask grid, it functions as an edge contamination mask. The
OK Cancel Environments << Hide Help	Tool Help

R

......

```
# Threshold
system("mpiexec -n 8 threshold -ssa loganssa.tif -src logansrc1.tif
-thresh 2000")
src1=raster("logansrc1.tif")
plot(src1)
zoom(src1)
```

The result is a grid stream network upstream of the outlet



13. This network is still only represented as a grid. To convert this into vector elements represented using a shapefile, the **Stream Reach and Watershed** function is used.

ArcMap		
Stream Reach and Watershed		
Input Pit Filled Elevation Grid		Stream Reach and Watershed
loganfel 🔽 🖬	2	
Input D8 Flow Direction Grid		This function produces a vector network and
E:\Users\dtarb\Scratch\Logan\loganp.tif	2	snapefile from the stream raster grid. The flow direction grid is used to connect flow paths
Input D8 Drainage Area		along the stream raster. The Strahler order of
E:\Users\dtarb\Scratch\Logan\loganad8.tif	2	each stream segment is computed. The
Input Stream Raster Grid		subwatershed draining to each stream segment
E:\Users\dtarb\Scratch\Logan\logansrc1.tif	2	(reach) is also delineated and labeled with the
Input Outlets Shapefile as Network Nodes (optional)		(watershed number) attribute in the stream
	2	reach shapefile.
🗖 Delineate Single Watershed		
Input Number of Processes		
	8	
Output Stream Order Grid		
E:\Users\dtarb\Scratch\Logan\loganord.tif	2	
Output Network Connectivity Tree (txt)		
E:\Users\dtarb\Scratch\Logan\logantree.txt	2	
Output Network Coordinates (txt)		
E:\Users\dtarb\Scratch\Logan\logancoord.txt	ž	
Output Stream Reach Shapefile		
E:\Users\dtarb\Scratch\Logan\logannet.shp	2	
Output Watershed Grid		
E:\Users\dtarb\Scratch\Logan\loganw.tif	≝ ⊡	×
OK Cancel Environments << Hide	Help	Tool Help

R

```
# Stream Reach and Watershed
system("mpiexec -n 8 Streamnet -fel loganfel.tif -p loganp.tif -ad8
loganad8.tif -src logansrc1.tif -o outlet.shp -ord loganord.tif -
tree logantree.txt -coord logancoord.txt -net logannet.shp -w
loganw.tif")
plot(raster("loganord.tif"))
zoom(raster("loganord.tif"))
plot(raster("loganw.tif"))
# Plot streams using stream order as width
snet=read.shapefile("logannet")
ns=length(snet$shp$shp)
for(i in 1:ns)
{
    lines(snet$shp$shp[[i]]$points,lwd=snet$dbf$dbf$Order[i])
}
```

The result is a number of outputs that need to be added to visualized. Here I visualized the watershed grid, loganw.tif, and stream network shapefile, logannet.shp, in R.



The subwatershed raster and stream network shapefile are key outputs from TauDEM. Each link in the stream network has a unique identifier that is linked to downstream and upstream links. Each subwatershed also has a unique identifier that is referenced in terms of the stream network that it drains to. This information enables construction of a subwatershed based distributed hydrologic model with flow from subwatersheds being connected to, accumulated in, and routed along the appropriate stream reaches. It is interesting to zoom in on the outlet and examine the properties of the stream network and subwatersheds near the outlet to identify how the linkages between stream links are represented and what other attributes there are for each stream link. This is easiest to do in an interactive visualization system such as ArcMap. It is a little cumbersome in R.

An important question in stream network delineation is what stream delineation threshold to use. The above used an arbitrary thresholds of 2000 grid cells. TauDEM also provides ways to do select stream delineation threshold objectively using a stream drop test following theory described in Tarboton et al. (Tarboton et al., 1991; 1992) and Tarboton and Ames (2001). This may be combined with more geomorphologically based methods for channel definition that attempt to capture topographic texture and spatial variability in drainage density. These will be illustrated next.

14. The **Peuker Douglas** function produces a "valley" network skeleton following the procedure described in their paper (Peuker and Douglas, 1975).

n Peuker Douglas	
Input Elevation Grid	Peuker Douglas
loganfel 🗾 🗃	
Center Smoothing Weight	Creates an indicator grid (1,0) of upward curved
0.4	grid cells according to the Peuker and Douglas
Side Smoothing Weight	smoothed by a kernel with weights at the
0,1	center, sides, and diagonals. The Peuker and
	Douglas (1975) method (also explained in Band,
Input Number of Processes	1986), is then used to identify upwardly curving arid colls. This technique flags the entire grid
1	then examines in a single pass each quadrant of
Output Stream Source Grid	4 grid cells, and unflags the highest. The
E:\Users\dtarb\Scratch\Logan\loganss.tif	remaining flagged cells are deemed 'upwardly
	curved, and when wewed, resemble a channel
OK Cancel Environments << Hide Help	Tool Help

ArcMap

R

```
# Peuker Douglas stream definition
system("mpiexec -n 8 PeukerDouglas -fel loganfel.tif -ss
loganss.tif")
ss=raster("loganss.tif")
plot(ss)
zoom(ss)
```

The result, derived entirely from a local filter applied to the topography is a skeleton of a stream network illustrated below



15. The **Peuker Douglas Stream Definition** function has a rather extensive set of inputs. It configures TauDEM to run Peuker Douglas, then use the Peuker Douglas stream skeleton as a weighted input to a D8 contributing area calculation. The result is then thresholded using a range of thresholds (the drop analysis thresholds at the bottom of the input) to identify the smallest threshold for which the mean stream drop of first order streams is not significantly different from the mean stream drop of higher order streams. This is the constant drop law (Broscoe, 1959), and TauDEM uses it here to identify the highest resolution stream network that complies with this law as an objective way of identifying the stream delineation threshold.

ArcMap

Input Elevation Grid	Peuker Douglas Stream Definition
loganfel	_
Input D8 Flow Direction Grid	This tool combines the functionality of the
Evil (sers) dtarb) Scratchill ogan) logann tif	"Peuker Douglas," "D8 Contributing Area,"
	"Stream Drop Analysis," and "Stream Definition
	by Threshold" tools in order to generate a
0.4	stream indicator grid (1,0) where the streams
	are located using a DEM curvature-based
U,I	method. With this method, the DEM is first
	center sides and diagonals The Peuker and
Accumulation Threshold	Douglas (1975) method (also explained in Band
S0	1986), is then used to identify upwardly curving
	grid cells. This technique flags the entire grid,
Check for edge contamination	then examines in a single pass each quadrant of
Input Outlets Shapefile (optional)	4 grid cells, and unflags the highest. The
outlet 🔽 😭	remaining flagged cells are deemed 'upwardly
,	curved, and when viewed, resemble a channel
	network. This proto-channel network sometimes
J	issues that were discussed in detail by Band
	(1986) The thinning and connecting of these
Jioganada 🗾 💆	arid cells is achieved here by computing the D8
Input Number of Processes	contributing area using only these upwardly
8 O ha h Sharan Guina Gild	curving cells. An accumulation threshold on the
	number of these cells is then used to map the
E:\Users\dtarb\Scratch\Logan\loganss1.tir	channel network where this threshold is
Output Accumulated Stream Source Grid	optionally set by the user, or determined via
E:\Users\dtarb\Scratch\Logan\loganssa1.tif	drop analysis.
Output Stream Raster Grid	
E:\Users\dtarb\Scratch\Logan\logansrc2.tif	
Output Drop Analysis Table (optional)	
E:\Users\dtarb\Scratch\Logan\logandrp.txt	
A Dava Analusia Banamatana	
- brop Analysis Parameters	
Use the range below to automatically select threshold by drop analysis	
Minimum Threshold Value	
5	
Maximum Threshold Value	
500	
Number of Threshold Values	
10	
Use logarithmic spacing for threshold values	
	V
,,,,,,	
OK Cancel Environments << Hide Help	Tool Help

The output results include a table that reports the stream drop statistics for each threshold examined. This is included in the completion dialog as well as written to the drop analysis table file shown below. The last column of this gives T statistics for the differences of first and higher order streams. Using a threshold of |2| as indicating significance in this T test the threshold of 299 is chosen in this case as the objective stream delineation threshold.

Peuker Douglas Stream Definition	×
Completed	Close
	<< Details
Close this dialog when completed successfully	
DropAnalysis version 5.0.6	
Threshold DrainDen NoFirstOrd NoHighOrd MeanDFirstOrd MeanDHighOrd StdDevFirstOrd StdDevHighOrd Tval	
5.000000 0.002463 2240 683 66.103836 124.935806 76.027199 132.216568 -14.588625	
8.340503 0.001857 1158 350 85.467384 144.971268 97.808640 142.422195 -8.886599	
13.912798 0.001540 770 238 96.449455 159.728210 103.430626 151.690506 -7.316723	
23.207947 0.001228 450 141 114.742607 182.002914 109.602211 158.783463 -5.662051	
38.713192 0.001000 293 96 116.358841 211.537094 107.481842 166.852936 -6.490214	
64.577499 0.000791 187 70 116.592140 209.407593 124.078995 156.084854 -4.961879	
107.721756 0.000635 109 38 153.991043 239.083878 144.088898 162.634705 -3.030640	
179.690720 0.000524 75 19 187.208069 269.439911 158.242188 156.966827 -2.026490	
299.742218 0.000411 50 14 197.519684 255.433441 137.707306 168.146484 -1.324365	
500.000183 0.000303 30 4 214.549347 289.485138 153.106644 135.973572 -0.928733	
299.742218 Value for optimum that drop analysis selected - see output file for details.	
Processes: 8	-

R. The ArcMap tool above ran 4 underlying TauDEM commands. The PeukerDouglas command was run earlier. Here are the next three.

```
# Accumulating candidate stream source cells
system("mpiexec -n 8 Aread8 -p loganp.tif -o outlet.shp -ad8
loganssa.tif -wg loganss.tif")
ssa=raster("loganssa.tif")
plot(ssa)
# Drop Analysis
system("mpiexec -n 8 Dropanalysis -p loganp.tif -fel loganfel.tif -
ad8 loganad8.tif -ssa loganssa.tif -drp logandrp.txt -o outlet.shp -
par 5 500 10 0")
# Deduce that the optimal threshold is 300
# Stream raster by threshold
system("mpiexec -n 8 Threshold -ssa loganssa.tif -src logansrc2.tif
-thresh 300")
plot(raster("logansrc2.tif"))
```

16. Next the **Stream Reach and Watershed** function is used to produce a vector stream shapefile from the resulting stream raster.

ArcMap

>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>		
Input Pit Filled Elevation Grid		Stream Reach and Watershed
loganfel 🔽	2	
Input D8 Flow Direction Grid		This function produces a vector network and
E:\Users\dtarb\Scratch\Logan\loganp.tif	🚔 🗌	snapenie from the stream raster gnd. The flow
Input D8 Drainage Area		along the stream raster. The Strahler order of
E:\Users\dtarb\Scratch\Logan\loganad8.tif	2	each stream segment is computed. The
Input Stream Raster Grid		subwatershed draining to each stream segment
E:\Users\dtarb\Scratch\Logan\logansrc2.tif	2	(reach) is also delineated and labeled with the
Input Outlets Shapefile as Network Nodes (optional)		(watershed number) attribute in the stream
	2	reach shapefile.
Delineate Single Watershed		
Input Number of Processes		
	8	
Output Stream Order Grid		
E:\Users\dtarb\Scratch\Logan\loganord2.tif	2	
Output Network Connectivity Tree (txt)		
E:\Users\dtarb\Scratch\Logan\logantree2.txt	2	
Output Network Coordinates (txt)		
E:\Users\dtarb\Scratch\Logan\logancoord2.txt	i 🗃	
Output Stream Reach Shapefile		
E:\Users\dtarb\Scratch\Logan\logannet2.shp	i 🗃	
Output Watershed Grid		
E:\Users\dtarb\Scratch\Logan\loganw2.tif	2	
OK Cancel Environments	Hide Help	Tool Help

R

```
# Stream network
system("mpiexec -n 8 Streamnet -fel loganfel.tif -p loganp.tif -ad8
loganad8.tif -src logansrc2.tif -ord loganord2.tif -tree
logantree2.dat -coord logancoord2.dat -net logannet2.shp -w
loganw2.tif -o Outlet.shp", show.output.on.console=F, invisible=F)
plot(raster("loganw2.tif"))
snet=read.shapefile("logannet2")
ns=length(snet$shp$shp)
for(i in 1:ns)
{
    lines(snet$shp$shp[[i]]$points,lwd=snet$dbf$dbf$Order[i])
}
```

Following is an illustration of the result. Notice how the stream network has been delineated more or less consistently with the contour crenulations depicting the texture of the topography.



Specialized Grid Analysis using TauDEM functions

TauDEM also includes a number of specialized grid analysis functions. A few are illustrated here.

17. The TOPMODEL wetness index is defined as Is(a/S) where a is specific catchment area and S is slope (tan of slope angle). In the TauDEM outputs above a is represented by sca, the D-Infinity specific catchment area grid and S by slp, the D-Infinity slope. sca is alreay in length units (the same units as grid cell size). TauDEM has a function to evaluate sar=S/a. This is done to leave to the user the choice as to how to handle grid cells that have S=0. Wetness index is then -In(sar).

Slope Over Area Ratio		
Input Slope Grid		Slope Over Area Ratio
logansip	- 🛋 🛛	
Input Specific Catchment Area Grid		Calculates the ratio of the slope to the specific
E:\Users\dtarb\Scratch\Logan\logansca.tif	- 🛋 🔰	catchment area (contributing area). This is algebraically related to the more common in
Input Number of Processes		(a/tan beta) wetness index, but contributing area
	1	is in the denominator to avoid divide by 0 errors
Output Slope Divided By Area Ratio Grid		when slope is 0.
E:\Users\dtarb\Scratch\Logan\logansar.tif	🖻 🖻	
OK Cancel Environments <	< Hide Help	Tool Help

Wetness index is evaluated using the ArcMap Raster Calculator

ArcMan

# Raster Calculator										? ×
Layers:							Arithmeti	c	- Trigonom	netric
loganord2 loganp	×	7	8 9	=	\diamond	And	Abs	Int	Sin	ASin
loganplen logansar logansca		4	5 6	>	>=	Or	Ceil	Float	Cos	ACos
logansd8 loganslp	- · ·	1	2 3	<	<=	Xor	Floor	IsNull	Tan	ATan
logansic logansic1 logansic2	- +	0		()	Not	Logarithr	ns	-Powers-	1
- Ln([logansar])						A	Exp	Log	Sqrt	
							Exp2	Log2	Sqr	
							Exp10	Log10	Pow	
						~				
About Building Expres	sions	<u>E</u> v	aluate	Cano	el	<<				

R

```
# Wetness Index
system("mpiexec -n 8 SlopeAreaRatio -slp loganslp.tif -sca
logansca.tif -sar logansar.tif", show.output.on.console=F,
invisible=F)
sar=raster("logansar.tif")
wi=sar
wi[,]=-log(sar[,])
plot(wi)
```

The result is illustrated below



18. The **D-Infinity Distance Down** function computes the distance to streams (or any designated target grid) a number of different ways

ArcMap

➢ D-Infinity Distance Down			×
Input D-Infinity Flow Direction Grid	<u>_</u>	D-Infinity Distance Down	
loganang	- 🖻		
Input Pit Filled Elevation Grid		Calculates the distance downslope to a stream	
E:\Users\dtarb\Scratch\Logan\loganfel.tif	- 🗃	flow model is a multiple flow direction model	
Input Stream Raster Grid		because the outflow from each grid cell is	
logansrc2	- 🗃	proportioned between up to 2 downslope grid	
Statistical Method		cells. As such, the distance from any grid cell to	
Average	•	a stream is not uniquely defined. Flow that	
Distance Method		originates at a particular grid cell may enter the	
Vertical	•	stream at a number of different cells. The	
Check for edge contamination		longest, shortest or weighted average of the flow	
Input Weight Path Grid (optional)		path distance to the stream. Also one of several	
	- 🗃	ways of measuring distance may be selected:	
Input Number of Processes		horizontal component of the straight line path.	
	8	the vertical component of the straight line path.	
Output D-Infinity Drop to Stream Grid		or the total surface flow path.	
E:\Users\dtarb\Scratch\Logan\logandd.tif	- E		
	_		7
OK Cancel Environments <	< Hide Help	Tool Help	

R

```
# Distance Down
system("mpiexec -n 8 DinfDistDown -ang loganang.tif -fel
loganfel.tif -src logansrc2.tif -m ave v -dd
logandd.tif",show.output.on.console=F,invisible=F)
plot(raster("logandd.tif"))
```

By selecting **-m ave v** as the distance method the result is the average vertical drop from each point, to a point on the stream as illustrated below.



There are many other options for distance methods that are described in the help file http://hydrology.usu.edu/taudem/taudem5.0/TauDEM_Tools.chm and command line guide http://hydrology.usu.edu/taudem/taudem5.0/TauDEM5CommandLineGuide.pdf that you could experiment with if you want to.

Appendix 1. Downloading DEM data from the USGS Seamless data server

This appendix illustrates the process of downloading and projecting DEM data from the USGS Seamless data server, for the Cub River watershed as it drains to the location of a USGS streamflow station #10096000 located just north of Preston, Idaho, illustrated below.



The USGS Seamless data server was used to obtain a National Elevation Dataset DEM.

The steps followed were

- 1. Access USGS Seamless data server http://seamless.usgs.gov/
- 2. Click view and download United States Data
- 3. Zoom to the area of interest. Activate layers on the right to help identify area of interest.
- 4. Define a download region that covers the area of interest.
- 5. Modify the data request to comprise the data sets (parameters) that you want to obtain
- 6. Download the data. I selected the 1/3 arc second National elevation dataset DEM (≈ 10 m grid)

Screen Image of the area that I selected



Screen Image of a Data Download Request



Projecting the Digital Elevation Model data

The Digital Elevation Model grid from the Seamless Data Server is in Geographic Coordinates. Projected data should be used when working with TauDEM because TauDEM uses grid dimensions (cell size) in its length and slope calculations and these will be incorrect if they are not consistent in E-W and N-S directions and in the same units as the vertical units of the DEM. The DEM from the USGS was added to ArcMap. Then the ArcToolBox Project Raster tool was used to project this data. The ProjectRaster Tool is found within Data Management Tools / Projections and Transformations / Raster.



In the Project Raster dialog that opens specify the input raster as the National Elevation Dataset DEM that was unzipped from the download. Name the output raster something convenient. Here I used "cubdem". Click on the button next to Output coordinate system to open the Spatial Reference Properties dialog.



At this Spatial Reference Properties dialog click "Select" and navigate to the NAD_1927_UTM_Zone_12N projection being used as the standard spatial reference system for this exercise. Click OK.

Spatial Reference	Propertie	5			?×	
Coordinate System						
Name: NAD_	Name: NAD_1927_UTM_Zone_12N					
Details:						
Alias: Abbreviation:				^		
Remarks: Projection: Transv	erse Mercat	or				
Parameters: False Easting: 51	00000.000000)				
False_Northing: (Central Meridian).000000 : -111.000000					
Scale_Factor: 0.9 Latitude_Of_Origi	99600 in: 0.000000					
Linear Unit: Meter Geographic Coord	(1.000000) dinate Systen	n:				
Name: GCS_North	n_American_	1927		~		
Select	Select a pi	redefined coordin	ate system.			
	Import a coordinate system and X/Y, Z and M					
	feature dataset, feature class, raster).					
New •	. Create a new coordinate system.					
Modify	Edit the properties of the currently selected coordinate system.					
Clear	Sets the coordinate system to Unknown.					
Save As Save the coordinate system to a file.						
		ОК	Cancel			

Back at the Project Raster dialog set the resampling technique to CUBIC (I have found by experience that this works best for DEMs) and set the output cell size to 20 m. The raw data in this case is at 1/3 arc second which is roughly 10 m. 20 m cell size is undersampling this a bit. Click OK. A processing dialog box should appear and after a few seconds indicate completion of the projection of the DEM. The DEM data has now been projected. The result is named 'cubdem'

References

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