Comprehensive Terrain Preprocessing Using Arc Hydro Tools

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Preface

This document is an update from the 2007 edition. The critical updates are the use of ArcGIS 9.3, a different computer (that has ramification on the speed of execution of the functions that are documented), and updated version of Arc Hydro tools that has all the preprocessing functions implemented within ArcToolbox as well as in the Arc Hydro toolbar.

Implementation of functions within the geoprocessing framework (as part of Arc Hydro toolbox), enables easy automation of the workflows. The intent is that as you define best processing practices for your particular conditions, you can encapsulate them in a script or a Model Builder model and then have them available through a single "click" processing instead of a sequence of operations. This document still focuses on the terrain process and how individual functions are used within that process. Automation of the processes is left to the user.

All terrain preprocessing functions described here can be found in the Terrain Preprocessing toolset of the Arc Hydro toolbox and can be interchangeably used with the tools available from the toolbar.

1.0 Introduction

This document presents the methodologies for terrain preprocessing in Arc Hydro. Only terrains represented as digital elevation models (DEM) in raster form (grid) are covered by the methods and tools discussed here. The following assumptions are made:

- Initial DEM and supporting layers (if any) exist. Preparation of the initial DEM and supporting layers is not discussed.
- DEM and derivatives will be in ESRI GRID format.
- Vector layers will be in the ESRI (geodatabase) feature class format.
- DEM and supporting layers are in consistent projection (the tools do not perform projections on the fly, so any layer that will be used by the tools must be in the same projection as the underlying DEM).
    - It is recommended that an equal area projection is selected for the basis of the analyses (unless the modeled processes for which the terrain is being used are mostly dependent on the transport through the drainage system in which case an equal length projection is recommended).
    - The DEM and the supporting layers should be prepared in the selected projection before the terrain preprocessing is undertaken.
        - NOTE: GRID, due to its rectangular nature, does not project – when the "projection" is performed on a GRID, the GRID is actually re-sampled. This affects computation of flow direction and basically requires that all preprocessing steps are repeated on the projected DEM (instead of reprojecting all the terrain processing derivatives).
        - Vector results from the terrain preprocessing can be projected after the analyses.

- Layer used for visualization purposes only (e.g. orthophotos) do not have to be projected.

- Horizontal and vertical units are known. While vertical units will not affect the flow direction and drainage system determination, they are critical for computation of terrain characteristics such as slope and volume.
- Any terrain derivatives generated by the tools will be discussed.

ArcGIS (at least ArcView license – Editor license is recommended) and Spatial Analyst extension are required.

1.1 Role of Terrain Preprocessing

Terrain preprocessing is one of the most important steps in data preparation for water resources analyses using Arc Hydro tools.

The role of preprocessing is twofold:

1) Development of hydrologically-correct DEM (HydroDEM) and its derivatives, primarily the flow direction and flow accumulation grids as well as identification of preferential flow path patterns in the vector environment.
2) Development of a series of inter-related layers that optimize the performance of Arc Hydro tools related to watershed delineation and characterization.

A HydroDEM is defined as the terrain in which the flow patterns meet the expectations of the analyst/analysis. This is on purpose a subjective definition. Not one terrain interpretation might meet all analyses expectations. For example, a terrain for analysis of peak flows might look slightly different than the terrain for analysis of low flows or for computation of groundwater recharge. The terrain representation also depends on the type of physical model and the modeling approach the terrain will be used to support.

Thus, it is possible to have different terrain representations of the same area as a function of the analyses to be performed. This document describes the Arc Hydro techniques and tools for terrain preprocessing. It is up to the analyst to apply them correctly and based on their understanding of local hydro-geomorphology develop the correct terrain representation(s) for analyses to be performed.

It is important to emphasize that the role of terrain preprocessing is NOT to develop the terrain representation to meet specific model (use) considerations, but as stated earlier, to establish correct drainage pattern. Developing terrain partitioning for a particular model implementation occurs after the general terrain preprocessing described here is completed. Additional (model specific) tools might be required to develop a model specific layout. Development of model specific layers should be viewed as development of specific watershed and subwatershed boundaries and matching layers, while development of catchments is what is done in Arc Hydro.

1.2 Key Elements in Terrain Preprocessing

Two components define the terrain behavior:

1) Flow direction. Flow direction defines movement of water between the terrain cells. The flow direction in Arc Hydro is based exclusively on topography, that is, on the slope defined by the terrain only – there is no consideration of potential hydraulic effects (such as backwater) on the movement of water. If such conditions exist, than a proper hydraulic model that takes into consideration the physics of water movement should be used.
2) Established drainage system (definition of drainage areas and their connectivity). Establishing a drainage system is more of a subjective task and there can be several developed on top of the same flow direction grid. The discussed drainage system focuses on performance and connectivity issues.

There are four key elements that define the expected "behavior" of the flow patterns in the terrain:

1) Sinks (depressions, pits). Sinks are the areas into which the water flows but does not exit as surface flow. In DEMs, most of the sinks are artificial and are artifacts of DEM construction. There are also real sinks. Sinks can be a function of the analysis. For low flow conditions, some sinks will capture water that will never leave the sink and will not contribute downstream, while under high flows, they will fill and spill over the sink boundary and eventually contribute to the flow downstream.
2) Known streams. Known streams represent observed drainage patterns captured as a vector polyline layer. The expectation is that the drainage pattern generated by the DEM will match the drainage pattern represented by the vector layer.
3) Known lakes. Known lakes represent observed lakes captured as a vector polygon layer. Lakes can be either sinks, where all the water drains into the lake and none comes out, or they can have an outlet stream (in which case the water entering the lake will exit through the stream draining the lake).
4) Known drainage area boundaries. Known drainage area boundaries represent known boundaries captured as vector polygon layers. Any "droplet" of water will stay within the drainage boundaries and drain either to the sink within the drainage area or to one drainage area outlet point.

The HydroDEM will satisfy behavior with respect to all four key drainage elements. The main derived layer for terrain analysis is the flow direction grid as that grid defines the path a drop of water (or a marble) would follow from the location where it was dropped until it is either captured by a sink or it exits the extent of the terrain (reaches the "end of the known world" as defined by the DEM extent).

This paper will present a stepwise approach for development of HydroDEM using Arc Hydro tools and general ArcGIS functionality. It will start with simple situations and then introduce additional flow path complexities. The first step will be establishment of proper flow direction grid, followed by development of drainage system elements.

Operation of individual functions and their parameters is not discussed here in details. Use Arc Hydro help or Arc Hydro documentation to get detailed explanation of the tool operation and their input parameters. Default values for tool parameters present an attempt to provide values that will work well in most cases, but due to the diversity of terrains, the user will often have to rerun the same function with different parameter values before the best result can be obtained.

1.3 Data

Several DEMs (all draining into the Gulf side of Florida) and supporting data will be used in this paper to demonstrate the key processing concepts. Here is a brief description of each:

Dataset Name	DEM Name	DEM Type	Size (cells)	Size (MB)	Cell size
Homosassa	dem10c	float	2750 x 2268	24	10 ft
Webster	webster5	float	3041 x 3041	35	5 ft
Hillsborough	hillsdem	float	536 x 556	1.14	100 m

Table 1. Description of base DEMs used in this paper.

2.0 Performance Issues

The maximum size of DEM that can be successfully processed depends on the computer specifications, the number of cells the DEM has, and operation being performed. For most common computers that can run ArcGIS software reasonably well, DEMs bigger than 20,000 by 20,000 cells will cause problems and potentially produce uncertain results (the function might or might not complete). This is particularly the case for the fill sinks function that is the most demanding one. In ArcGIS 9.3, the fill function has been rewritten and dramatically decreases the processing times compared to previous versions of ArcGIS.

In terms of complexity and resources demands on the hardware the most demanding core DEM processing functions are (in the order of complexity):

1. Fill sinks (except in ArcGIS 9.3)
2. Flow accumulation
3. Flow direction

If the terrain to be modeled is too large, the terrain will have to be split into parts and then processed one part at a time. Arc Hydro has the capability to utilize large DEM datasets partitioned into multiple parts (referred to as “Global” functionality). Partitioning and processing of these DEMs is not discussed in this document.

> **TECHNICAL NOTE.** The Windows registry key:
> `HKEY_LOCAL_MACHINE\SOFTWARE\ESRI\Raster\Preferences\grid.max_table_range`
> contains the maximum number of records that are allowed for creation of VAT (STA) for a grid. The default is 65536. When processing large DEM, that number might be too small and the function will fail (especially when performing fill sinks operation). Increasing that number (e.g. to 1000000) might fix a problem.

2.1 Selection of DEM Type: Floating point vs. Integer

DEMs come in two formats – integers or floating points. It can be beneficial to convert the floating point DEM into integer DEM before terrain preprocessing. There are several benefits, including reduction in DEM size, reduction in the number of sinks, and faster performance.

The approach to make the DEM an integer GRID is as follows:

1. Find the vertical accuracy of the z measurement for the DEM (e.g. 1/10th of a foot) and from it identify number of significant digits that DEM actually contains. You might have to do vertical unit conversion to get the right number (e.g. if the vertical units for the DEM are in feet, than DEM is precise to one significant digit).
2. Determine if you want to add another significant digit to accommodate any rounding errors (e.g. in our example we might round up to two significant digits, or keep it at one – we’ll choose one).

3. Take the number of significant digits from step #2 (n) and calculate the multiplier as 10^n (e.g. n=1 and the multiplier is 10^1=10).
4. In the Raster Calculator (available from Spatial Analyst toolbar), multiply the DEM by the multiplier and then integer the result (e.g. INT(([elevationDEM] + 0.05) * 10). Since the INT() function truncates the values, 0.05 (0.5/multiplier = 0.05) will be added to the DEM to achieve the rounding to the first significant digit.

Arc Hydro tools will manage different horizontal and vertical units if that is specified in the DEM's prj file (otherwise the tools will assume that the horizontal and vertical units are the same). It is strongly recommended that the prj file for the integer DEM is immediately updated after the calculation is completed to reflect the difference in horizontal and vertical units. The Arc Hydro tools help describes how to update the prj file in the "Define ground unit and z-unit" topic in the "How to …" chapter.

2.1.1 Homosassa Example

For comparison, 1, 10, and 100 multipliers were applied to the Homosassa DEM, producing dem10ci1, dem10ci10, and dem10ci100 DEMs respectively. The following table presents the difference in size of the DEMs.

Dataset Name	DEM Name	DEM Type	Size (MB) uncompressed	Size (MB) compressed
Homosassa	dem10c	Float	24	N/A
Homosassa	dem10ci1	Integer	6	2
Homosassa	dem10ci10	Integer	12	5
Homosassa	dem10ci100	Integer	12	9

Table 2. Description of DEMs for comparison of float vs. integer issues for Homosassa dataset.

For each DEM a series of operations were performed and timed.
1. Flow direction. For all cases, it took about 12 seconds to perform the calculations.
2. Calculate the number of sinks. For all cases, it took about 5 seconds to perform the calculations. For each of the four DEMs, a different number of sinks and areas identified as sinks were identified. Table 3 presents the results.
3. Fill sinks. There was variability in processing times – these are presented in Table 3 as well. For ArcGIS 9.2, these times were at least an order of magnitude slower (3-4 minutes as opposed to about 15 seconds).
4. Flow accumulation. For all cases, it took about 34 seconds to perform the calculations.

DEM Name	Number of sinks	Number of cells in sinks	Time to fill sinks (min:sec)
dem10c	1353	108,286	0:15
dem10ci1	499	301,340	0:07
dem10ci10	978	122,935	0:10
dem10ci100	1277	109,351	0:10

Table 3. Sink processing results for Homosassa dataset.

The DEM processing results indicate that converting a floating point grid into an integer elevation grid produces smaller DEMs that process faster (specially for more complex operations). It is also important to note that with DEM generalization (smaller multiplier), the number of identified sinks decreases and its extent increases. It is expected that for larger DEMs (# of cells), these distinctions will be even more pronounced.

2.1.2 Webster Example

To compare the impact of the size of DEM, the Webster dataset was used to perform similar exercise. Webster dataset is about 50% bigger than the Homosassa dataset (~9,000,000 vs. 6,000,000 cells). The original and integer grids scaled by 1 and 100 were processed (webster5, webster5i1, and webster5i100 DEM respectively).

Dataset Name	DEM Name	DEM Type	Size (MB) uncompressed	Size (MB) Compressed
Webster	webster5	Float	35	N/A
Webster	webster5i1	Integer	9	3
Webster	webster5i100	Integer	18	16

Table 4. Description of DEMs for comparison of float vs. integer issues for Webster dataset.

For each DEM a series of operations were performed and timed.

1. Flow direction (Table 5). It is interesting to note that the performance was not as uniform as for the Homosassa dataset.
2. Calculate the number of sinks. For all cases, it took about 15 seconds to perform the calculations. For each of the three DEMs, a different number of sinks and areas identified as sinks were identified. Table 5 presents the results.
3. Fill sinks. There was variability in processing times – these are presented in Table 5. The difference between the times to fill sinks between the 9.2 and 9.3 versions of ArcGIS were even more pronounced in absolute times (20 seconds vs. 8 minutes), but are still in the order of magnitude in reduction.
4. Flow accumulation. For all cases, it took about one minute to perform the calculations.

DEM Name	Number of sinks	Number of cells in sinks	Time to calculate flow direction (min:sec)	Time to fill sinks (min:sec)
Webster5	204,187	457,021	0:10	0:20
Webster5i1	17,741	418,188	0:29	0:08
Webster5i100	189,494	436,322	0:10	0:20

Table 5. Sink processing results for Webster dataset.

2.2 Recommendations

To streamline DEM processing:

1. Upgrade to ArcGIS 9.3.
2. Develop an integer grid of elevations using DEM vertical accuracy as a guideline.
3. Do not be conservative with the number of significant digits used to make the integer grid as that can have significant impact on later processing times without contributing to the accuracy of the process. Try to match rounding to the vertical accuracy of the DEM as closely as possible.
4. Immediately update the prj file for the integer DEM to capture the difference in horizontal and vertical units.
5. Limit the spatial extent of the area to be processed as the increase in DEM size significantly increases processing time and analyst involvement (i.e. do not include in the DEM the neighboring areas that are known not to contribute to the area being analyzed).

3.0 Preprocessing Dendritic Terrains

Dendritic drainage pattern is characterized by a stream system where the streams merge at confluences going downstream. In this pattern, there are no inner basins (areas draining into sinks – endorheic drainage basins) and the drainage basin is drained through the main drainage stem at the outlet of the basin. It is possible to have flow splits (bifurcations or braided streams).

This chapter first presents the basic processing of dendritic terrains to establish the overall processing methodology. It then expands on the basic process to include some special cases where there is better knowledge of the existing drainage patterns and describes techniques on how to impose that knowledge into the processed terrain.

3.1 Basic Dendritic Terrain Processing

Basic dendritic processing involves processing of the DEM only. No additional information is used, so all the drainage patterns are determined exclusively from DEM characteristics. Appendix 1 presents workflow for basic dendritic terrain processing.

3.1.1 Basic Flow Direction Determination

Defining flow direction for a dendritic terrain is a fairly simple process. Since there are no sinks in a dendritic configuration, the first step is to fill sinks. This can be accomplished using the "Fill Sinks" function under the "Terrain Preprocessing -> DEM Manipulation" Arc Hydro menu. Make sure that the "Deranged Polygon" entry in the form is set to "Null" and that "Fill All" radio button is active. This function will insure that all the sinks in the original terrain are filled and that all the water in the drainage basin is routed into the stream system. The function will generate the "filled DEM" with no sinks in it.

Once the sinks have been filled, the flow direction can be established by running the "Flow Direction" function in the "Terrain Preprocessing" Arc Hydro menu. Input into this function is the filled DEM. The flow direction function generates a grid that defines for each cell the steepest descent direction based on the eight neighboring cells (D8 method). Flow direction grid should have only eight distinct values (1, 2, 4, 8, 16, 32, 64, and 128). If not, that is an indication that the sinks were not filled successfully.

3.1.2 Basic Drainage System Definition

Once the sinks have been filled and the flow direction grid is established, the rest of the terrain preprocessing steps include (in this order):

1. Flow Accumulation. The flow accumulation step generates a grid that contains a number of upstream cells that drain through each cell.

2. Stream Definition. The stream definition step identifies those cells that are “streams”. The streams are defined as those cells that drain more area than a user specified threshold (also referred to as “synthetic streams”). The users should keep the threshold to the default value of 1% of the maximum flow accumulation value, or maybe bring it down to 0.5%. The threshold and the resulting drainage lines are used for optimization of the performance for subsequent operations. Reducing the threshold below 0.5% does not improve the performance and complicates the remaining preprocessing steps, so it should be avoided. Increasing the threshold can also be done, but increasing it significantly above 1% might have performance ramifications (slower watershed delineation and characterization).
3. Stream Segmentation. The stream segmentation step uniquely numbers stream segments (links) between the confluences. Make sure that the “Sink Link Grid” and “Sink Watershed Grid” entries in the form are set to “Null” (to ensure that the whole DEM is processed).
4. Catchment Grid Delineation. The catchment grid delineation step identifies drainage areas (in grid format) that drain to each stream link.
5. Catchment Polygon Processing. The catchment polygon processing step defines catchments in vector format.
6. Drainage Line Processing. The drainage line processing step defines stream segments in vector format.
7. Adjoint Catchment Processing. The adjoint catchment processing step determines the cumulative area upstream from a catchment (in vector format).

All these steps (using the functions with the matching name to the step to be executed) are performed from the Arc Hydro tools “Terrain Preprocessing” menu. After each step, the results should be reviewed since the following steps will not produce good results if the previous steps did not produce good results. Some critical things to look for:

- Flow direction grid should have only eight distinct values (1, 2, 4, 8, 16, 32, 64, and 128).
- After the flow direction has been computed, it is good to use the “Flow Path Tracing” tool in Arc Hydro and randomly trace downstream from a number of different locations in the DEM. If there are any significant drainage inconsistencies, they can be rather easily identified (visually). Any flow path issues need to be addressed immediately by generating the correct flow direction grid before proceeding with the next preprocessing steps (how to correct those will be discussed later on). The inconstancies might include:
    i. Flow path is not reaching the DEM edges (there are sinks in the DEM).
    ii. Flow paths are not following the perceived streams (might need to burn the streams).
    iii. Flow paths are not following the perceived drainage boundaries (might need to fence the boundaries).
- The number of stream segments should match the number of catchments. In general, that number should be less than 1,000. For a 25,000,000 cell DEM, 50-100 stream segments/catchments is a good number.

3.1.3 Homosassa Example

The eight preprocessing steps were performed for the Homosassa DEM. A 40,000 cell threshold was used to define streams, resulting in 56 distinct drainage lines (stream segments) and catchments. The times to perform each step (pure processing – not including user populating the input forms associated with each tool) are presented in Table 6.

Function	Time (sec)	Function	Time (sec)
Flow direction	15	Catchment grid delineation	8
Flow accumulation	32	Catchment polygon processing	9
Stream definition	6	Drainage line processing	4
Stream segmentation	3	Adjoint catchment processing	8

Table 6. Times of execution for terrain preprocessing functions for Homosassa DEM.

These times should be used with caution. As already demonstrated, larger terrains will require longer processing time. The processing times are not linear with the size of the DEM, so extrapolation of processing times should be done only to get rough estimates. Also, the processing times will depend on other factors, such as the number of drainage lines/catchments defined for the DEM. The larger number of drainage lines will significantly increase processing times for vector functions, in particular processing adjoint catchments (as it involves upstream tracing).

Figure 1. presents the resulting catchments and drainage lines superimposed on the hillshaded DEM. The hillshade was done on the original DEM, so it still shows the areas that were filled to get the depressionless DEM. In general, once the flow direction grid is established, a 25,000,000 cell DEM (which would be typical for an 8-digit HUC 30m DEM), can be preprocessed in about 20 minutes including quality checks.

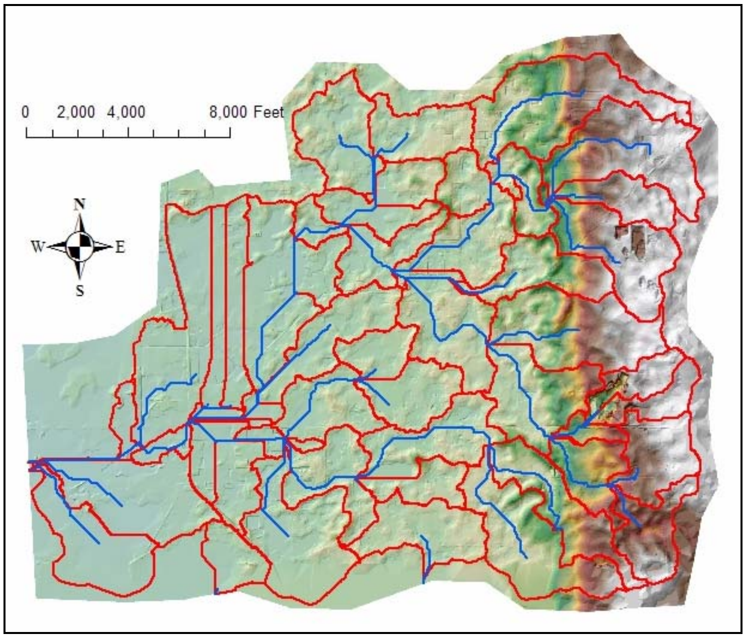


Figure 1. Homosassa DEM with catchments and drainage lines for a 40,000 cell threshold.

3.2 Modifying Basic Dendritic Flow Patterns

At times, the drainage pattern established through basic DEM processing is not adequate and needs to be supplemented with additional information. Four special cases will be discussed:

1. Imposing known streams
2. Imposing flow pattern through lakes
3. Imposing known drainage boundaries
4. Imposing flow splits

The purpose of these four cases is to establish an improved flow direction grid that better represents the known flow patterns in the DEM. The supplemental information should be of the same origin (accuracy and time) as the DEM, otherwise inconsistent and unexpected results can happen (this is not related to how the tools operate, but rather to the coherency of the results).

The final result in all four cases is the modified flow direction grid. To complete the definition of the drainage system once the updated flow direction is defined, steps presented in section 3.1.2 need to be completed.

3.2.1 Imposing Known Drainage Pattern – Streams

If stream system over the landscape is known and the drainage pattern generated by the DEM is not matching it, it is possible to “impose” the known drainage pattern into the DEM. The methodology is known as “burning” in the streams. Burning the streams should not be taken lightly. The analyst should understand why there is a discrepancy between the DEM generated flow patterns and those that are “known”. It is recommended that the only time to burn the streams is when the sources of the data for the DEM and for known streams are the same (in scale and time), and when the discrepancies in the patterns are due to the artifacts of the DEM construction and D8 flow direction determination. Burning should not be used when the data sources are of different scale or age.

In most cases, burning can enhance the DEM flow patterns in terrains with low relief (flat areas) since D8 method often generates unnatural results. If the original elevation data used to generate the DEM are available, it is a better solution to rebuild the DEM using the original elevation data supplemented by the stream data using one of the advanced terrain building functions/tools (such as TOPOGRID), than to burn in the streams into the DEM.

In Arc Hydro tools, the “DEM Reconditioning” function under “Terrain Preprocessing -> DEM Manipulation” menu performs the stream burning. Before executing the function, the know stream layer to be imposed onto the DEM should be “cleaned”. The clean stream dataset to be used in the burning process should:

- Have only the main stems of the stream system (eliminate braids).
- Be dendritic (flow split management will be described later).
- Extend the most downstream reach beyond the watershed boundary if necessary.
- Ensure that the buffers around streams with the distance equal to the one specified in the function’s UI (“Stream buffer (no of cells”)) are completely within the watershed boundary (except for the most downstream stream segment).

The burning process implemented in the Arc Hydro tools follows the AGREE method (Hellweger, 1997). The process might take several iterations to get acceptable results (by changing the three input parameters). After the function is completed, make sure to fill the sinks to eliminate any potential depressions introduced by the burning process.

Appendix 2 presents workflow for imposing the known stream drainage patterns.

3.2.1.1 Homosassa Example

As an example, a known stream layer was developed for the Homosassa dataset ("mainstem" layer), Figure 2.

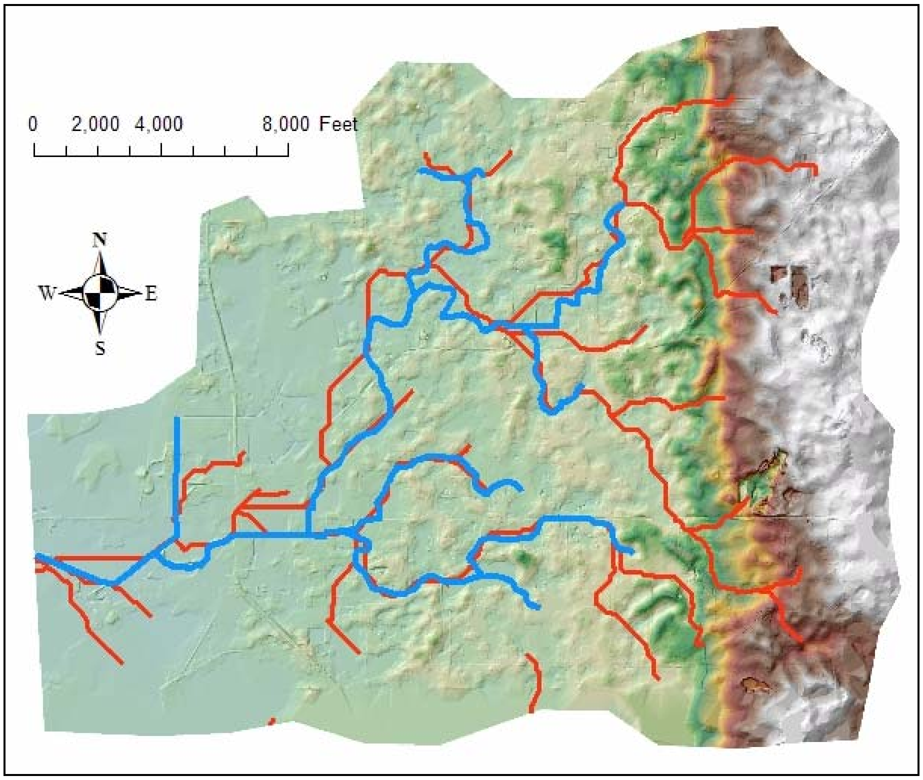


Figure 2. Synthetic (red) and known (blue) stream layers for Homosassa DEM.

The known stream layer was used to burn the streams into the (filled) DEM. The standard AGREE parameters were used (Figure 3). The process took about fifty (50) seconds to execute (one of the most expensive operations).

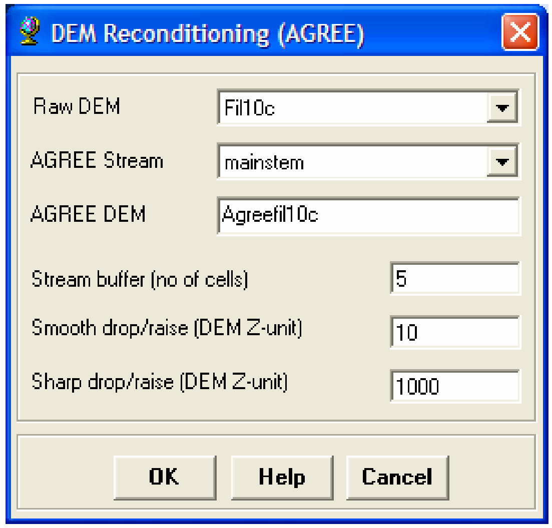


Figure 3. DEM Reconditioning input form for Homosassa DEM.

Once the streams have been burned in, the rest of the preprocessing steps were executed (including filling sinks and computing flow direction). The process generated 47 drainage lines and catchments compared to 56 for DEM that did not have the streams burned in. Figure 4. presents the resulting drainage lines and catchments after the streams have been burned.

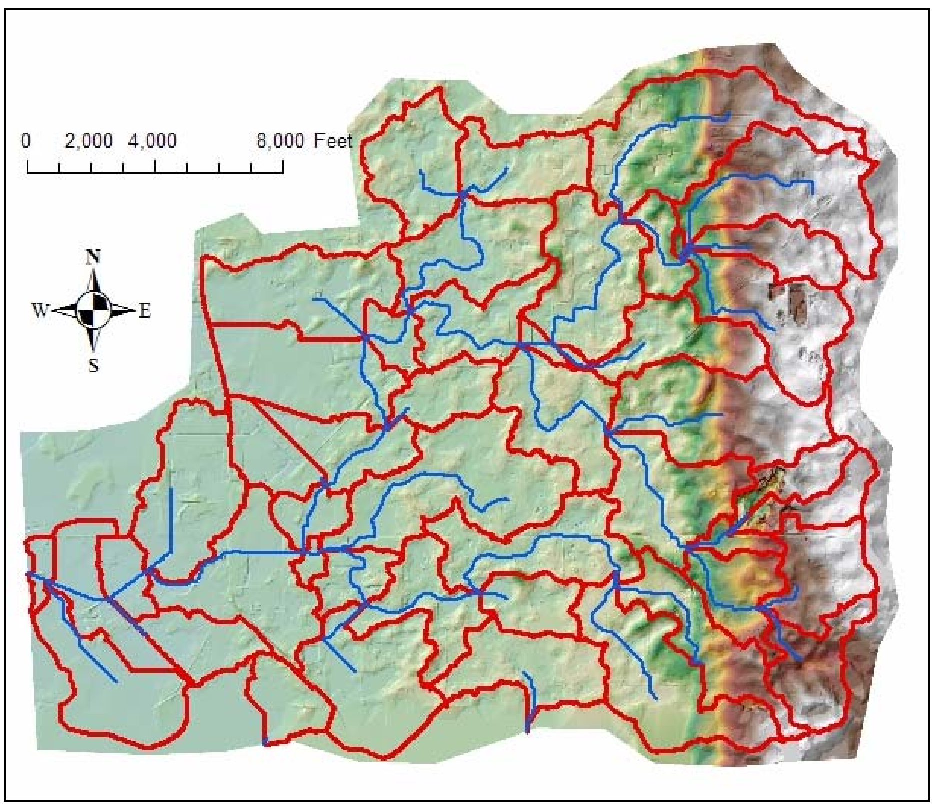


Figure 4. Homosassa DEM with catchments and drainage lines for a 40,000 cell threshold and burned streams.

Figure 5. presents the two sets of catchments developed using a 40,000 cell threshold for the DEM without (yellow) and the DEM with burned streams (red). The burned streams are presented as a reference (blue). The impact of burned streams can be quite dramatic, specially in flat areas where automated methods for flow direction determination are limited (such as in the NW portion of the Homosassa DEM).

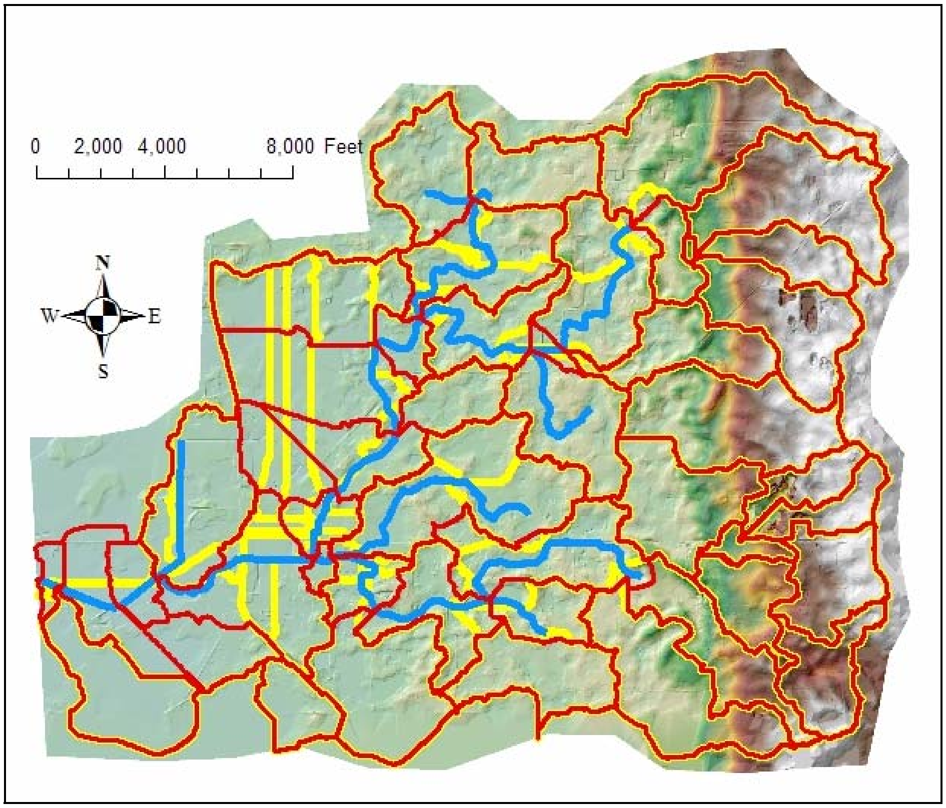


Figure 5. Catchments based for a 40,000 cell threshold for a DEM without (yellow) and the DEM with burned streams (red). Burned streams are in blue.

3.2.2 Imposing Known Drainage Pattern – Lakes

When lakes are present in the system, they can be either in an enclosed basin (the lake is the water body into which the whole drainage area drains into), or they can be drained by the stream. When a lake is drained by the stream, it is expected that once a drop of water reaches the lake shore, it will exit the lake through the stream that drains it. The regular DEM preprocessing, even with burned streams, does not guarantee such behavior. This is specially the case in large flat areas where the D8 method can generate multiple parallel "streams". To impose the flow pattern through lakes, the "Adjust Flow Direction in Lakes" function under "Terrain Preprocessing" menu can be used. Before executing the function, the known stream layer and the known lake layer need to be available. Only those lakes that have streams going through them (at least one) will be processed. A stream should have only one entry and one exit from the lake (multiple inflows and outflows from the lake might produce unexpected results).

This function modifies an existing flow direction grid (unlike the DEM Reconditioning that modifies a DEM). The input into the function should be the flow direction grid that had the streams already burned in (if at all). If the stream layer is not available, then the synthetic streams can be used.

Appendix 3 presents workflow for imposing flow direction within lakes.

3.2.2.1 Homosassa Example

For 17 lakes in the DEM, the bowling process took 35 seconds to execute. Figure 6. shows the flow traces from several locations around one of the lakes before and after the flow direction was modified within the lake.

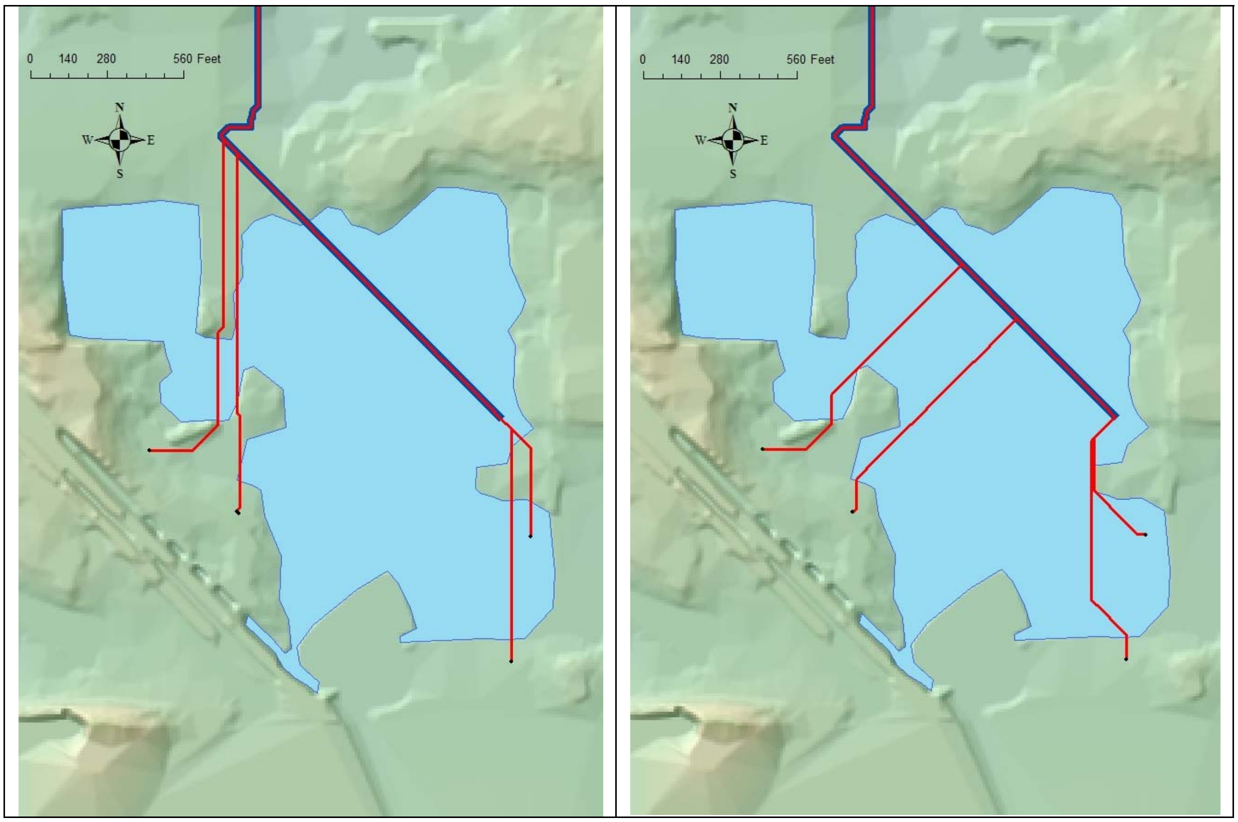


Figure 6. Flow traces through a lake for DEM without modified lake flow direction (left) and with the modified lake flow direction (right). The thin red lines are the flow traces, while the thick blue line is the stream draining the lake.

3.2.3 Imposing Known Drainage Pattern - Drainage Boundaries

At times, main drainage boundaries are known for the area of interest. If the DEM does not reflect the expected drainage boundaries, they can be imposed onto the DEM. This process is often called walling or fencing. It is conceptually the same as the stream burning, only in this case the known vector information is not "pushed" into the terrain (burned in), but rather "pulled" out of the terrain (fenced out).

The same considerations about the quality of the superimposed data as for the stream burning need to be observed (accuracy and timeliness). Two types of "walls" can be built.

- Outer walls. Outer walls define the main watershed boundary. Any terrain outside of the outer wall will not contribute to the flow within the watershed.
- Inner walls. Inner walls provide internal subdelineation within the main watershed. The terrain within inner walls will eventually contribute to the flow and exit the watershed through its drainage system.

In order for water to be able to get out of the walled areas, a "breach line" layer needs to be specified. Breach lines define the locations in the walls where the water will be able to get out of the enclosed area. Breach lines are normally the drainage lines (streams) for the DEM.

In Arc Hydro tools, the "Build Walls" function under "Terrain Preprocessing -> DEM Manipulation" menu builds walls. Appendix 4 presents workflow for imposing drainage boundaries onto the DEM.

3.2.3.1 Homosassa Example

A known drainage boundary dataset comprising of the inner wall, outer wall, and breach line feature classes were developed based on manual evaluation of the drainage system for the Homosassa dataset (InnerWall, OuterWall, and BreachLineFAf10c40k layers respectively), Figure 7.

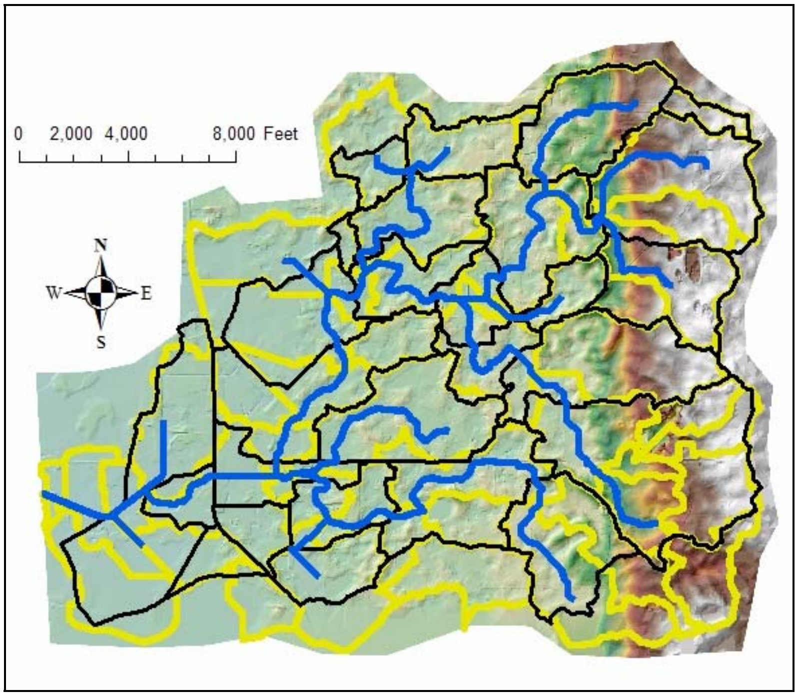


Figure 7. Manually defined drainage areas (black) and breach lines (blue). For reference, catchments developed in example 3.2.1.1 are presented as well (yellow).

There are several areas where significant differences between the catchments developed using automated and manual methods exist. To impose the drainage areas, the “Build Walls” function was run (the reconditioned DEM was used as the base). The standard Build Walls parameters were used (Figure 8). The process took about sixty five (65) seconds to execute (one of the more expensive operations). After the walls were built, the resulting DEM was not filled (this might or might not be the desired process – see later discussion).

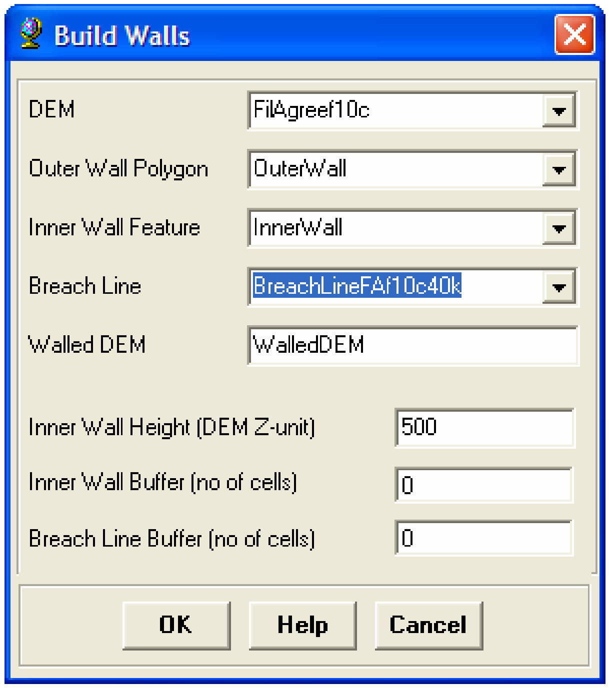


Figure 8. Build Wall input form for Homosassa DEM.

Next several figures present the changes in the drainage pattern introduced by the walling. Several key behaviors can be observed.

- Introduction of pits back into the terrain (Figure 9). This will occur if an inner basin is not breached by a breach line. This behavior can be circumvented by filling the sinks after walling, or by extending the breach lines into all the internal drainage areas so that each subbasin has at least one outlet breached.
- Exclusion of contributing areas (Figure 10).
- Redirection of flow (Figure 11).
- Inclusion of areas that contribute to the flow (Figure 12).
- Inclusion of areas that do not contribute to the flow (Figure 13). This behavior can be circumvented by filling the sinks after walling is done.

The walling process can introduce many positive and negative artifacts. It is important to perform detailed quality control on the new flow patterns after this process. If necessary, the wall boundaries and breach lines can be modified and the process repeated until the satisfactory results are obtained.

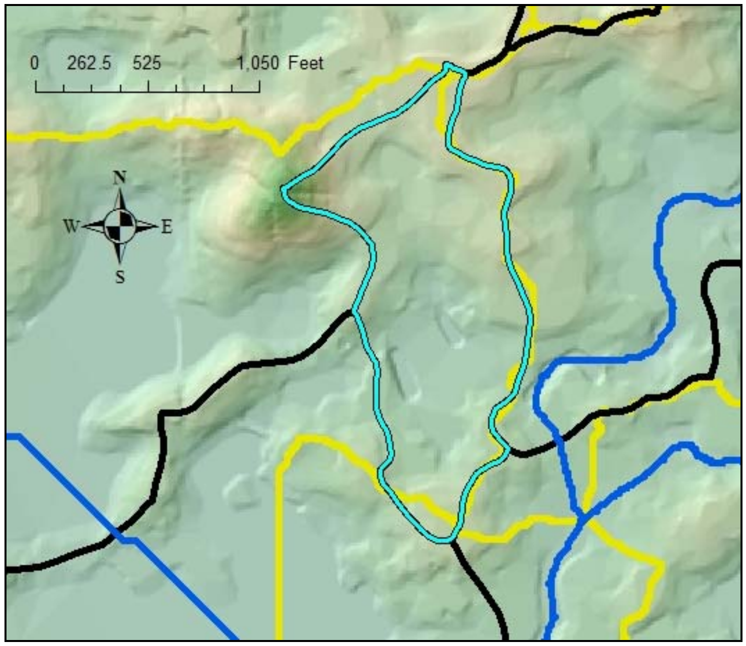


Figure 9. Introduction of pits into the DEM due to the lack of a breach line (blue) crossing the imposed boundary (black). The problem subbasin is highlighted in light blue. For reference, catchments developed in example 3.2.1.1 are presented in yellow.

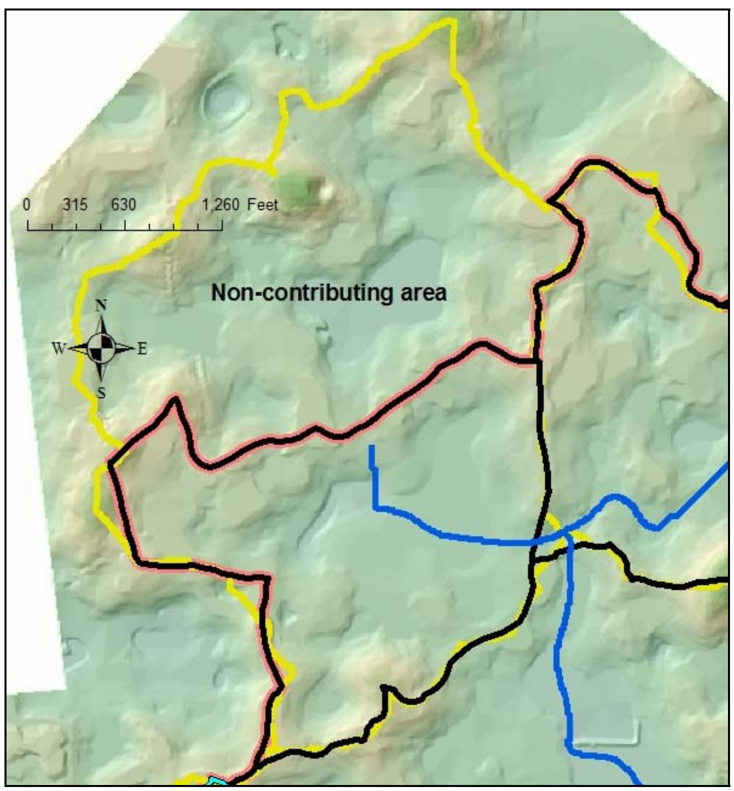


Figure 10. Non-contributing area is introduced since it resides outside of the outer wall (peach). For reference, catchments developed in example 3.2.1.1 are presented in yellow.

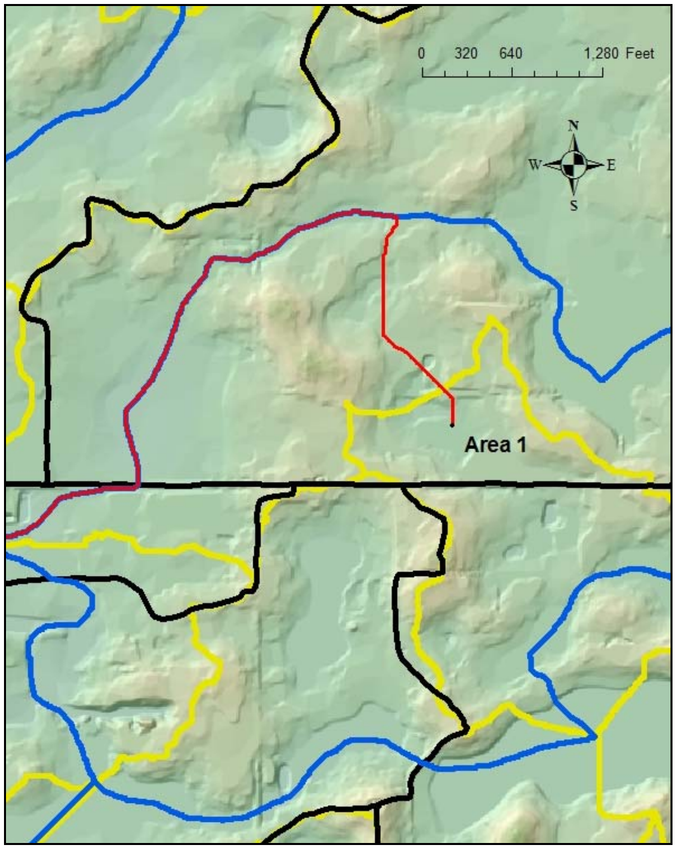


Figure 11. Area 1 (between the yellow and black lines) now flows North (red line), where as before it used to flow South. For reference, catchments developed in example 3.2.1.1 are presented in yellow.

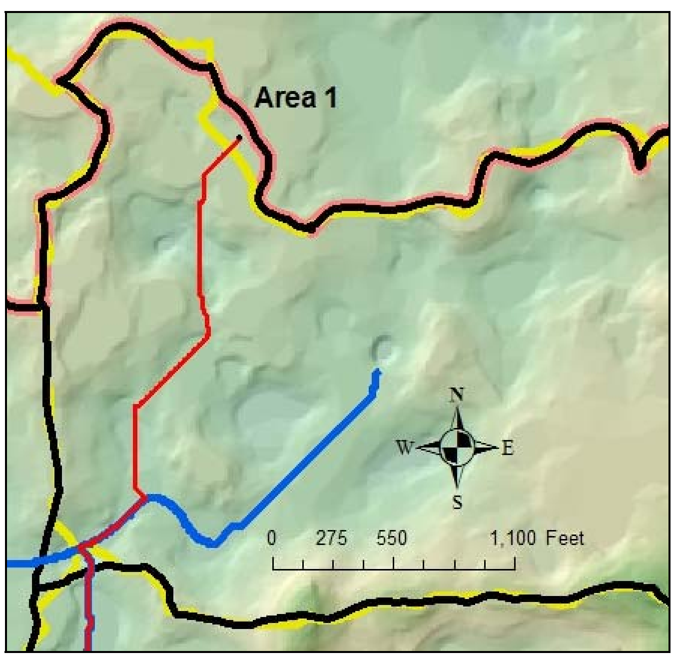


Figure 12. Area 1 (between the yellow and peach/black lines) now flows South (red line) and contributes to the flow in the main watershed, where as before it used to flow North and not contribute.

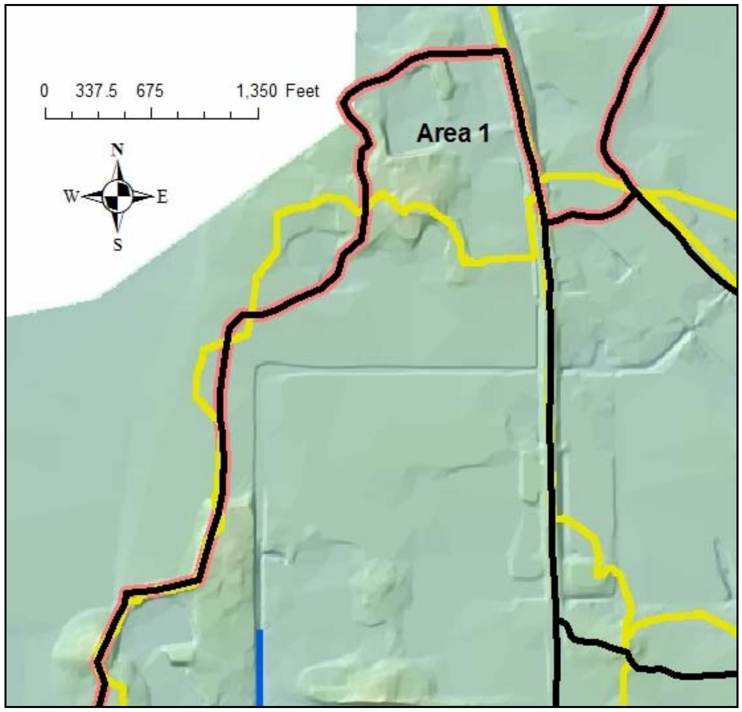


Figure 13. Area 1 (between the yellow and peach/black lines) appears to be included in the contributing area. Upon inspection using the flow trace tool, the flow traces do not flow South (as might be expected). Instead Area 1 is now a pitted area that does not contribute to the flow.

3.2.4. Imposing Known Drainage Pattern – Flow Splits and Circular Patterns

All the techniques for flow pattern modification presented so far dealt with non-braided systems. Imposing a braided system into an existing DEM is similar to imposing a non-braided stream system (Section 3.2.1), but it includes several more steps. The key problem to overcome is the inability of D8 method to "split" the flow direction at a given cell in the raster world.

Besides the DEM to process, the user needs to have a vector representation of the stream system. The stream layer must be "clean" as described in Section 3.2.1, but it can have the braids. The "flow" direction (digitized direction) for stream segments in a braid should be in the predominant flow direction.

The following steps have to be performed (in the specified order):

1. Impose the stream system into the DEM (same as steps described in 3.2.1).
2. Generate flow direction grid for the DEM with imposed streams.
3. Run "Flow Direction with Streams" function from the "Terrain Preprocessing" Arc Hydro menu. This function operates on the existing flow direction grid and modifies it under the stream so that the flow direction in the cells under the stream are enforced based on the direction defined by the stream lines. This function generates several other layers that will be discussed in section 3.3 (not important for this workflow).

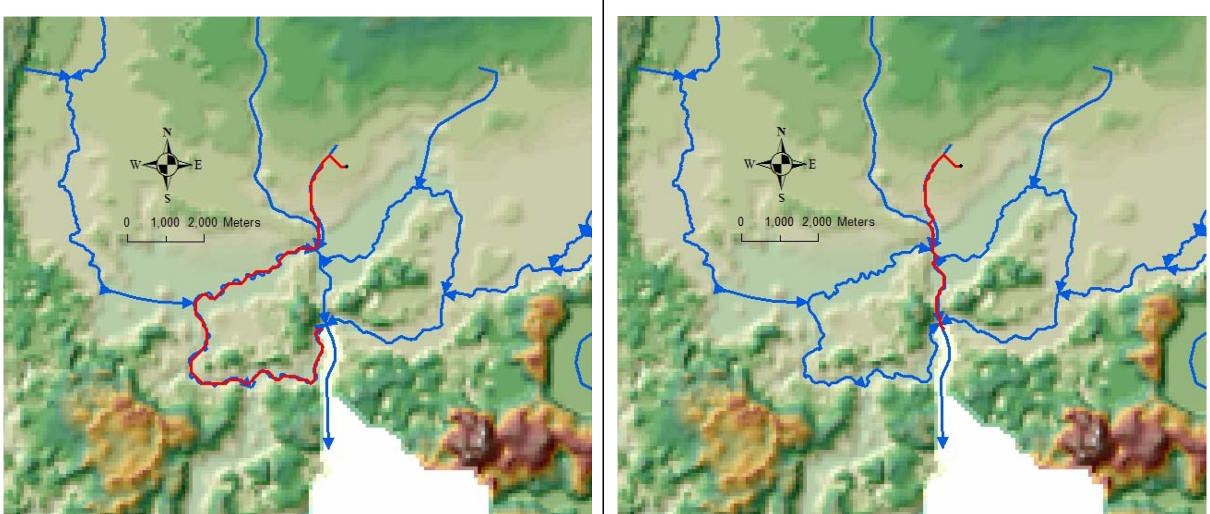
This process generates a flow direction grid that follows stream's digitized direction. Appendix 5 presents workflow for imposing braided flow patterns onto the DEM.

Section 3.3 will discuss how to impose the braided catchment delineation (or for that matter, any catchment delineation where the user wants to impose their own drainage lines as the input).

3.2.4.1 Hillsborough Example

Figure 14. presents the impact of applying "Flow Direction with Streams" process. Part a) shows a flow trace based on the DEM where the streams were burned using the "DEM Reconditioning" process only. Notice how the trace abruptly changes direction from South towards West (contrary to the digitized direction along the stream indicated by the arrow at the to_node of the stream segment) and then loops until it exits the terrain. Part b) shows a flow trace from the same point after the terrain was processed using the "Flow Direction with Streams" function. The trace follows the South direction all the way through.

This problem is caused by the lack of elevation detail in the DEM. The D8 method does not have enough elevation information at the confluence and will sometimes generate unexpected results. Imposing the elevation along the streams alleviates that problem. For this function to work properly, the user has to insure that the stream network is properly oriented (downstream). This might require some additional work in data preparation, but is a good overall approach to data development (as this data can be used for other purposes where the directionality is important, such as flow tracing through stream network).



(a) (b)

Figure 14. Flow trace (red) from the same location for terrain: (a) that was only reconditioned and (b) that on top of reconditioning had the stream slope assigned. Imposing the slope prevented the flow direction to go against the direction of the stream segment.

3.3 Imposing Drainage System Definition – User Defined Drainage Lines and Catchments

There are times when the basic drainage system definition described in section 3.1.2 does not produce acceptable results. In general, these should be rare occasions, because as stated earlier, the preprocessing steps are primarily geared towards optimization of the performance and quality control, not for achieving a specific end result that meets certain application requirements.

Once the acceptable flow direction grid is established, drainage system definition includes development of drainage lines, catchments, and adjoint catchments (in vector representation, and for the first two layers in raster representation as well). The standard Arc Hydro methodology uses synthetic streams generated from flow accumulation grid and a user specified threshold as the base from which to identify the drainage lines (stream links). If user has a vector layer that has drainage lines already defined, it is possible to use them in the process instead of the synthetic streams.

The stream layer to be used for drainage lines has to satisfy several requirements:

- Features (streams) need to be snapped at confluences.
- Features need to be digitized in downstream direction.
- Each feature has to have a unique integer identifier (HydroID will work well).
- Feature class needs to have a GridID field (long integer). The values in GridID have to be the same as in HydroID.

The stream layer should be used for DEM reconditioning to produce the Agree DEM and consequently the flow direction grid to be used in the analysis. If the stream layer contains braided streams, process described in section 3.2.4 should be applied as well (in that case, skip step #2 – Flow Direction with Streams as it will already be executed). Once the stream feature class and flow direction grid are properly developed the rest of the terrain preprocessing steps include (in this order):

1. *Optional.* Flow Accumulation (same as for the basic terrain preprocessing). The flow accumulation grid is not required for this process, but might be later on, so it is a good practice to do this step now.
2. Flow Direction with Streams. This function besides the updated flow direction grid also generates:
    a. Stream link grid.
    b. Drainage line feature class.
3. Catchment Grid Delineation (same as for the basic terrain preprocessing). The catchment grid delineation step identifies drainage areas (in grid format) that drain to each stream link developed in step 2 (make sure that use the flow direction grid and stream link grid developed in step 2 as inputs).
4. Catchment Polygon Processing (same as for the basic terrain preprocessing).
5. ***!!! Notice that we are skipping function "Drainage Line Processing" that is normally executed in standard processing – the drainage line feature class is already generated by the "Flow Direction with Streams" function executed in step #2. !!!***

6. Adjoint Catchment Processing (same as for the basic terrain preprocessing). If there are flow splits, the information about NextDownID for multiple catchments will be stored in the CatFlowSplit table.

Functions for all steps except #2 are found in “Terrain Preprocessing” menu in the Arc Hydro toolbar. Find Next Downstream Line function is in “Attribute Tools” menu in the Arc Hydro toolbar. Appendix 6 presents workflow for alternative dendritic terrain processing.

3.3.1 Hillsborough Example

Figure 15. shows results of basic terrain preprocessing for Hillsborough terrain using the flow direction developed in section 3.2.4.1. Notice several places where the synthetic streams do not match the known streams. There are some synthetic streams where there are no specified streams, and especially in the looped area, there are several specified streams that do not have the matching synthetic stream. For flow split junctions, the synthetic stream generation process will define only one side of the flow split. Also, synthetic streams by definition extend from a confluence to a confluence; while user defined streams can have multiple segments between the confluences.

Figure 16. shows drainage system developed using the user specified drainage lines (stream segments). Notice the difference between the two drainage systems. Figure 17. presents details of catchments in the vicinity of the looped drainage lines.

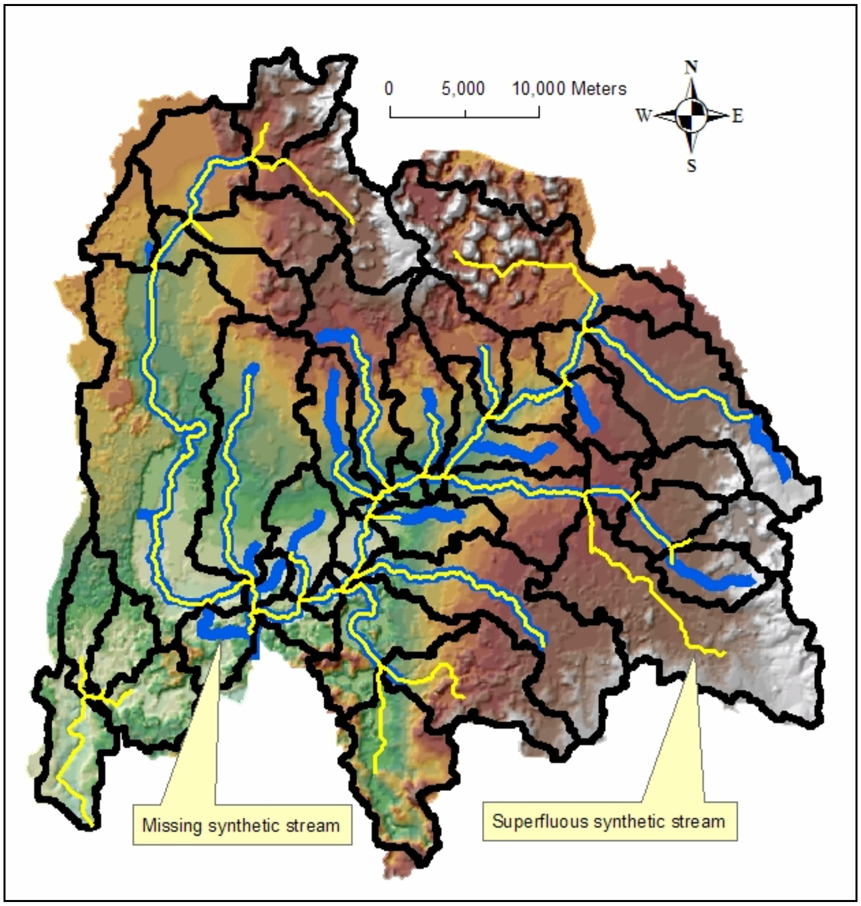


Figure 15. Hillsborough DEM processed using basic Arc Hydro terrain preprocessing using 2,000 cell threshold. Catchments (black) are for the synthetic streams (yellow). User defined streams (blue) are provided for a reference.

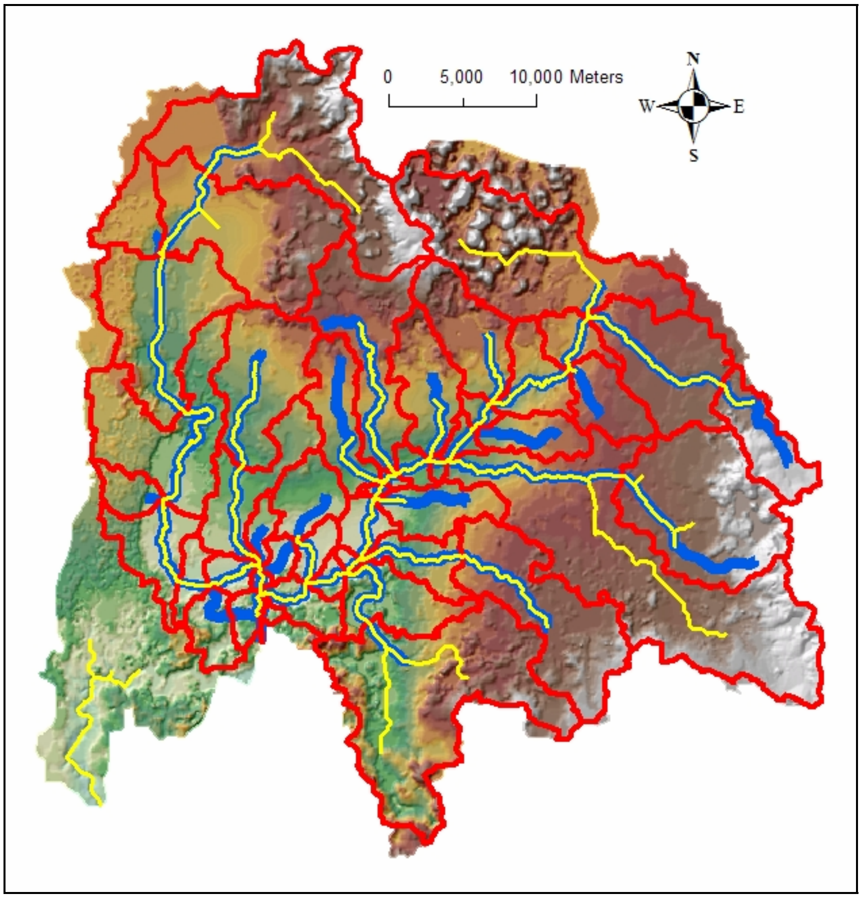


Figure 16. Hillsborough DEM processed using user specified stream segments. Catchments (red) are for the user defined streams (blue). Synthetic streams (yellow) are provided for a reference

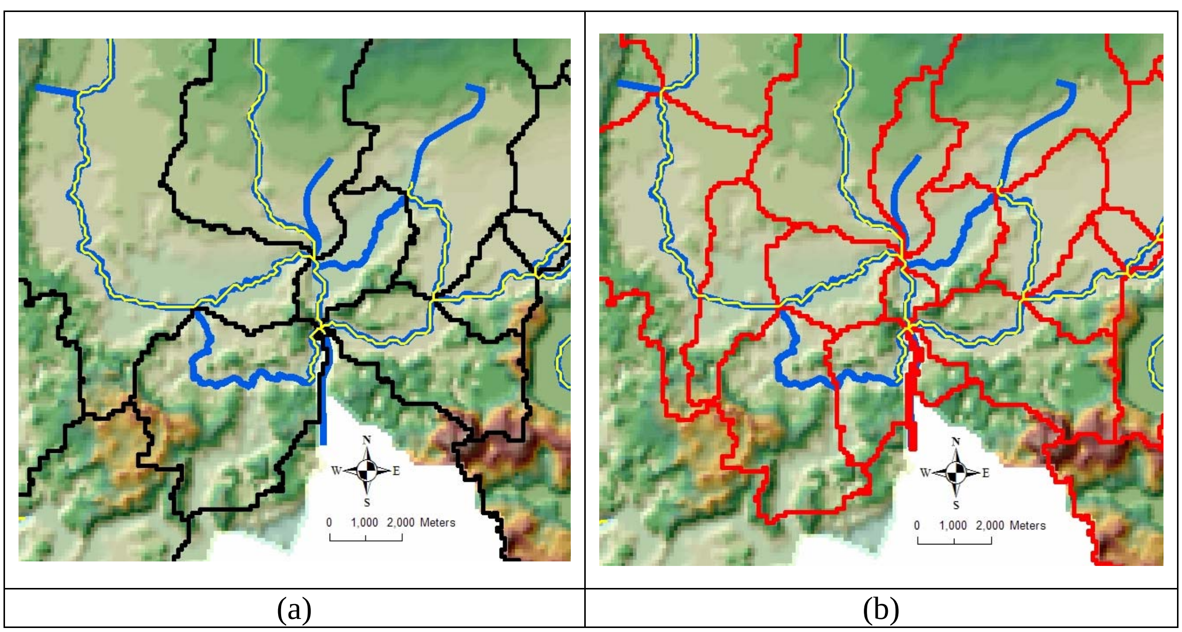


Figure 17. Catchment delineation using: (a) basic preprocessing and (b) imposed stream segments. Notice how in (b) each segment comprising the loop has a catchment associated with it.

4.0 Preprocessing Non-dendritic ("Deranged") Terrains

In non-dendritic or also called deranged terrains, there is not one stream system that collects the water and drains it out of the watershed. There can be many individual drainage areas that drain into depressions/sinks (inner or endorheic drainage basins). Under different hydrologic conditions, some of the inner basins can fill up and spill over into the adjacent drainage basins. These drainage areas can be combined with a dendritic system.

For deranged terrains, the preprocessing is centered on identification of sinks and their inclusion in the flow direction grid. Once the flow direction is established, drainage areas can be determined. A set of morphologic characteristics is computed for each inner basin (elevation-area-volume) as well as for the basin boundaries (elevation-width-area). These characteristics can then be used for computations of water retention within the basins and water movement over the boundaries (in the event that the basin fills up and spills into the neighboring basins).

This chapter first presents the basic processing of deranged terrains to establish the overall processing methodology. It then expands on the basic process to include some special cases where there is better knowledge of the existing drainage patterns.

4.1 Basic Deranged Terrain Processing

For basic deranged terrain processing it is assumed that besides the terrain the user knows the location of the sinks as a set of polygons in a feature class. Sinks can be viewed as bottoms of depressions or known lakes or wetlands that are not drained by a stream. Section 4.2 will present methodology for sink identification based on DEM only (so the user can develop the sink polygon feature class to go into the basic processing described here).

Before starting the deranged terrain analysis, it is recommended that the original DEM is conditioned to reduce spurious data in the DEM. Spurious data can significantly increase processing time without contributing to the understanding of actual flow patterns. Also, if there are know sinks that are small enough so they can be ignored in the analyses, they should be identified with "IsSink=0" in the sink feature class. Three steps are recommended (with caution):

1. Level the DEM where that information is available to remove spurious elevations within the lake/sink. Use Arc Hydro "Level DEM" function from "Terrain Preprocessing -> DEM Manipulation" menu. If elevation in the sink is known it can be specified in a field for each polygon and passed on to the function that will "level" the DEM under the polygon at the specified elevation. If the elevation is not known, the minimum elevation along the polygon boundary will be determined and used for leveling. This function needs to be used carefully. By leveling the lake, it is possible to introduce sinks at the boundary of the lake and the surrounding DEM if lake elevation is higher than the surrounding DEM. This can be avoided by ensuring that the level in the lake is lower than any of surrounding bank cells. If the lakes will be used as sinks, the leveling is not useful for flow direction computations since the elevations within the sinks are

ignored in the processing. The optimal process would include leveling the lakes that are NOT sinks.

2. Make the DEM an integer grid that matches the accuracy of vertical DEM measurements (see section 2.1). This step reduces the number of spurious sinks that are the artifact of using floating points values to too many significant digits.
3. Set IsSink field to 0 for all the sinks in the sink feature class that can be ignored (filled) and to 1 for all the sinks to be preserved.

Appendix 7 presents the basic deranged terrain processing workflow, while Appendix 8 presents the deranged terrain characterization workflow.

4.1.1 Basic Flow Direction Determination

Defining flow direction for a deranged terrain when location of sinks is known is a fairly simple process. The first step is to fill sinks and use the sink feature class to identify which sinks not to fill (the item IsSink for sinks not to be filled should be set to 1). This can be accomplished using the “Fill Sinks” function under the “Terrain Preprocessing -> DEM Manipulation” Arc Hydro menu. This function will insure that all the sinks in the original terrain are filled everywhere except in specified sinks where the original DEM will be maintained. The function will generate the “filled DEM”.

The function uses term “Deranged Polygon” to specify the polygon layer that contains the polygons to be excluded from the filling process. This is a more generic term than sinks, as the polygons we might be interested in filling can include sinks, lakes, depressions, or any combination of these. These polygons can also change with the type of the analysis we are doing, so a more generic term was used to describe this purpose.

Once the sinks have been filled, the flow direction can be established by running the “Flow Direction with Sinks” function under the “Terrain Preprocessing -> DEM Manipulation” Arc Hydro menu. Input into this function is the filled DEM and the deranged polygon (should be the same one used to fill sinks). This function defines the flow direction outside of the sinks based on the input DEM, while within the sinks, the flow direction is derived in a synthetic way, so that it points into a single point somewhere within the sink polygon (in order to facilitate connectivity computations later on). The points will be stored in the sink point feature class.

This function will also create the sink link grid as well as the sink watershed grid. The sink link grid is created by converting the deranged polygons with IsSink=1 into a grid using HydroID as the field for conversion (so each individual sink has a matching grid region with the same identifier). The sink watershed grid defines the areas draining into each of the sink links. The value in this grid is the same as for the sink link grid (HydroID of the sink polygon). These two layers will be used later in the processing.

Since the terrain had sinks, the flow direction grid should have a range of directions between 1 and 255.

4.1.2 Basic Drainage System Definition

Once the terrain has been processed and the flow direction grid is established, the rest of the terrain preprocessing steps include (in this order):

1. Flow Accumulation. The flow accumulation step generates a grid that contains a number of upstream cells that drain through each cell.
2. *(Optional)* Catchment Grid Delineation. The catchment grid delineation step identifies drainage areas (in GRID format) that drain to each sink. As the link grid, pass the sink grid developed in the previous step. This is optional since for pure deranged terrain preprocessing, the catchment grid delineation was generated by the "Flow Direction with Sinks" function (section 4.1.1) as a sink watershed grid.
3. Catchment Polygon Processing. The catchment polygon processing step defines catchments in vector format. These catchments define drainage areas draining into the sinks. Verify that the input catchment grid is correctly pointing to the appropriate grid (which will not necessarily be the case if you skipped step 2 and are using sink watershed grid defined by the flow direction function as the catchment grid).
4. Drainage Point Processing. The drainage point processing step generates points with maximum flow accumulation within each drainage area. These points are the same as the sink points generated during the flow direction computations, except that they are snapped to the center of the cell.
5. *(Optional)* Drainage Area Characterization. This function will generate the elevation-area-volume (EAV) table with information about area and volume for each drainage area (catchment). Make sure you use the raw DEM for these computations.
6. Drainage Boundary Definition. This function will generate:
    a. Drainage boundary feature class (polylineZ) that contains as 3D linear feature of each boundary between drainage areas. The minimum and maximum elevation along that line is also stored in the feature class.
    b. *(Optional)* External boundary feature class (polygon) that contains the outside polygon encompassing all of the drainage areas.
    c. Drainage connectivity (DrainConn) table that specifies the left and right catchments for each drainage boundary (using their respective HydroIDs).
7. *(Optional)* Drainage Boundary Characterization. This function will generate:
    a. Elevation-width-area (EWA) table with information about width and area for each boundary between drainage areas. Make sure you use the raw DEM for these computations.
8. Drainage Connectivity Characterization. This function will generate:
    a. Boundary drainage line. The boundary drainage line feature class (polyline) defines the connectivity between the drainage areas. The connectivity is established by taking the lowest point at the boundary between the two drainage areas, and then trace from that point into each of the drainage areas (the ending point will be the drainage point for that drainage area). Each boundary drainage line knows the boundary it is on (LinkID) as well as which drainage area it is in (DrainID).
    b. Hydro Edge. The hydro edge feature class (polyline) contains the combination of boundary drainage lines and streams (if dendritic component is present). Since process described in this chapter does not include dendritic component, the hydro edges will contain only the boundary drainage lines.

c. Hydro Junction. The hydro junction feature class (point) contains the points that participate in the connectivity. This includes the “centers” of sinks from the drainage point feature class as well as the points on the boundaries.

Steps 1 through 4 (using the functions with the matching name to the step to be executed) are performed from the Arc Hydro tools “Terrain Preprocessing” menu. Steps 5 through 8 (using the functions with the matching name to the step to be executed) are performed from the Arc Hydro tools “Terrain Morphology” menu. After each step, the results should be reviewed since the following steps will not produce good results if the previous steps did not produce good results. Some critical things to look for:

- After the flow direction has been computed, it is good to use the “Flow Path Tracing” tool in Arc Hydro and randomly trace downstream from a number of different locations in the DEM. If there are any significant drainage inconsistencies, they can be rather easily identified. Any flow path issues need to be addressed immediately by generating the correct flow direction grid before proceeding with the next preprocessing steps. The inconstancies might include:
    i. Flow paths are not reaching the expected sinks (sinks have not been correctly identified, or have not been specified as being sinks).
    ii. Flow paths are ending in areas that should not have sinks (sinks have not been correctly identified, or have been specified as being sinks so they are not filled).
    iii. Flow paths are not following the perceived streams (might need to burn the streams).
    iv. Flow paths are not following the perceived drainage boundaries (might need to fence the boundaries).

To just establish the connectivity between the drainage elements, steps 5 and 7 do not have to be performed.

4.1.3 Webster Example

The steps for basic deranged terrain drainage system definition were performed for the Webster DEM (integer *10 - webster5i10). From 140 user specified water bodies, 71 were selected as sinks, primarily based on their size (larger than 4000 square feet). Detailed methodology for supporting identification of real sinks will be described in section 4.2.

Figure 18. presents the resulting sinks, catchments, and drainage connectivity superimposed on the hillshaded DEM. The hillshade was done on the original DEM, so it still shows the areas that were filled to get the depressionless DEM. Figure 19. shows a zoomed in area with more detail.

Function	Time	Function	Time
Fill sinks	26 s	Drainage point processing	14 s
Flow direction with sinks	79 s	Drainage area characterization	27 m
Flow accumulation	43 s	Drainage boundary definition	2 m
Catchment polygon processing	7 s	Drainage boundary characterization	3 m

		Drainage connectivity characterization	1 m

Table 7. Times of execution for selected terrain preprocessing functions for Webster DEM.

Table 7. presents times of executions for several of the operations. The operations that are not mentioned did not require more than ten seconds to process. Several of the steps required extended processing times; drainage connectivity characterization and drainage area characterization in particular. These two functions (drainage boundary characterization as well) perform a number of complex operations. The number of identified sinks/drainage areas and their extents will define the required processing time. If some of the areas or boundaries are known to be of no interest for later processing, they can be excluded from the characterization and thus reduce the required processing time (they can always be processed at a later time if need arises).

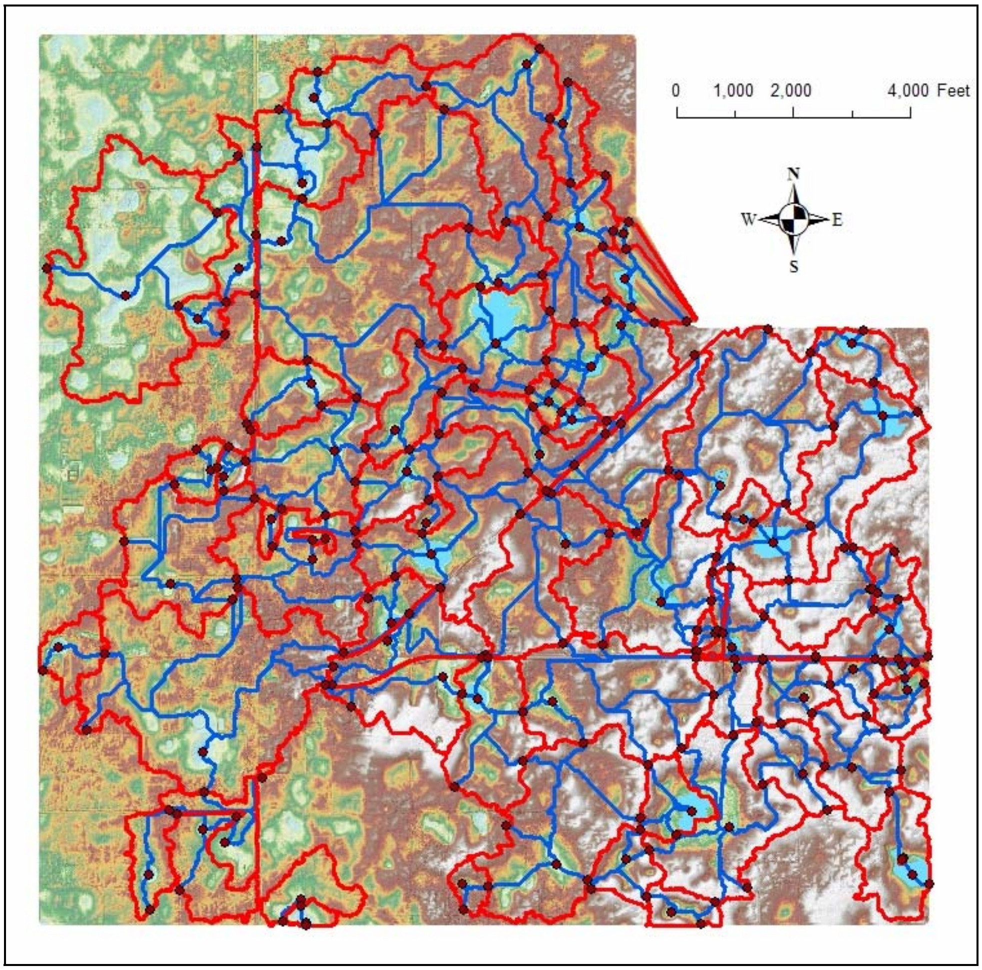


Figure 18. Webster DEM with sinks (light blue polygons), sink drainage areas (red lines), hydro junctions (red dots), and drainage lines (blue lines).

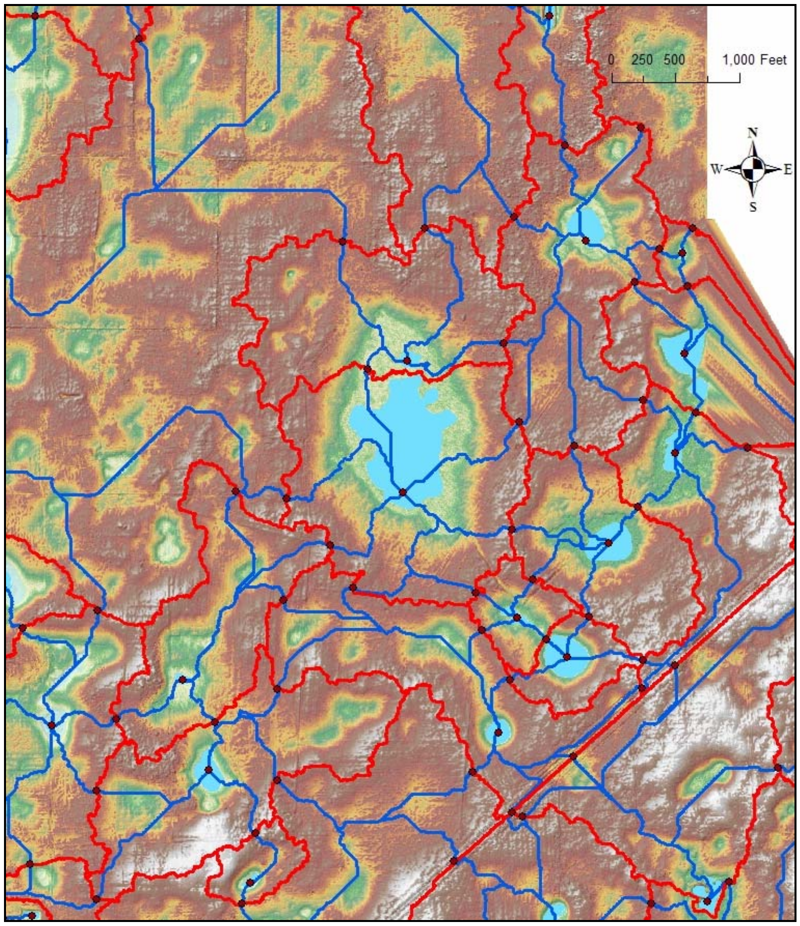


Figure 19. Zoomed in area of Webster DEM with sinks (light blue polygons), sink drainage areas (red lines), hydro junctions (red dots), and drainage lines (blue lines). Notice how hydro junctions reside either on the catchment boundaries or in the centers of the sinks and how the drainage lines connect them all.

4.2 Identifying Sinks

Depending on how a DEM was generated, it might contain numerous pits. In most cases, the pits are not real depressions in the terrain, but rather an artifact of DEM construction process and should be eliminated as part of the terrain preprocessing. Sometimes though, the pits are actual depressions and should not be filled. Differentiating "real" sinks from terrain construction artifacts is not always a straightforward process and often involves some subjective interpretation. As discussed in section 1.1, what constitutes a sink is also a function of the type of the analysis that is being performed. This section describes the process and tools for identifying and specifying sinks that can then be used in terrain processing described in section 4.1.

The DEM to be used in the sink identification process should always be the integer DEM that has been scaled to the level of the accuracy of the data (section 2.1). This will immediately eliminate all the sinks that are artifacts of floating point representation and inaccuracy of the elevation measurements.

Sink evaluation involves functions that require long processing times, so some of the functions are developed to reduce unnecessary processing and speed up overall preprocessing effort. Several tools are developed to help the analyst decide on which pits to fill and which to keep:

- Sink prescreening – eliminate pits that cannot be ever considered as real sinks.
- Sink evaluation – calculate properties of the sinks that can help the analyst to make decision of which pits are the real sinks and which should be filled.
- Sink selection – interactive tool that allows the analyst to select the real sinks.

The end result of the process is a polygon feature class that has “IsSink” attribute. That attribute contains one (1) for those polygons that are considered to be sinks and zero (0) for those that are not. This feature class then becomes input to the preprocessing functions described in section 4.1. Appendix 9 presents workflow for sink identification.

4.2.1 Sink Prescreening

Sink prescreening is used to reduce the number of potential sinks that can “never” be considered as sinks. The primary role of this function is to reduce the number of potential sinks that will be characterized in the following step. Sink evaluation is a time consuming function, so reducing the number of potential sinks is important to get the function to run efficiently. Also, eliminating as many potential sinks early on will reduce complexity in the sink selection process that involves user interpretation.

The input to the sink prescreening function is the DEM (as mentioned before, it is recommended that the scaled integer DEM is used) and the threshold drainage area draining into a sink (a single numeric value). If a sink has the area draining into it less than the specified threshold area, then the sink will be filled, otherwise it will be left as is. (Notice that this function works differently than the standard “fill sinks” function in Spatial Analyst, which allows the user to specify threshold DEPTH that defines the sink). The function:

1. Calculates flow direction based on the input DEM.
2. Identifies sinks.
3. Identifies areas draining into sinks.
4. Compares the draining areas to the specified threshold value and fills those sinks whose area is less than the specified value.

It is important to note that the sink selection function (section 4.2.4) provides user the ability to interactively select which pits are real sinks and which should be filled on a very detailed level, based on a number of different criteria. The prescreening function should NOT eliminate any potential real sinks, so a conservative approach is recommended when selecting the area threshold (basically, if in doubt, use a smaller threshold area – that will produce longer processing time and more potential sinks, but they can then be analyzed and eliminated later on).

The result of the function is a pre-filled DEM and the sink grid that shows where the left over sinks are.

4.2.2 Sink Evaluation

Sink evaluation takes the DEM (any DEM - the one that has been prescreened for sinks is recommended) and identifies sinks and sink areas (areas draining into each sink).

For each sink, the following attributes are calculated:

- DrainArea – area (in map units) of the sink area draining into the sink.
- BottomElev – elevation at the bottom of the sink.
- FillElev – elevation that it takes to fill the sink (this is the minimum elevation along the sink area boundary).
- FillDepth – depth to fill the sink (FillElev – BottomElev).
- FillArea – area (in map units) of the filled surface within the drainage area draining to the sink that would have to be filled for the sink .
- FillVolume.

Depending on the number of sinks that are being evaluated, this function can take significant processing time, so early reduction in spurious pits should be performed (by using the integer elevation grid and performing sink prescreening). The information about the sinks can then be used to identify the “real” sinks (by setting IsSink field to 1) using the sink selection tool.

4.2.3 Depression Evaluation

Depressions are defined as areas that need to be filled to completely fill all the sinks in the DEM (difference between the completely filled DEM and the original DEM). One depression can contain one or several sinks. Depression evaluation takes the DEM (any DEM - the one that has been prescreened for sinks is recommended) and identifies depressions and depression areas (areas draining into depressions). For each depression the same set of attributes as for sinks are calculated. As with the sink evaluation, this function can take significant processing time, so early reduction in spurious pits should be performed (by using the integer elevation grid and performing sink prescreening).

This is an optional step. Depressions and depression drainage areas are calculated to facilitate the sink selection process. Depressions will in general be larger than the sinks and will indicate where the sinks will flow if filled (which is sometimes difficult to interpret from the sinks alone). Since the depression feature class has the same data structure as the sink feature class, it can be used as the input layer for the sink selection process. This might simplify “real” sink selection if depressions are deemed to represent better what to and what not to fill.

4.2.4 Sink Selection

Once the sinks have been characterized, the sink selection tool can be used to set the IsSink field equal to one for those sinks that are deemed to be the “real” sinks that should not be filled. Figure 20 presents the tool’s input form. In it, the user can specify the conditions that if true will define the polygon to be a sink. Only those attributes that are checked will be included in the selection process. The checked attributes are used in an "and" composite query, that is, all the conditions must be satisfied for a polygon to be identified as a sink. If a user wants an "or" query, they need to rerun the tool for each of the individual variables (one at the time) and make sure that they check off the option to overwrite the existing sinks.

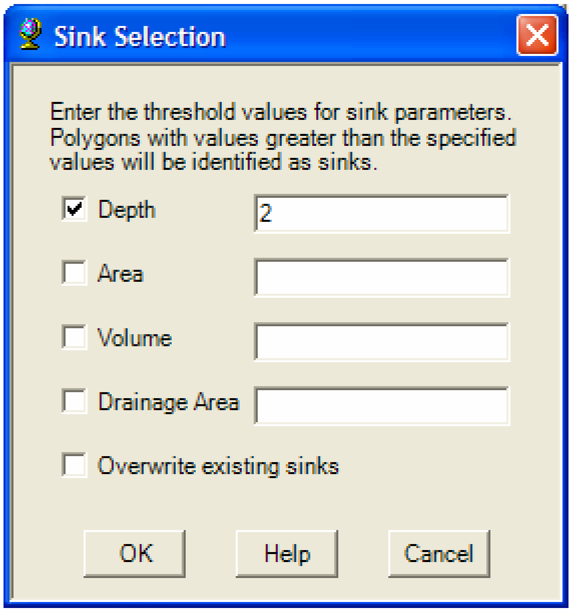


Figure 20. Sink Selection tool user interface.

Since IsSink is just an attribute of the sink feature class, the user can also use any other method for polygon selection and value assignment that is available in ArcGIS, including assigning the value to manually selected polygon..

4.2.5 Webster Example

Sink identification was performed on Webster DEM. The DEM was not leveled in order to simulate conditions when no additional data besides DEM existed. The DEM was though rounded up to one decimal place (to match the 1/10 ft vertical measurement accuracy) and made integer.

The sink prescreening process identified 107,331 initial sinks. Using 10,000 ft sq. as the sink drainage area threshold, 2,443 sinks were kept and the rest (104,888) were filled. The process took about 1.5 minutes to complete. Sink evaluation of 2,443 sinks took 3 minutes. Depression evaluation produced 665 depressions and took 3 minutes to process.

Actual identification of what are "real" sinks is quite involved and requires good understanding of the underlying data. In order to approximately match the 71 sinks selected in section 4.1.3 (where we had a layer of water bodies to start with) several individual queries were made on the 2,443 sinks developed in this example. The results are presented in Table 8. The value in the table is the value that the criteria variable must be greater or equal to for the sink to be identified as the "real" sink.

Criteria	Value	No. of sinks selected
Fill depth	2.2 ft.	72
Fill volume	32,000 cu.ft.	70
Fill area	26,000 sq. ft.	71
Drainage area to sink	265,000 sq. ft.	70

Table 8. Criteria and thresholds to select around 70 sinks from the 2,443 characterized.

If a composite criteria is made, that is, only those sinks that satisfy ALL the four criteria are selected (SELECT * FROM Layers.SinkPolys WHERE: "FillDepth" >= 2.2 AND "FillVolume" >= 32000 AND "FillArea" >= 26000 AND "DrainArea" >= 265000), only 35 sink polygons are found. Of the 35, 22 have also been selected in section 4.1.3 (based on the criteria that the area of the sink is greater than 4,000 sq.ft.).

Consider Figure 21. In (a) we had a prior knowledge of the location of pits and their elevation. The pit/lake elevation was imposed on the DEM first (Level DEM function), and then the rest of the preprocessing steps was performed. The known sinks are in pink, while their drainage area is in red. In (b), we did not have the prior information about the pits/lakes, so the DEM was not leveled. The derived sinks are in blue, while their drainage area is in black.

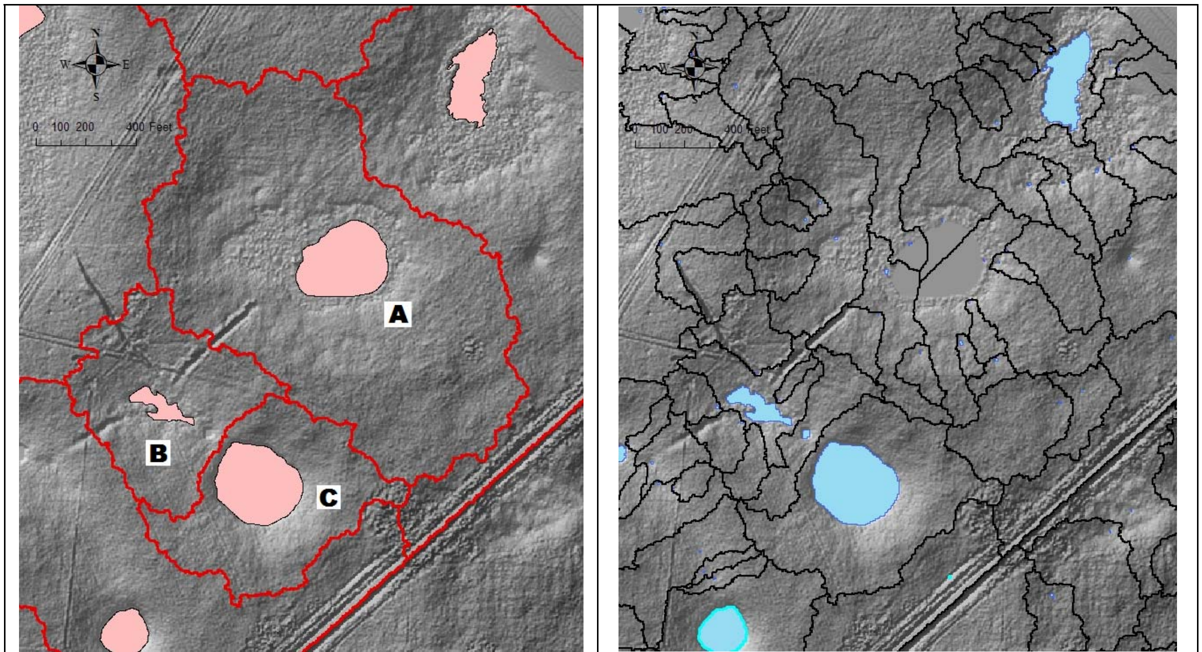
The resulting pits in (b) are quite different from the ones defined by (a). In area A, the user defined sink polygon is not even identified, but rather there are several small sinks around its edge. In area B, the main sink is identified and accompanied by few smaller ones. In area C, both the user defined and DEM derived sinks are the same. Figure 22. shows the superimposed Figures 21 (a) and (b).

If we wanted to assemble the same sinks for both approaches we would have to:

- For area C set IsSink field to 1 for a single polygon.
- For area B set IsSink field to 1 for the large polygon and insure (or set) that the six neighboring sinks have their IsSink set to 0 (so they will be filled and will drain into the main sink).
- For area A, it will be difficult to identify which of the minor sinks surrounding the main depression should be left as a sink and which should be filled to get the same effect as when we knew where the sinks are.

This example demonstrates how important it is to have good terrain representation early in the analysis process. If the elevation in pits/lakes is known, it can be immediately incorporated into the terrain model and subsequent analysis will require less effort. Otherwise, quite a bit of interpretation will be needed later on to understand the drainage patterns and make DEM adjustments to reflect them.

Figure 23. presents the sinks and depressions superimposed over the same area as in the Figure 22. Notice how sinks in B and C belong to the same depression, while sink in A belongs to a different depression. Also, notice how the depressions can be used to visually identify which sink area spills into which of its neighbors and to identify the predominant direction of flow in each depression (e.g. B & C to West and A to Northeast).



(a)	(b)

Figure 21. Areas draining into sinks: (a) starting from known sinks (peach polygons) burnt into DEM and (b) by evaluating sinks (blue polygons) derived from DEM without prior knowledge of sinks. Notice how in (b) there can be multiple sinks and sink areas that are within a single sink in (a).

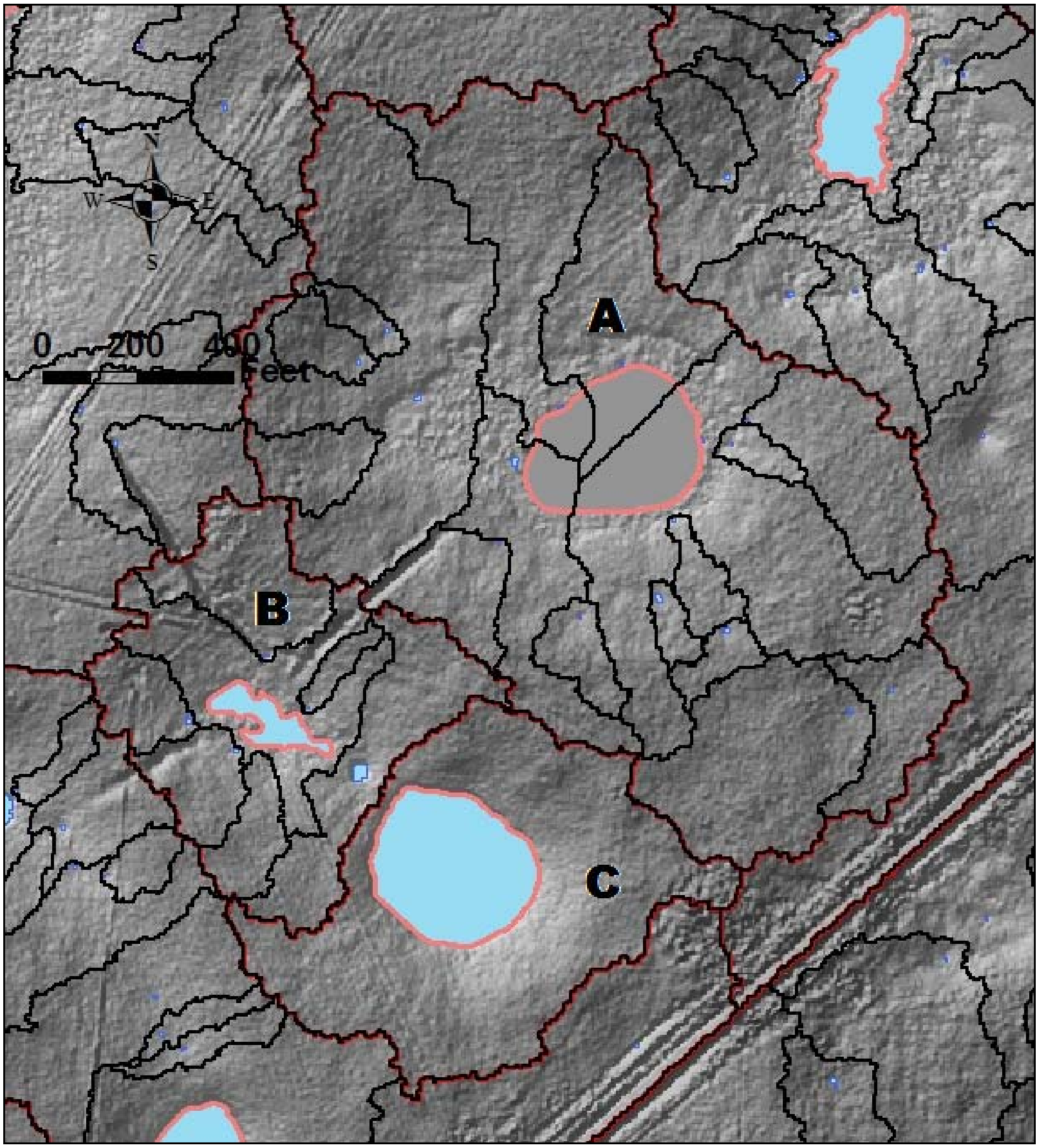


Figure 22. Sinks (blue) and sink drainage areas (black). Known sinks (peach) and their drainage areas (red) are presented for reference.

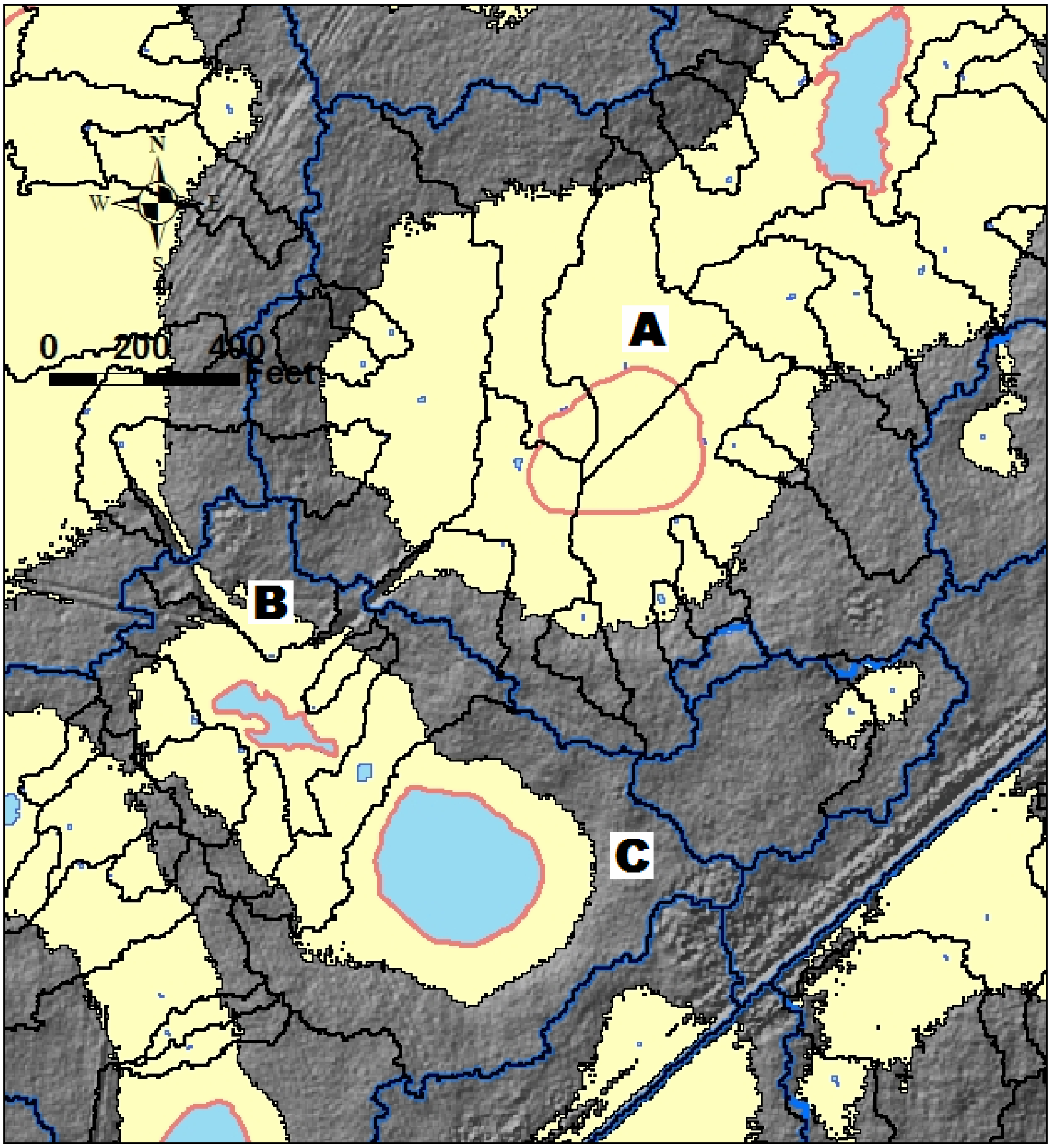


Figure 23. Sinks (light blue), sink drainage areas (black), depressions (beige), and depression drainage areas (dark blue). Known sinks (peach) are presented for reference.

5.0 Preprocessing of Combined Dendritic and Non-dendritic Terrains

Combined terrains include portions that are both dendritic as well as deranged. Their processing will involve a combination of the tools and processes discussed so far. As with all the other preprocessing, the basic workflow is simple. As additional requirements are added (like imposing stream pattern), the workflows can get quite complicated since both dendritic as well as deranged options might have to be considered. Some of the options will be discussed in this chapter, but some of them are left to the user to combine based on the processes described for dendritic and deranged workflows.

5.1 Basic Combined Terrain Processing

The first step in combined terrain processing is determination of sinks. Sinks and their drainage areas will identify part of the terrain with deranged characteristics, while the rest of the overall terrain will have dendritic terrain characteristics. The process for sink evaluation is exactly the same as discussed in section 4.2. The result of the process is a sink polygon feature class in which the "IsSink" field is set to 1 for those polygons that are to be considered as sinks (will not be filled).

5.1.1 Basic Flow Direction Determination

Defining flow direction for a combined terrain when location of sinks is known is a fairly simple process. This process is exactly the same as for deranged terrain processing described in detail in section 4.1.1. The two-step process includes:

- Fill sinks using the "Fill Sinks" function under the "Terrain Preprocessing -> DEM Manipulation" Arc Hydro menu. Make sure to specify the sink polygon feature class as input to exclude filling of the established sinks. The function will generate the "filled DEM".
- Determine flow direction by running the "Flow Direction with Sinks" function under the "Terrain Preprocessing -> DEM Manipulation" Arc Hydro menu. Input into this function is the filled DEM and the deranged polygon (should be the same one used to fill sinks).

5.1.2 Basic Drainage System Definition

Once the terrain has been filled and the flow direction grid is established, the rest of the terrain preprocessing steps include a combination of dendritic and deranged terrain processing functions (executed in this order):

1. Flow Accumulation. The flow accumulation step generates a grid that contains a number of upstream cells that drain through each cell.

2. Stream Definition. The stream definition step identifies those cells that are "streams". The streams are defined as those cells that drain more area than a user specified threshold (also referred to as "synthetic streams"). At this point in the process, the stream grid is defined for both the deranged as well as the dendritic part of the terrain.
3. Stream Segmentation. The stream segmentation step uniquely numbers stream segments (links) between the confluences. There are two options when defining stream links in combined terrain:
    a. Exclude the stream segments from deranged areas. This will generate a system in which there are no streams draining into the sinks. Make sure that the "Sink Watershed Grid" entry in the form is set to the sink watershed grid generated by the "Flow Direction with Sinks" function (to ensure that deranged areas of DEM are excluded from sink segmentation). "Sink Link Grid" option can be left blank (null).
    b. Include the stream segments within the deranged areas. This will generate stream links that drain into the sinks (if any streams are defined within the sink watershed areas). The stream links will terminate at the sink edge. Make sure that the "Sink Watershed Grid" entry in the form is set to "Null" and that the "Sink Link Grid" is set to the sink link grid generated by the "Flow Direction with Sinks" function.

    Either of these two approaches will produce viable results. It is up to the analyst to decide which one to use for their terrain.
4. Combine Stream Link and Sink Link. This function combines the stream and sink link grids into a single link grid that will be used for catchment delineation. The stream link grid will come from step 3, while the sink link grid will be the result of the "Flow Direction with Sinks" function (step two in section 5.1.1).
5. Catchment Grid Delineation. The catchment grid delineation step identifies drainage areas (as grids) that drain to each link (that now include both sinks and streams). As the link grid, pass the combined link grid developed in the previous step.
6. Catchment Polygon Processing. The catchment polygon processing step defines catchments in vector format.
7. Drainage Line Processing. The drainage line processing step defines stream segments in vector format. Notice how drainage lines within deranged areas terminate at the edges of sinks. Their NextDownID will be -1 as they are considered to be the "outlet" drainage lines.
8. Adjoint Catchment Processing. The adjoint catchment processing step determines the cumulative area upstream from a catchment (in vector format).
9. Drainage Point Processing. The drainage point processing step generates points with maximum flow accumulation within each drainage area. These points are the same as the sink points generated during the flow direction computations, except that they are snapped to the center of the cell.
10. *(Optional)* Drainage Area Characterization. This function will generate the elevation-area-volume (EAV) table with information about area and volume for each drainage area (catchment). The drainage area feature class needs to have "IsPitted" field (short integer) set to 1 for those areas that need to be processed (pitted areas). The easiest way to populate this field is to look at the catchment feature class, and for those catchments that have the "NextDownID" field set to "null", set the "IsPitted" to 1. The alternative is to use spatial selection (e.g. select all catchments that contain sink points). Make sure you use the raw DEM for these computations.

11. Drainage Boundary Definition. This function will generate:
    a. Drainage boundary feature class (polylineZ) that contains as 3D linear feature of each boundary between drainage areas. The minimum and maximum elevation along that line is also stored in the feature class.
    b. *(Optional)* External boundary feature class (polygon) that contains the outside polygon encompassing all of the drainage areas.
    c. Drainage connectivity (DrainConn) table that specifies the left and right catchments for each drainage boundary (using their respective HydroIDs).

    This function needs to have "IsPitted" field populated for those drainage areas (catchments) that are draining into the sinks (see step 10 on how to do that).
12. *(Optional)* Drainage Boundary Characterization. This function will generate:
    a. Elevation-width-area (EWA) table with information about width and area for each boundary between drainage areas. Make sure you use the raw DEM for these computations.

    This function needs to have "IsPitted" field populated for those drainage areas (catchments) that are draining into the sinks (see step 10 on how to do that).
13. Drainage Connectivity Characterization. This function will generate:
    a. Boundary drainage line. Boundary drainage line feature class (polyline) defines the connectivity between the drainage areas. The connectivity is established by taking the lowest point at the boundary between the two drainage areas, and then trace from that point into each of the drainage areas (the ending point will be the drainage point for that drainage area). Each boundary drainage line knows the boundary it is on (LinkID) as well as which drainage area it is in (DrainID).
    b. Hydro Edge. Hydro edge feature class (polyline) contains the combination of boundary drainage lines and streams (if dendritic component is present). Since process described in this chapter does not include dendritic component, the hydro edges will contain only the boundary drainage lines.
    c. Hydro Junction. Hydro junction feature class (point) contains the points that participate in the connectivity. This includes the "centers" of sinks from the drainage point feature class as well as the points on the boundaries.

    This function needs to have "IsPitted" field populated for those drainage areas (catchments) that are draining into the sinks (see step 10 on how to do that).

Steps 1 through 9 (using the functions with the matching name to the step to be executed) are performed from the Arc Hydro tools "Terrain Preprocessing" menu. Steps 10 through 13 (using the functions with the matching name to the step to be executed) are performed from the Arc Hydro tools "Terrain Morphology" menu.

To preprocess terrain to enable efficient watershed delineation and characterization only, steps 1-8 need to be performed. The remaining steps are not required.

5.1.3 Homosassa Example

The combined terrain preprocessing was performed for the Homosassa DEM (using the integer DEM scaled to first decimal place). The sinks were determined by:

1) Performing sink prescreening using 20,000 cells as the threshold drainage area (2,000,000 sq. ft or 0.072 sq. mi), resulting in 46 potential sinks.
2) Performing sink evaluation to understand the potential sink characteristics.
3) Selecting manually sinks in the "upper" (eastern) portion of the watershed, resulting in 23 selected sinks.

The process took about forty (40) seconds for sink prescreening and fifty (50) seconds for sink evaluation.

Once the sinks were determined, the basic preprocessing steps for combined terrain were executed. A threshold of 40,000 cells was used for synthetic stream definition (same as in section 3.1.3). Processing of combined terrain took somewhat longer than when processing fully filled DEM, although not dramatically longer. All the preprocessing steps (except the optional Drainage Area Characterization), executed in less than a minute each and some significantly faster.

Figure 24. presents the resulting catchments and drainage lines for combined terrain characterization. This terrain definition was obtained by excluding the streams from deranged areas.

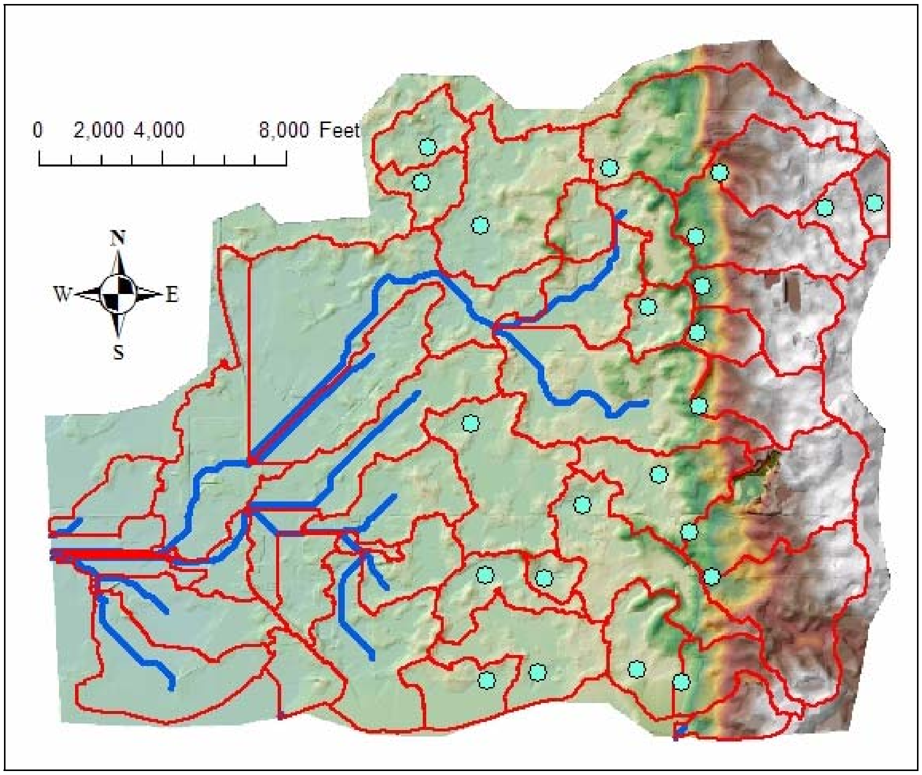


Figure 24. Homosassa combined DEM with stream threshold of 40,000 cells and no streams in deranged areas. The light blue dots indicate the sinks.

Compare this figure to Figure 1 that represents Homosassa dendritic terrain configuration. Besides the Eastern part of the terrain that is deranged and does not connect directly to the stream system, note the difference in drainage pattern in the synthetic streams, specially at the Western outlet(s). This difference is due to use of integer DEM in this section vs. using the floating point DEM in section 3. The conclusion of this comparison is that in flat areas, even a small perturbance in the terrain can significantly impact identification of drainage patterns. In cases like that, it would be good to know stream patterns that can be imposed into the terrain and thus reduce (or eliminate) the possibility of generating spurious streams due to terrain uncertainty.

Figure 25. presents the same drainage system as in Figure 24, except that it also shows hydro edges and hydro junctions. Hydro junctions are defined as lowest points on the drainage area boundary and points with highest flow accumulation within a drainage area. Hydro edges just connect the hydro junctions. Hydro edges together with drainage lines make the "spider web" in a combined terrain (collection of potential flow paths).

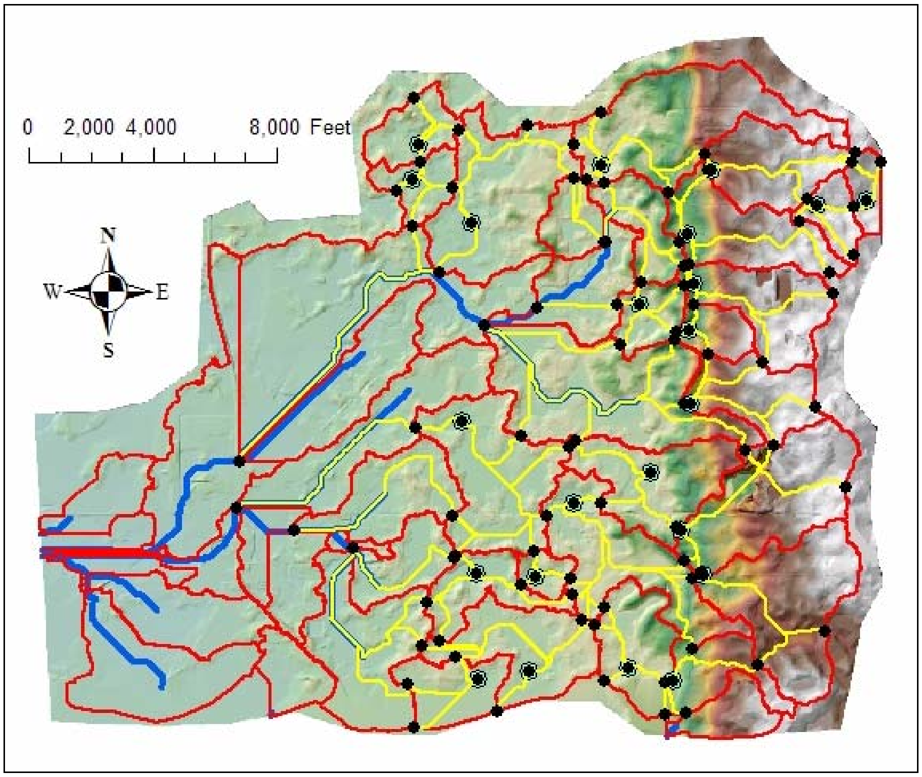


Figure 25. Homosassa combined DEM with spider web. The light blue dots indicate the sinks. Black dots are hydro junctions. Yellow lines are hydro edges while blue lines are drainage lines.

Figure 26. presents the alternative where the streams are not excluded from the deranged areas. Notice a more complex drainage structure in the deranged areas (east section) of the terrain. Compare this figure to Figure 24. where streams were not kept in the deranged areas. Figure 27. presents the spider web for alternative with streams in the deranged areas.

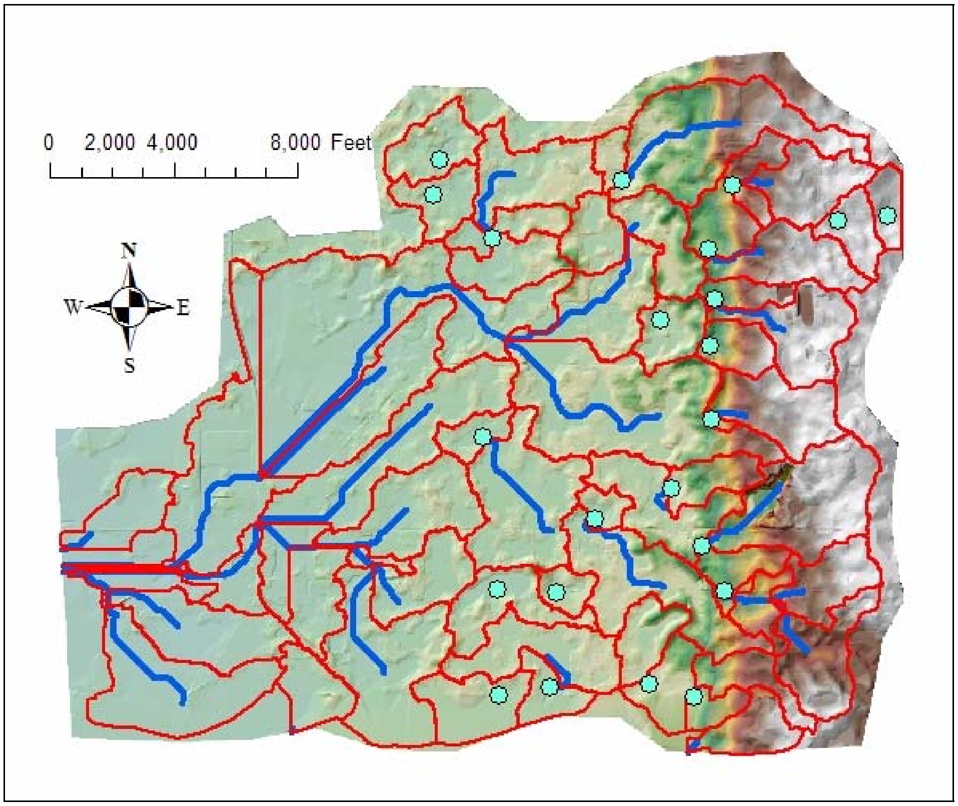


Figure 26. Homosassa combined DEM with stream threshold of 40,000 cells and streams kept in the deranged areas. The light blue dots indicate the sinks.

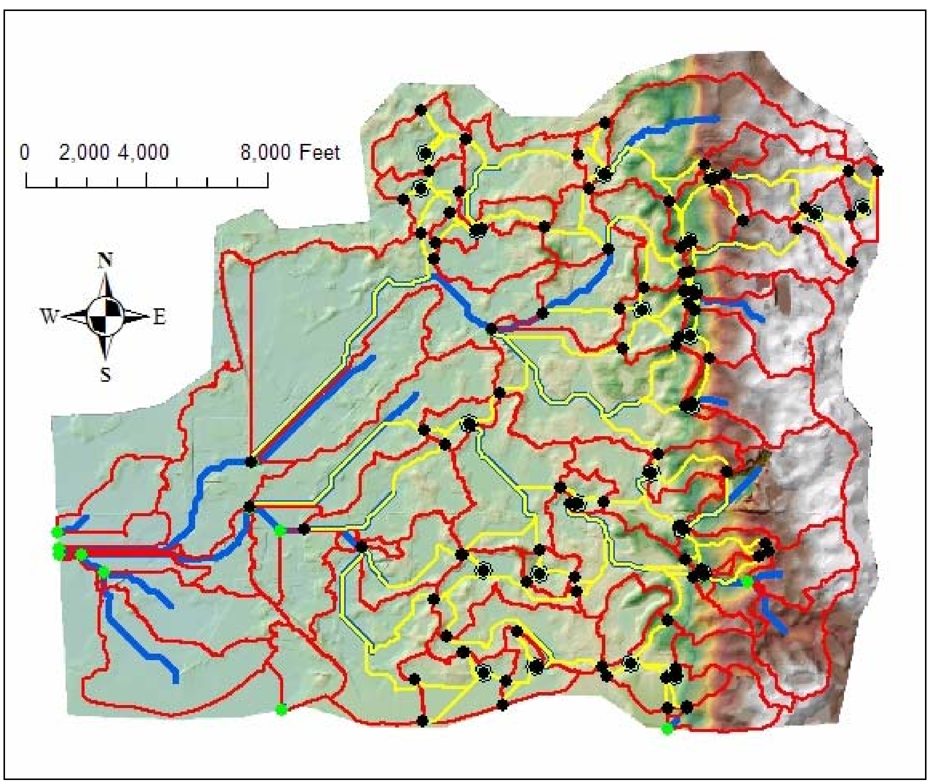
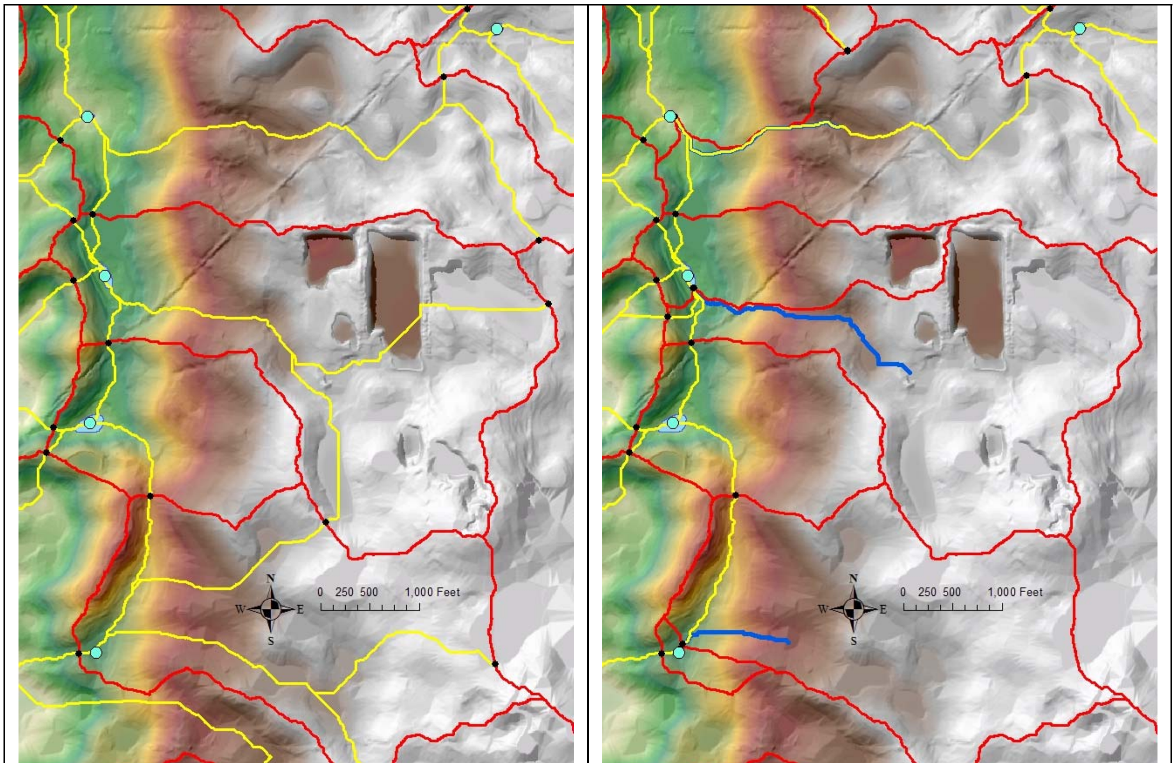


Figure 27. Homosassa combined DEM with spider web for alternative with streams in deranged areas.

Figure 28. presents a detail of the two alternatives for combined terrain processing. The connectivity of catchments is defined by the "IsPitted" field. In the example, only the catchments that contain the sinks are defined as pitted. In the alternative approach where the streams are kept in the deranged areas, if the "IsPitted" is set to 1 for catchments draining to pitted streams, additional connection lines can be generated.



(a) (b)

Figure 28. Catchment boundaries (red), drainage area connectors (yellow), synthetic streams (blue), hydro junctions (black points), sinks (blue points): (a) no streams within deranged areas and (b) streams within deranged areas.

5.2 Modifying Basic Combined Flow Patterns

If necessary, the known flow patterns can be imposed on combined terrain in the same way as for dendritic one. Consult sections 3.2 and 3.3 for all available options.

6.0 Conclusions and Recommendations

Terrain preprocessing is an important first step in mobilizing the terrain data for GIS analyses. Its role is to define the hydrologically-correct DEM and its derivatives, as well as to define a set of layers that will optimize performance later on, when the terrain is used for actual water resources analyses. It is important to reiterate that terrain preprocessing is NOT a water resources analysis in itself – it is data preparation for the analysis that will follow.

Terrain preprocessing requires significant computer resources and processing time, but needs to be done only once and will significantly improve performance for the analyses to follow. The preprocessing also serves as a quality control for DEM and derived layers – if the quality is not insured at this stage, any of the following results based on the terrain will not be reliable.

Terrain preprocessing is a function of the analyses that will be performed on it. Arc Hydro has a suite of tools for terrain preprocessing, but ultimately it is up to the analyst to correctly apply the tools within the scope of the required analyses. A single set of elevation measurements might result in different DEMs and their derivatives, depending on the analysis that they need to support.

The DEM to be processed should be focused to the particular area of interest and match its vertical accuracy (use of integer DEM). This can significantly improve the performance of required functions and simplify necessary decisions that the analyst will have to make. Any known drainage patterns should be imposed as early on in the process as possible.

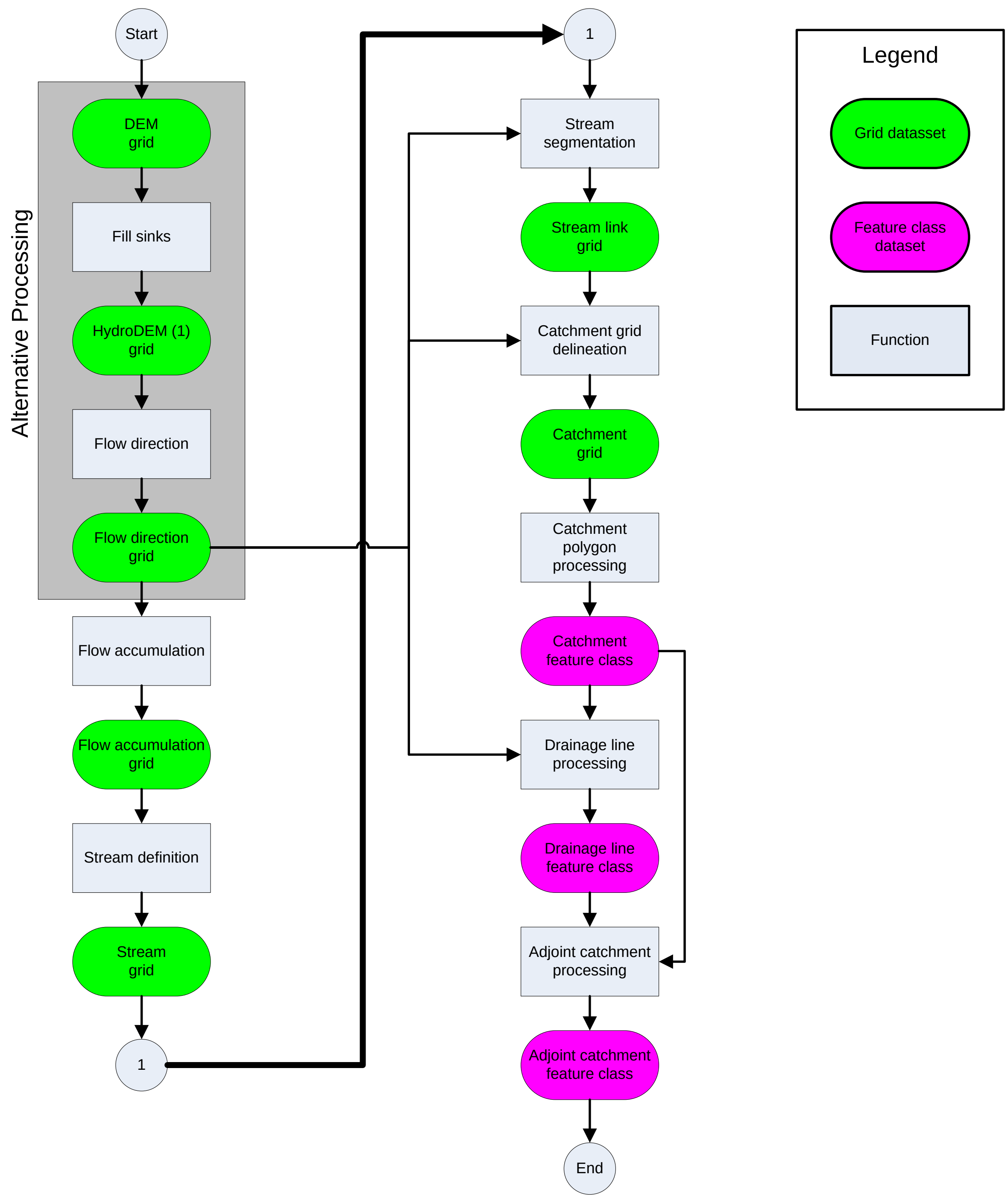
When modifying the initial DEM, make sure that the data that are being used to impose changes in the DEM are matching the DEM in quality (scale) and timeliness. Imposing the external data that are of different scale and age from the DEM is not recommended and should be applied with extreme caution.

References

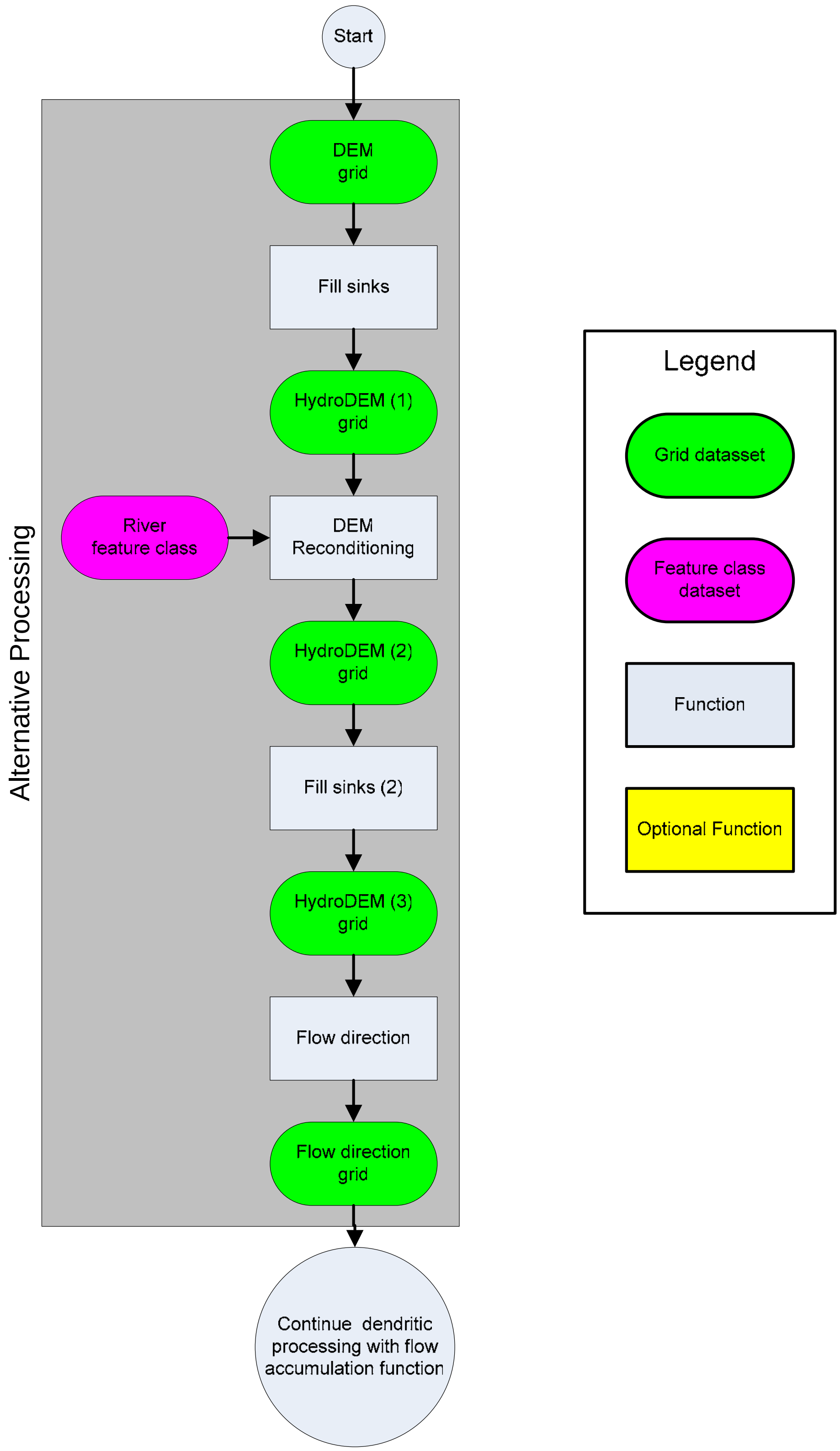
Hellweger F., 1997.
http://www.ce.utexas.edu/prof/maidment/GISHYDRO/ferdi/research/agree/agree.html.

Appendix

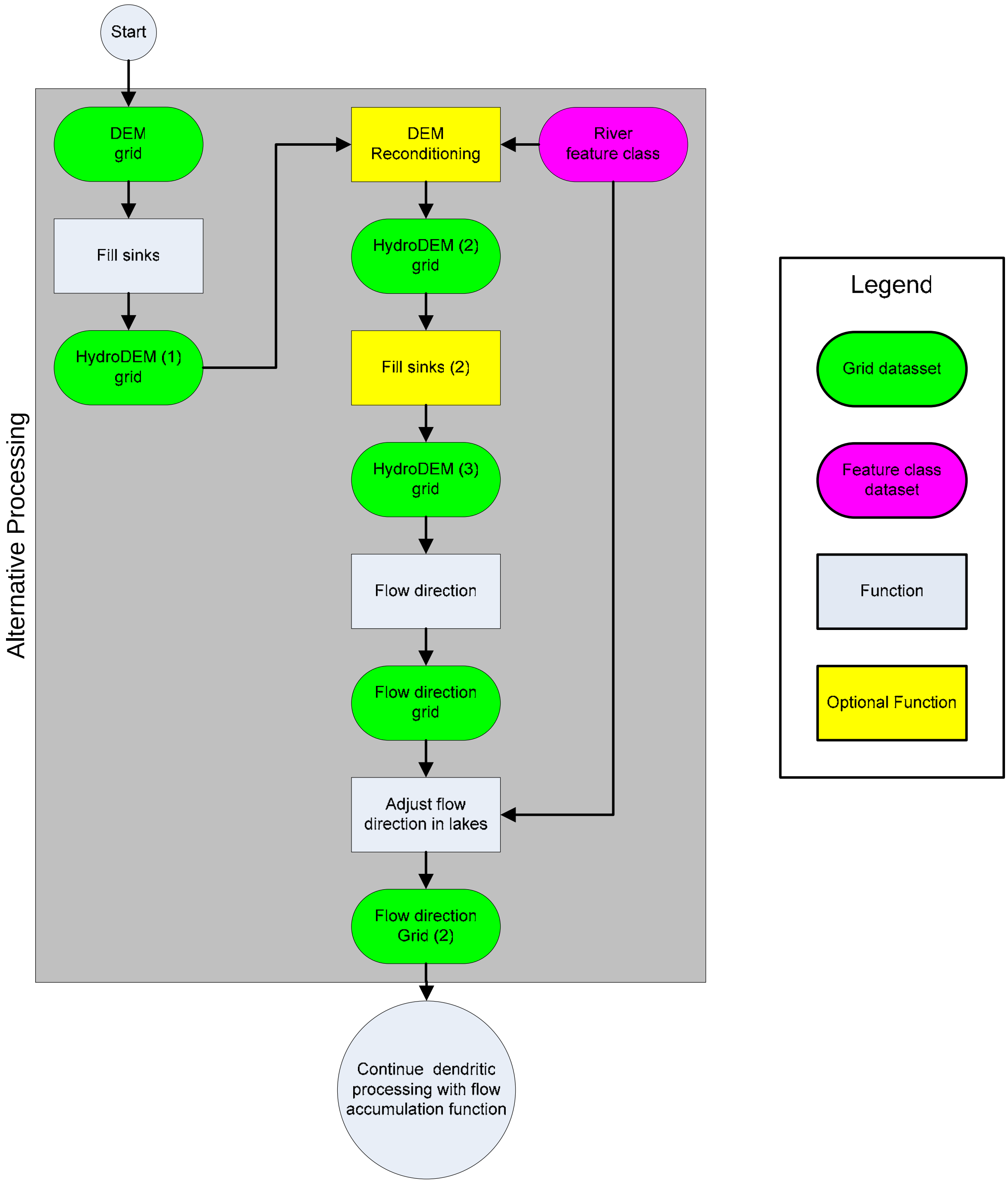
Appendix 1. Basic dendritic terrain processing workflow



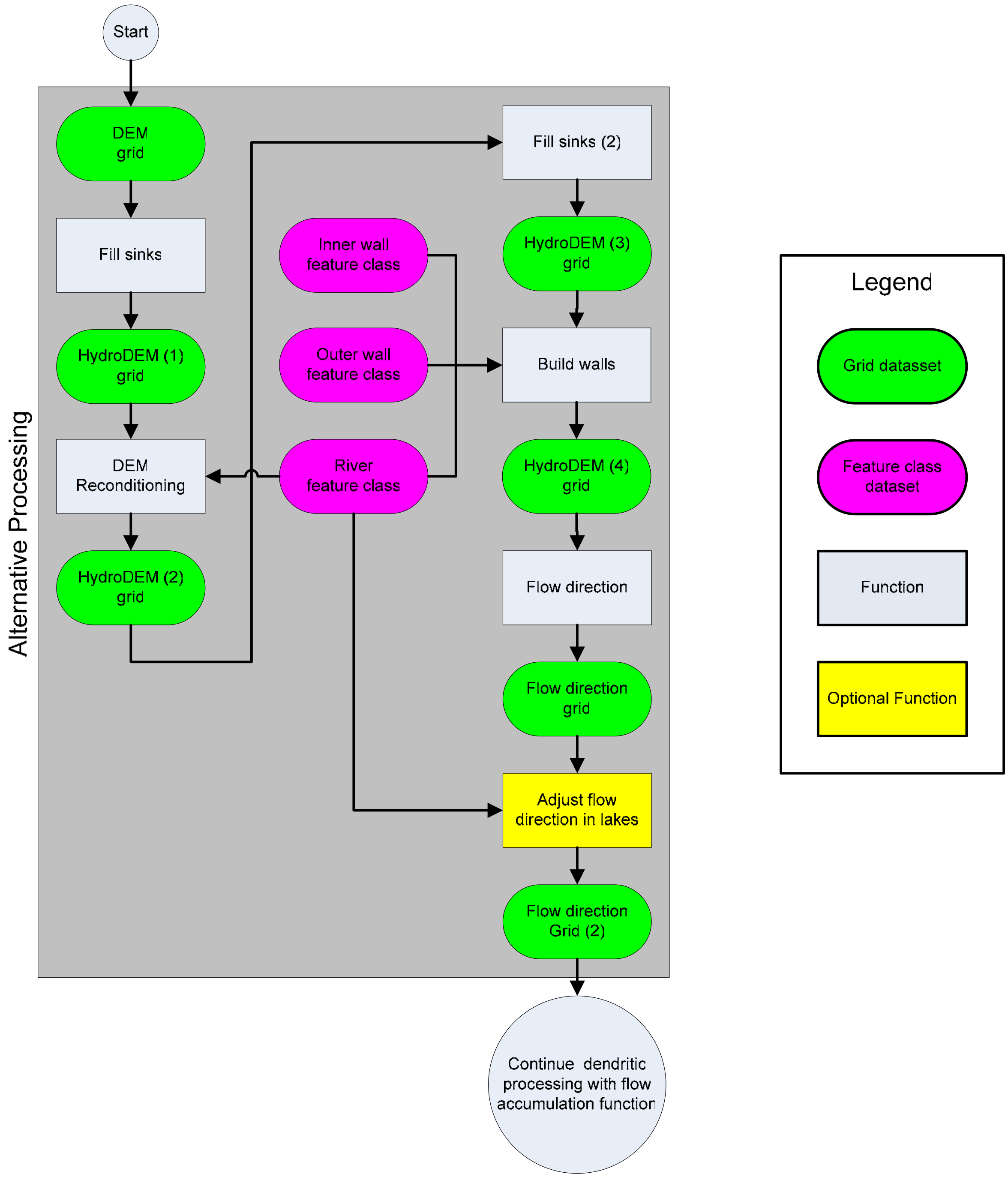
Appendix 2. Workflow for imposing the known stream drainage patterns



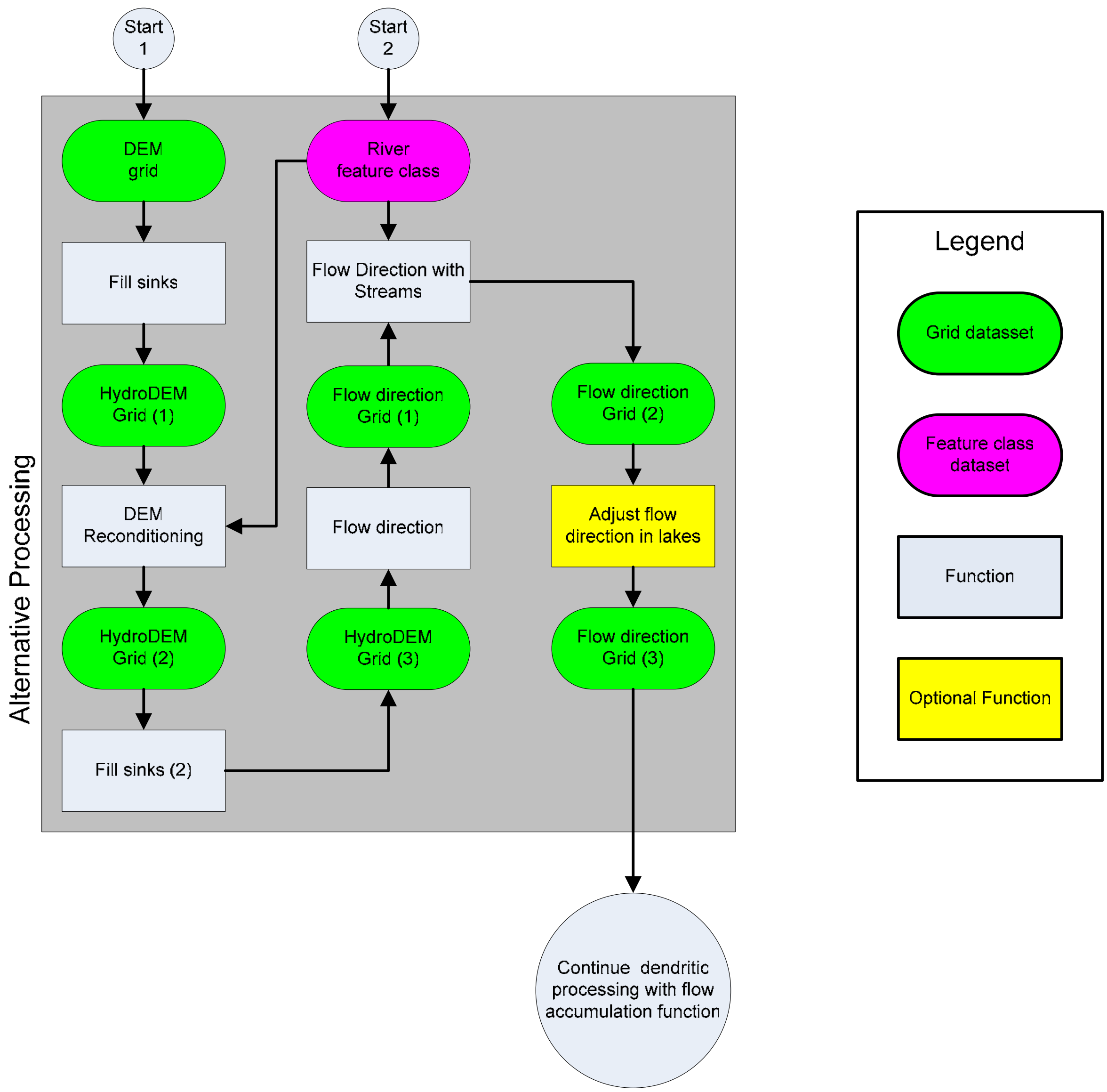
Appendix 3. Workflow for imposing flow direction within lakes



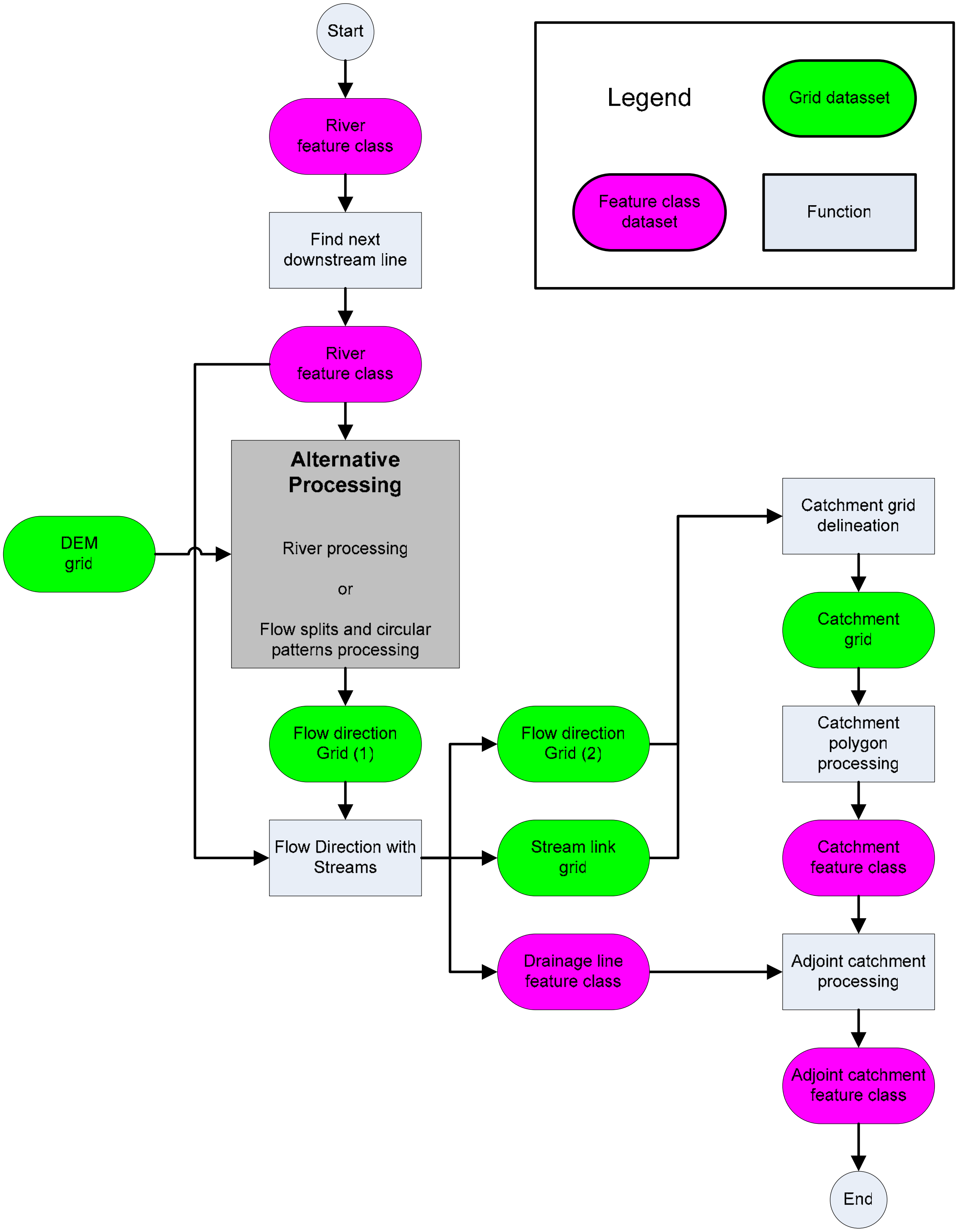
Appendix 4. Workflow for imposing drainage boundaries



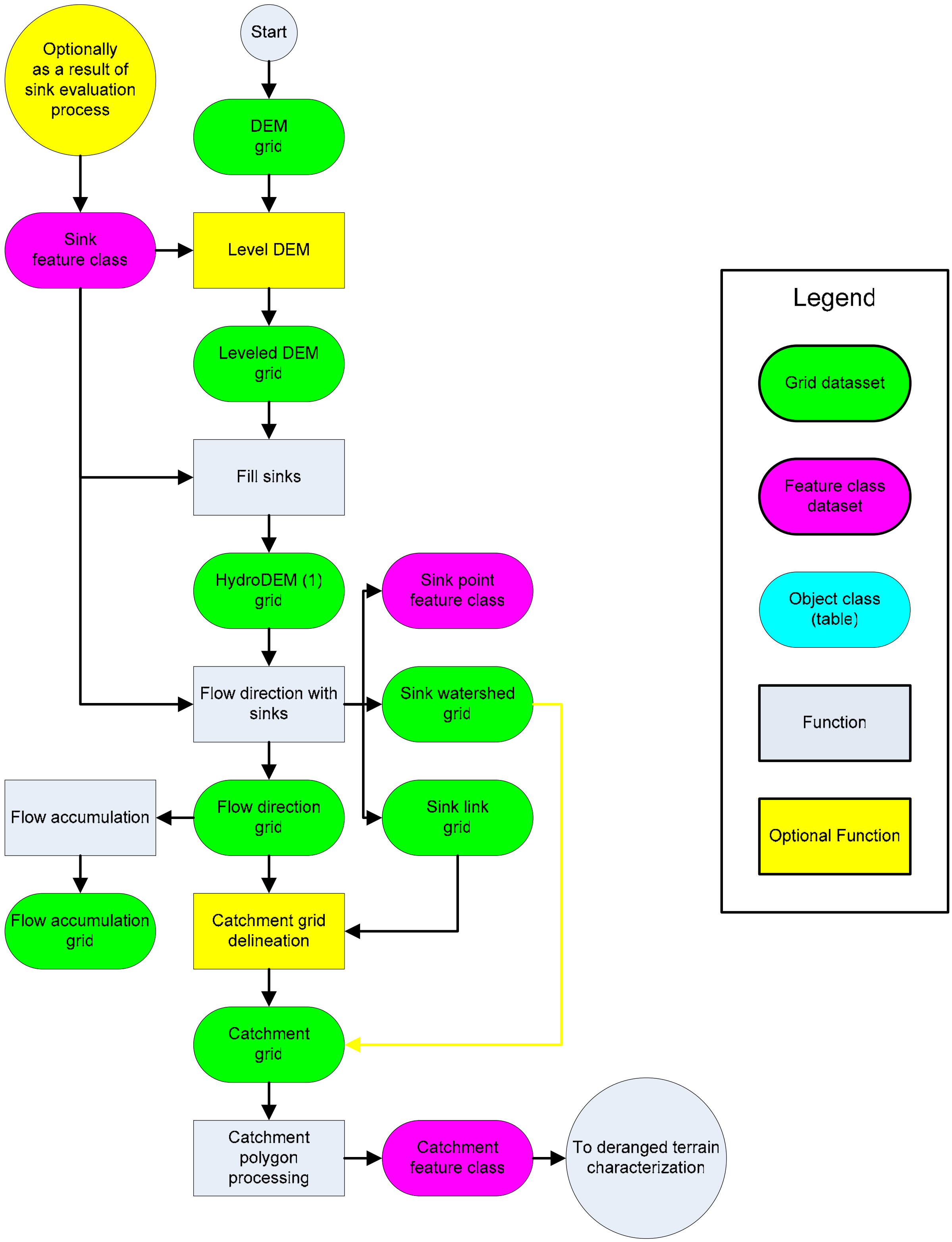
Appendix 5. Workflow for imposing braided flow patterns



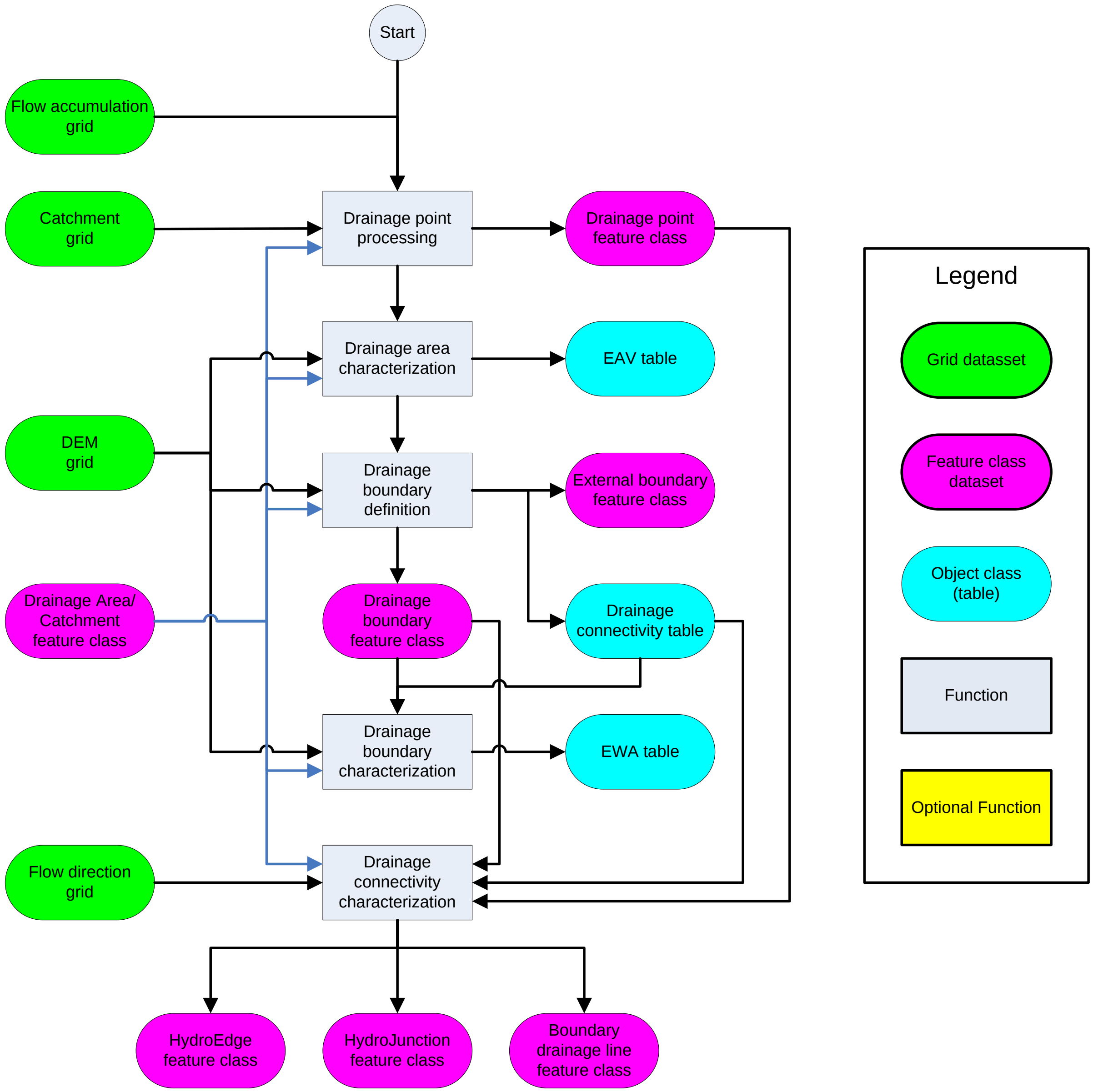
Appendix 6. Workflow for alternative dendritic terrain processing



Appendix 7. Basic deranged terrain processing workflow



Appendix 8. Deranged terrain characterization workflow



Appendix 9. Workflow for sink identification