A Robust Cellular Automaton Surface Drainage Preprocessing Algorithm for High Resolution Digital Elevation Models

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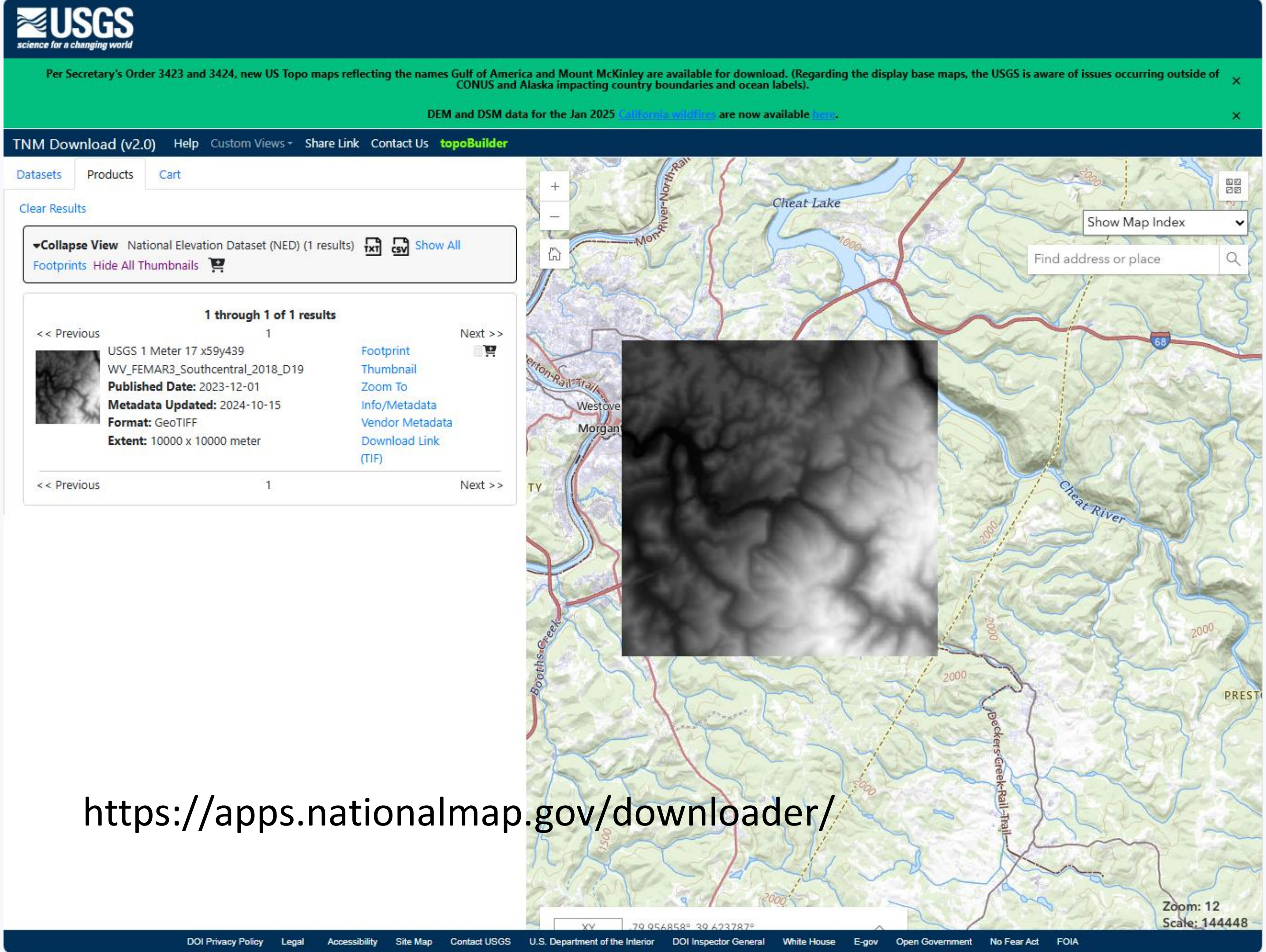


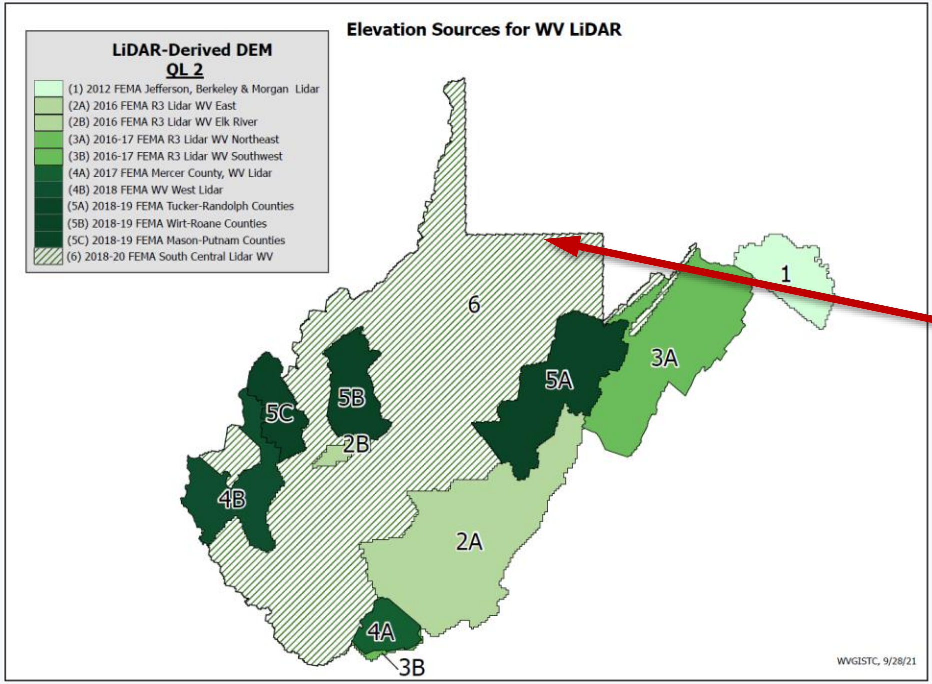
https://apps.nationalmap.gov/downloader/

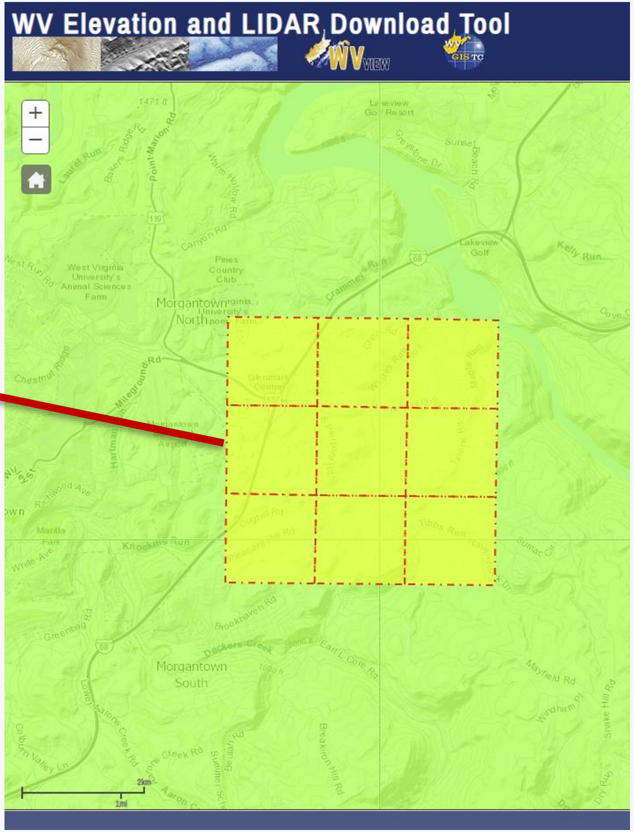
1-Meter Digital Elevation Model (DEM) Characteristics:

- **Lidar Point Clouds are processed to produce “bare earth” DEMs.**
  - Trees, Buildings, automobiles, etc., removed.
  - Bridges also removed.

- **USGS data sets: 10 km x 10 km tiles, 1-meter grid resolution with 9-meter overlap.**
- **UTM map projection, GeoTIFF file format (.tif).**
- **Raster grid image format (row/column).**
- **Elevation in meters (10 cm RMSE accuracy).**

Example Data Set: 1-m DEM – 4500 x 4500 m





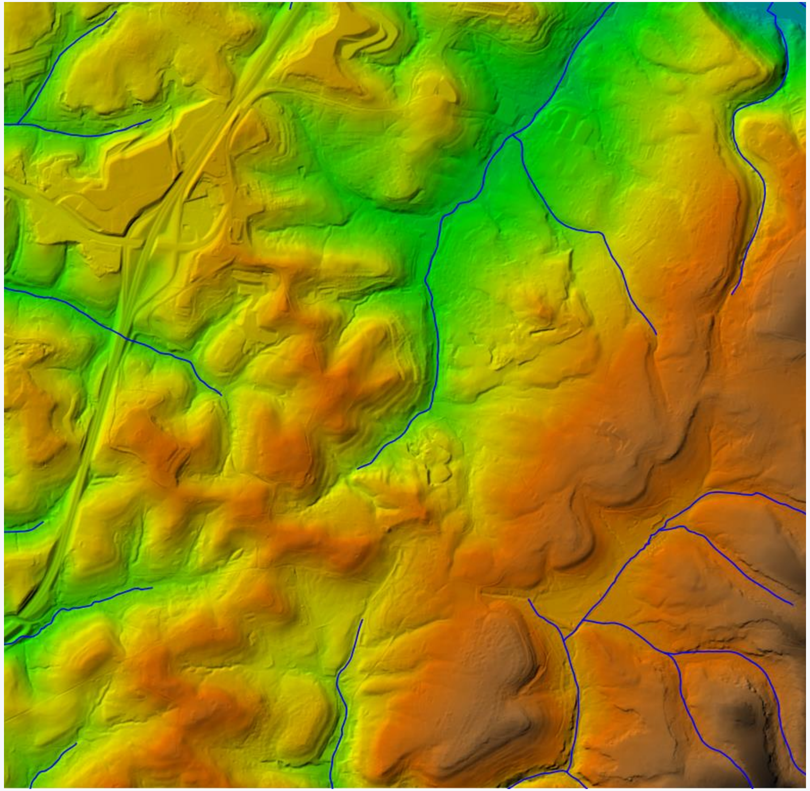
Upper Whites Run 1-meter DEM

(Hill shade with NHDPLUS HU4 Overlay)

Size: 4500 x 4500 m – (9 tiles)
EPSG:6346, NAD83(2011)/UTM Zone 17N

<u>Metadata:</u>

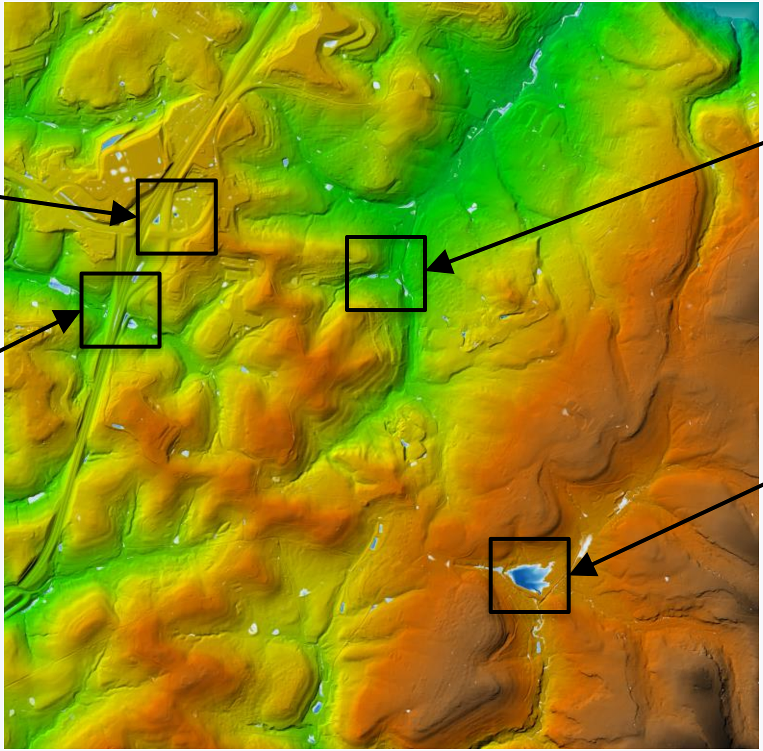
- Acquired and processed: 2018-2020
- Tile Size: 1500 x 1500m
- Grid Resolution: 1 meter
- Horizontal Accuracy: N/A
- Vertical Accuracy: 10 cm RMSE
- UTM Zone 17N
- Horizontal Datum: NAD83
- Vertical Datum: NAVD88
- Elevation Units: meters
- FEMA Project: FEMA_2018_20_SouthCentral_WV_UTM17



High Resolution DEMs Create New Problems for Surface Drainage Algorithms

“Bare Earth” building structure removal artifacts

Dams resulting from large roadway fills



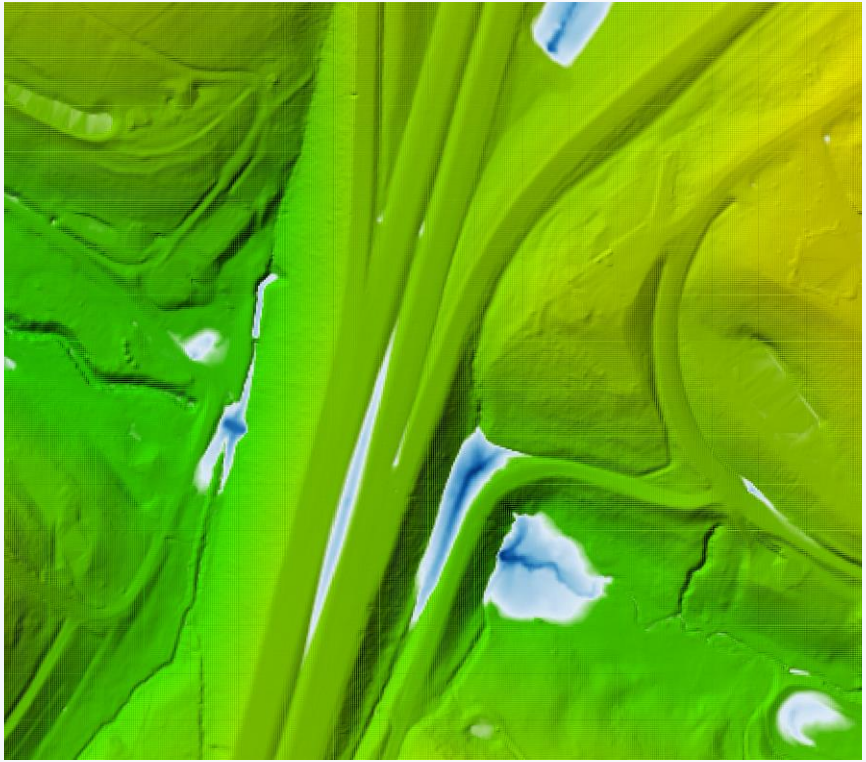
Complex combinations of pond drainage and culverts

Decommissioned reservoirs

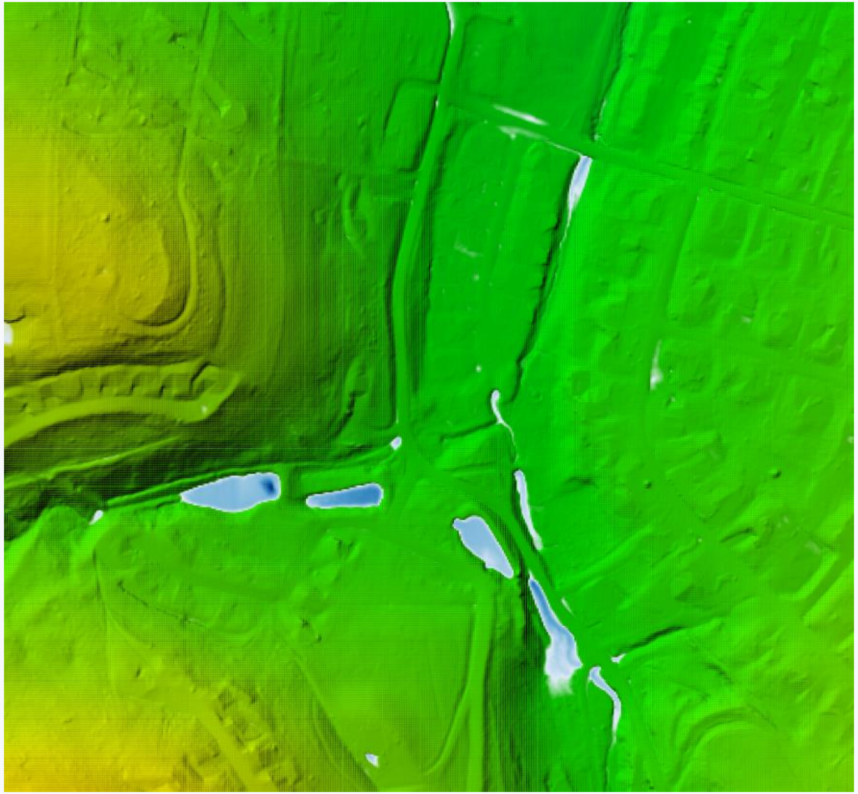
(QGIS Image with HydroFill overlay of virtual-ponded water at 2.5 m maximum depth)

“Bare Earth” building structure removal artifacts

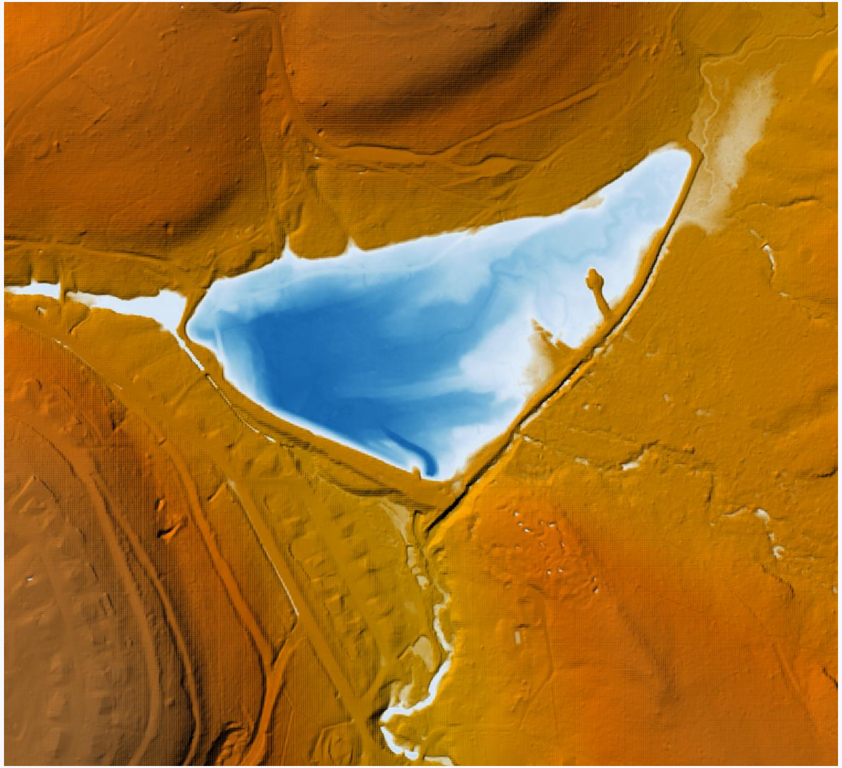
Dams resulting from large roadway fills

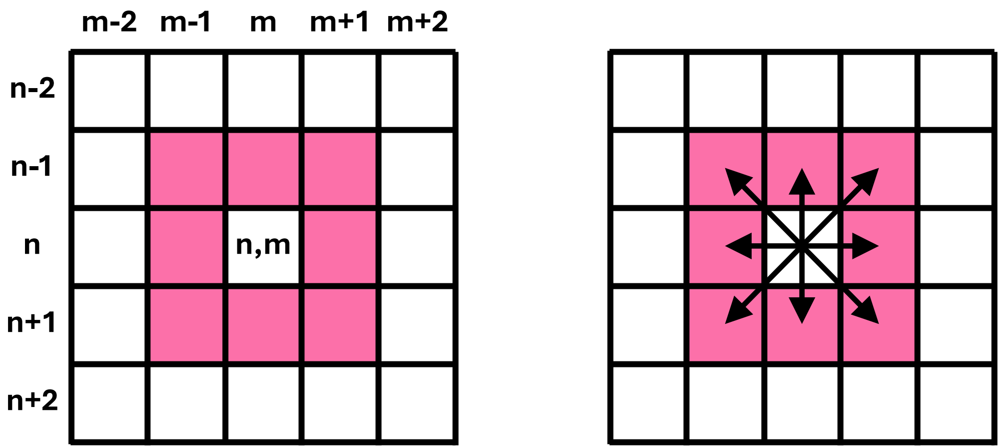


Complex combinations of pond drainage and culverts



Decommissioned reservoirs





- **Raster DEM format allows grid cell location by row-column indexing.**

- **"D8" raster drainage algorithms send surface flow from cell (n,m) to one of 8 neighbor grid cells with steepest downslope.**
  - <u>Weaknesses:</u>
    - Flow directions limited by 45-degree increments.
    - Raster grid orientation flow direction biases .
  - <u>Strengths:</u>
    - Computationally simple: Yields acceptable results with high resolution DEMs.

Impediments to Surface Drainage

- **Pits**
  - Grid cells that have an elevation lower than all the surrounding D8 neighbor cells.
- **Depressions**
  - Areas of contiguous lower elevation grid cells surrounded by a higher barrier that prevents drainage.
- **Flat Areas**
  - Areas of contiguous grid cells with identical elevations.

HydroFill Algorithm Features

- Utilizes a 2-D Cellular Automaton (CA) algorithm to preprocess the DEM using integer arithmetic.
  - Generates "Virtual-Ponding" to help identify artificial barriers to topographic drainage paths.
  - Provides for inclusion of subsurface drainage structures to breach artificial barriers and complete drainage continuity.
  - Completes downslope drainage continuity for all grid cells within the DEM using minimal "Unit- Depth" fill increments (e.g., 1 mm).

DEM Preparatory Steps for HydroFill Processing

1. Provide a raster (row-column format) DEM with no missing data.

2. Select a small unit-depth increment (e.g., 1-mm) that defines the minimum surface gradient (=0.001 slope for a 1-m DEM).

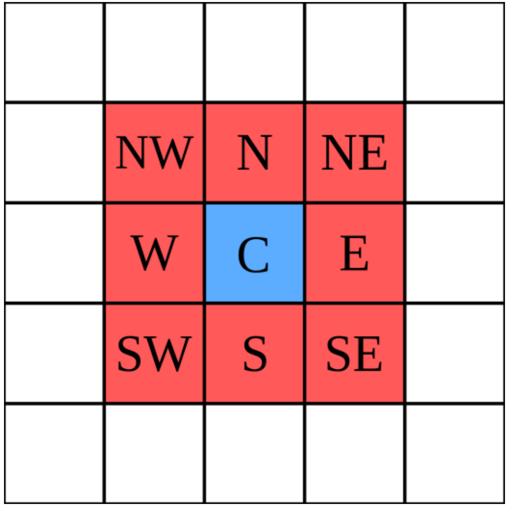
3. Convert the floating point (float32) DEM elevations to integer (int32) iDEM elevations that matches the precision of the chosen unit-depth increment (e.g., 324.668-m becomes 324668-mm).

4. Convert all Pits to Flats in the iDEM by filling the pits to an elevation equal to the lowest surrounding D8 grid cell.

- 2-D Cellular Automata (CA) is defined on a square grid with each cell being surrounded by 8 neighbor cells.*

- The 2-D CA "evolves" by updating the state of each cell in the grid as a fixed function of the current states of its 8 surrounding cells.

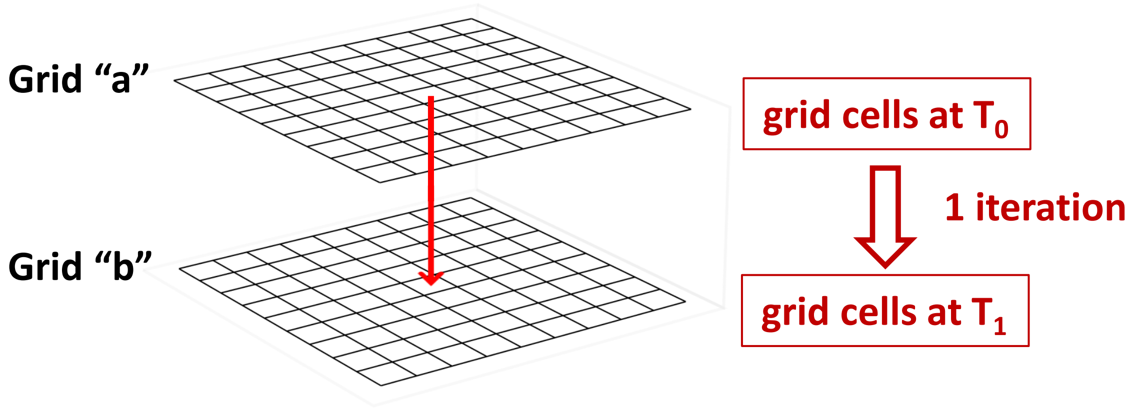
- Grid cell state updates during each iteration are stored on a parallel grid to avoid overwriting current cell states.



***8-cell, 2-D CA Neighborhood (Wikipedia)**

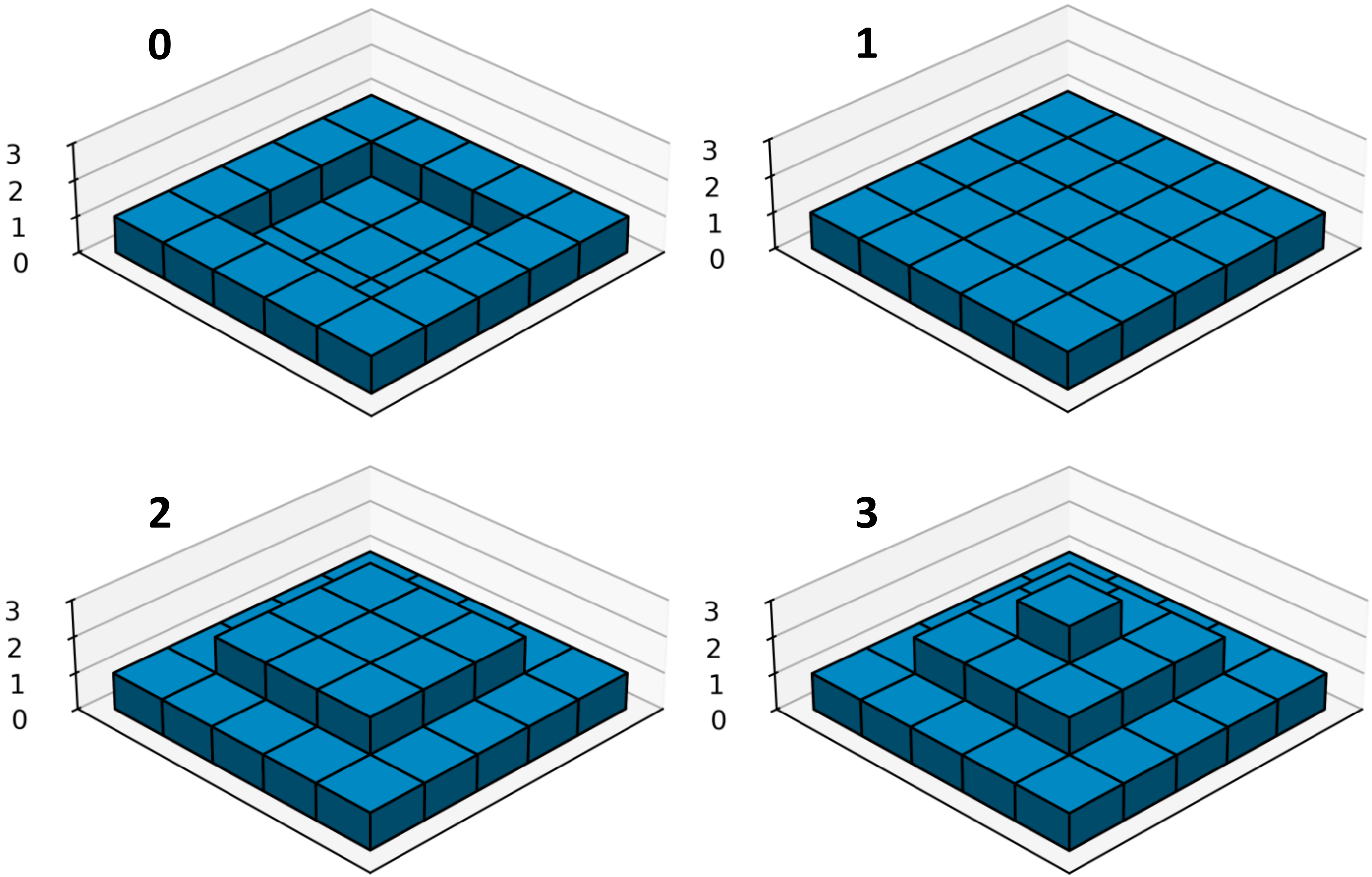
HydroFill CA Rule Definition:

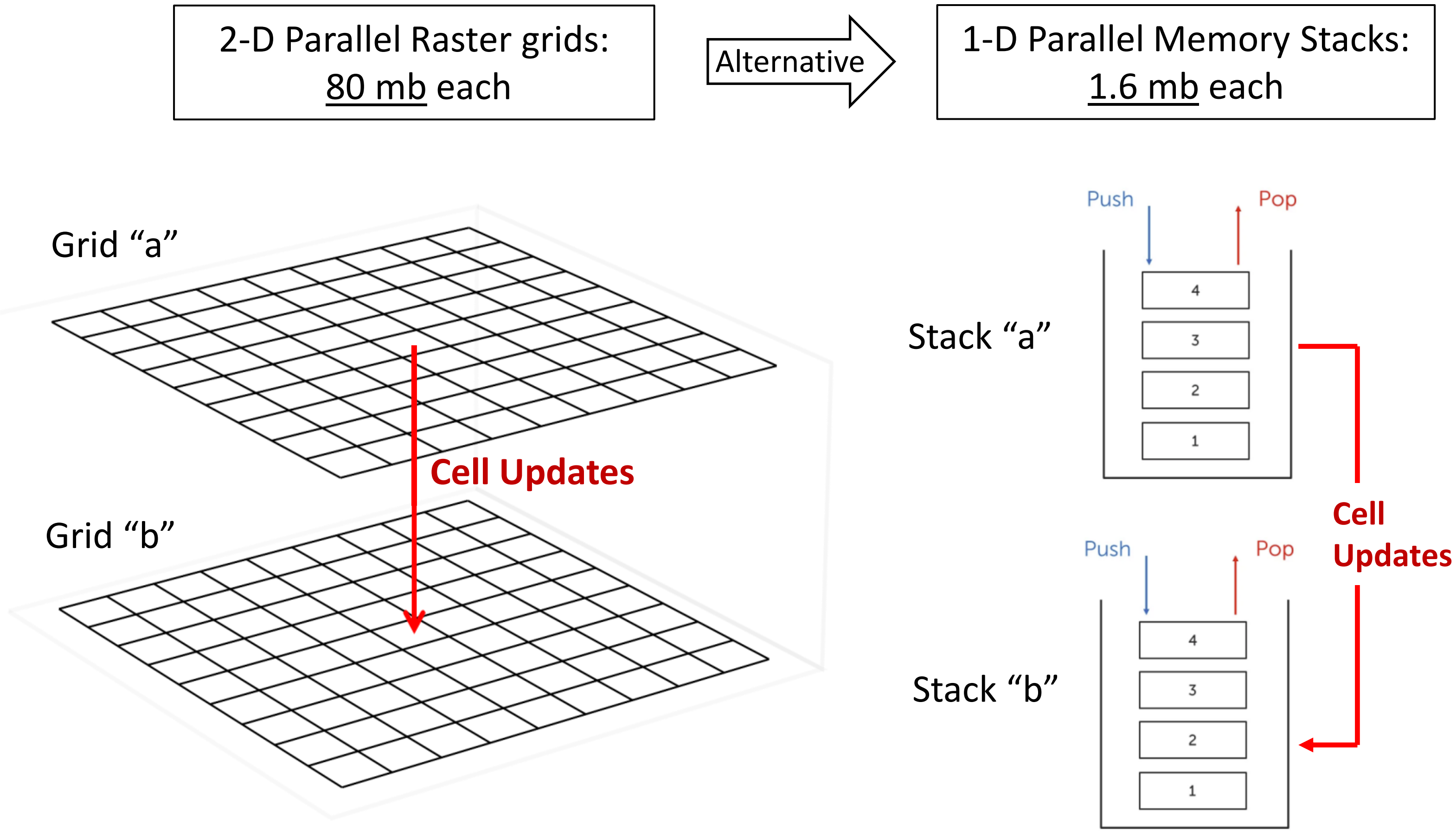
- Raise all flat grid cells* within the iDEM by one unit-depth during each iteration.

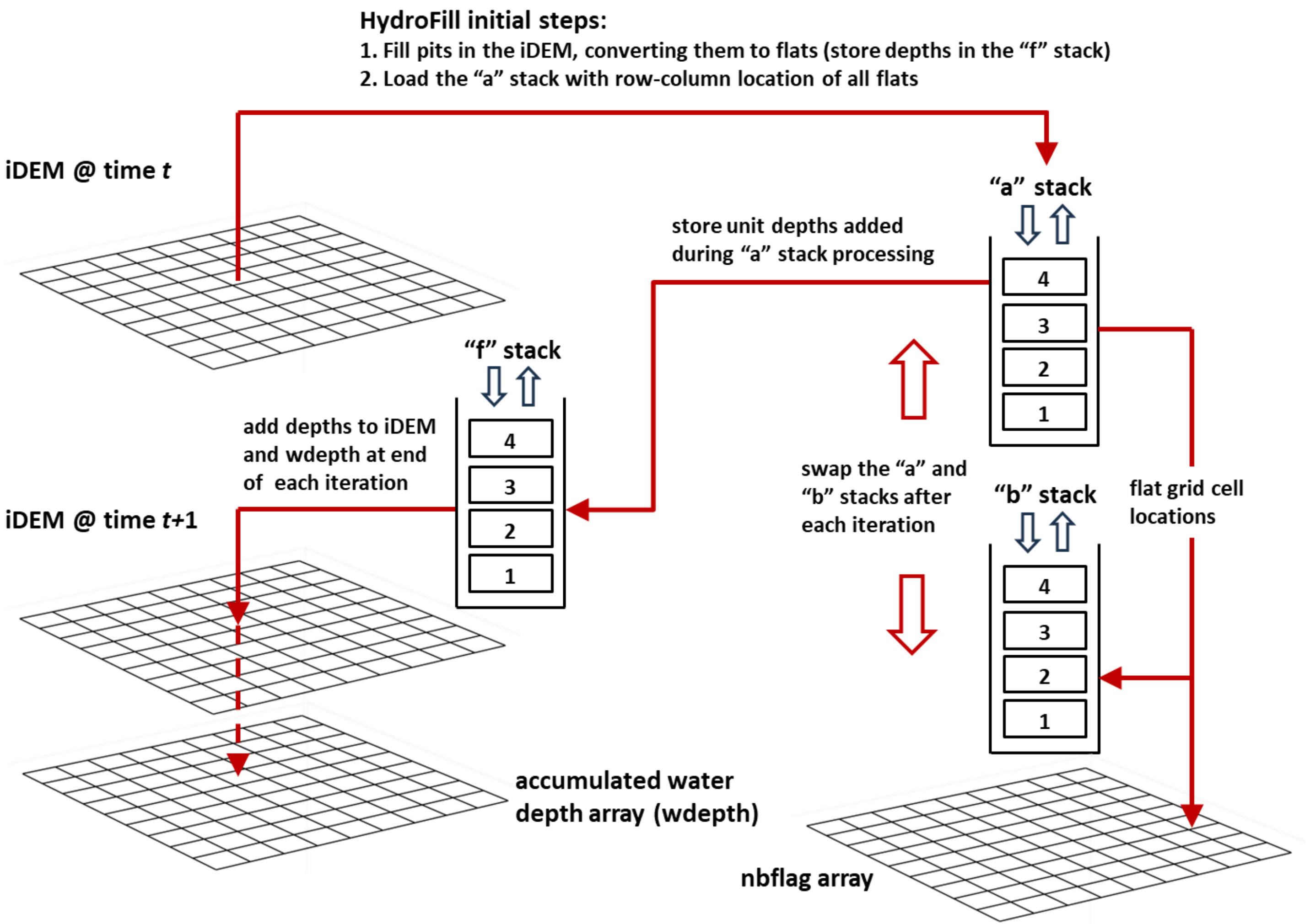


* Flat grid cells are defined as having an elevation equal to at least one surrounding D8 neighborhood grid cell but lower than the remaining grid cells.

HydroFill CA algorithm applied to a 5 x 5 grid

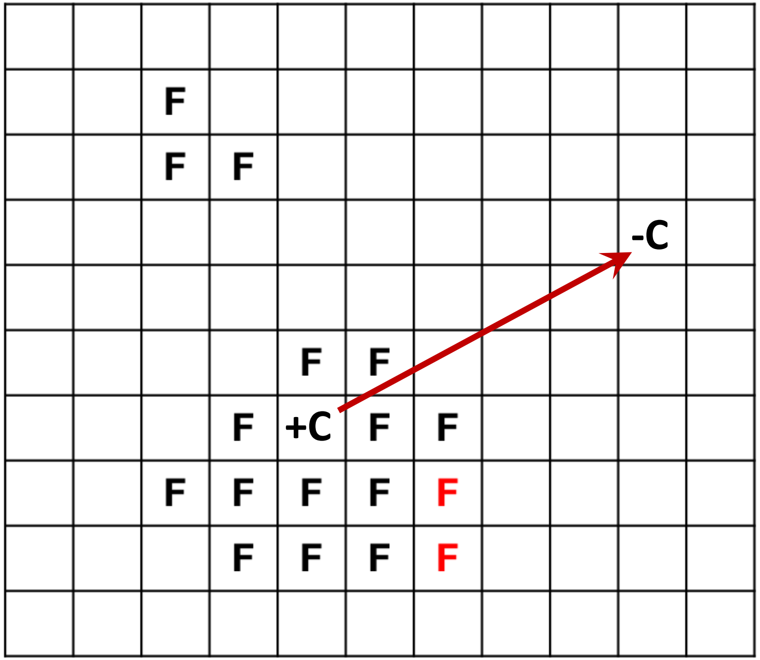



2-D Parallel Raster grids:
80 mb each
Alternative
1-D Parallel Memory Stacks:
1.6 mb each
Grid “a”
Cell Updates
Grid “b”
Push
Pop
Stack “a”
4
3
2
1
Cell
Updates
Push
Pop
Stack “b”
4
3
2
1


HydroFill initial steps:
1. Fill pits in the iDEM, converting them to flats (store depths in the "f" stack)
2. Load the "a" stack with row-column location of all flats
iDEM @ time t
"a" stack
store unit depths added during "a" stack processing
4
3
2
1
"f" stack
4
3
2
1
add depths to iDEM and wdepth at end of each iteration
iDEM @ time t+1
swap the "a" and "b" stacks after each iteration
"b" stack
4
3
2
1
flat grid cell locations
accumulated water depth array (wdepth)
nbflag array

❑ "nbflag" array is co-located with iDEM

1. Marks location of flat grid cells stored in the "b" stack.
   - Includes any additional D8 grid cells with +1 elevation.
2. Locates culvert (and drain) entrances and exits.
   - Note: entrance-exit locations are generated in QGIS.



F = flat grid cell

F = grid cell at +1 elevation in D8

+C = culvert (or drain) entrance.

-C = culvert (or drain) exit.

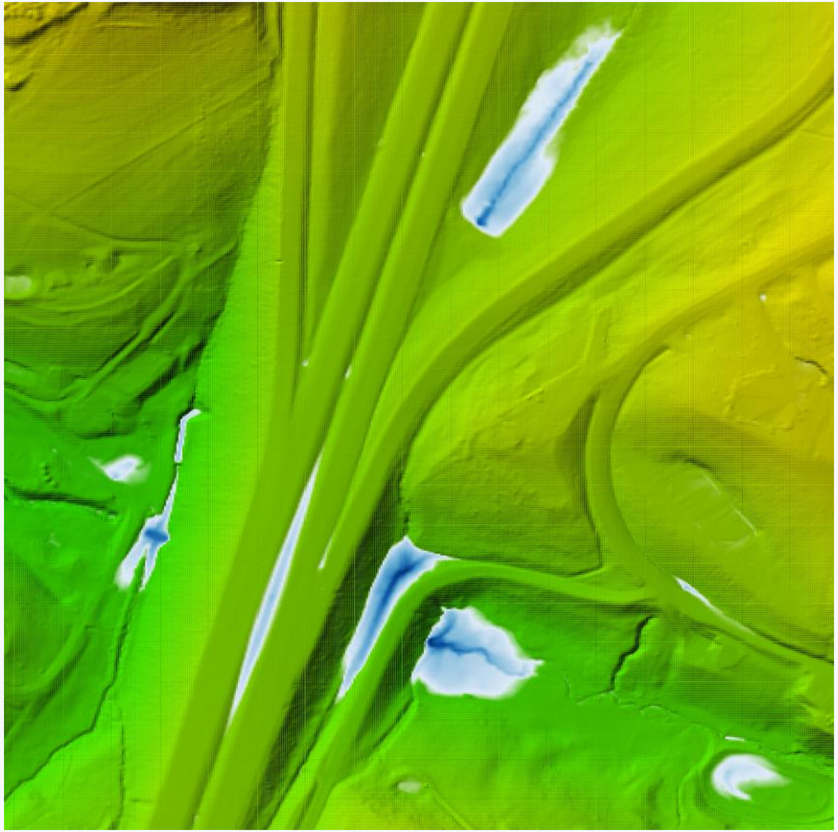
DEM Drainage Processing Algorithms*

- **HydroFill** – Provides a continuous downslope flow path from each interior DEM grid cell to the outer boundary cells of raster format DEMs.

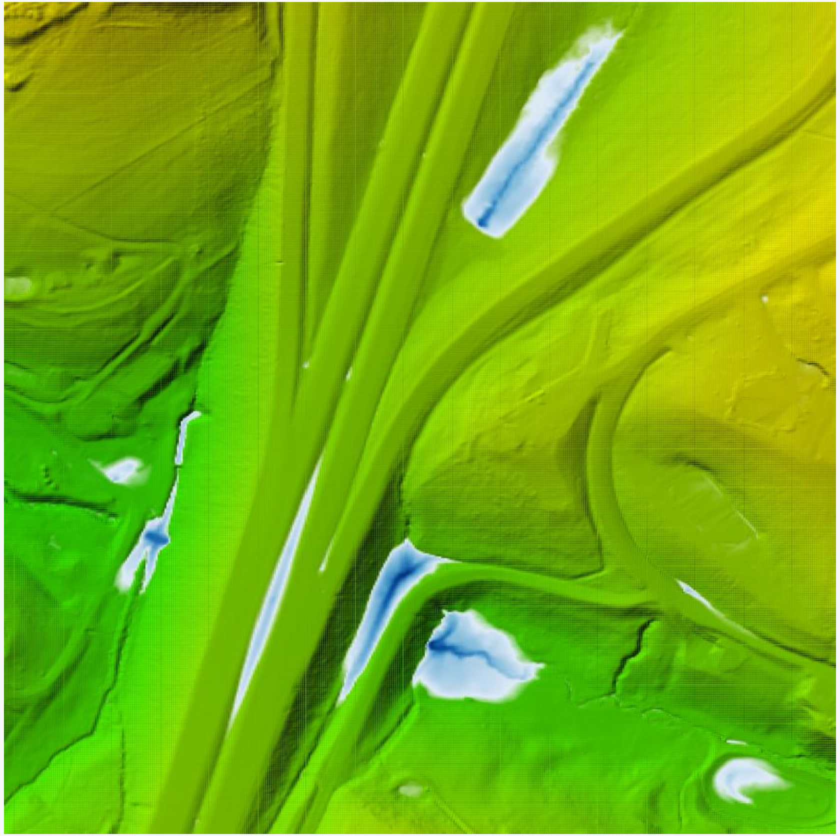
- **HydroDrain** – Follows HydroFill and assigns drainage basin ID numbers to the DEM outer boundary grid cells and labels each interior grid cell with its corresponding basin ID number and tributary area.

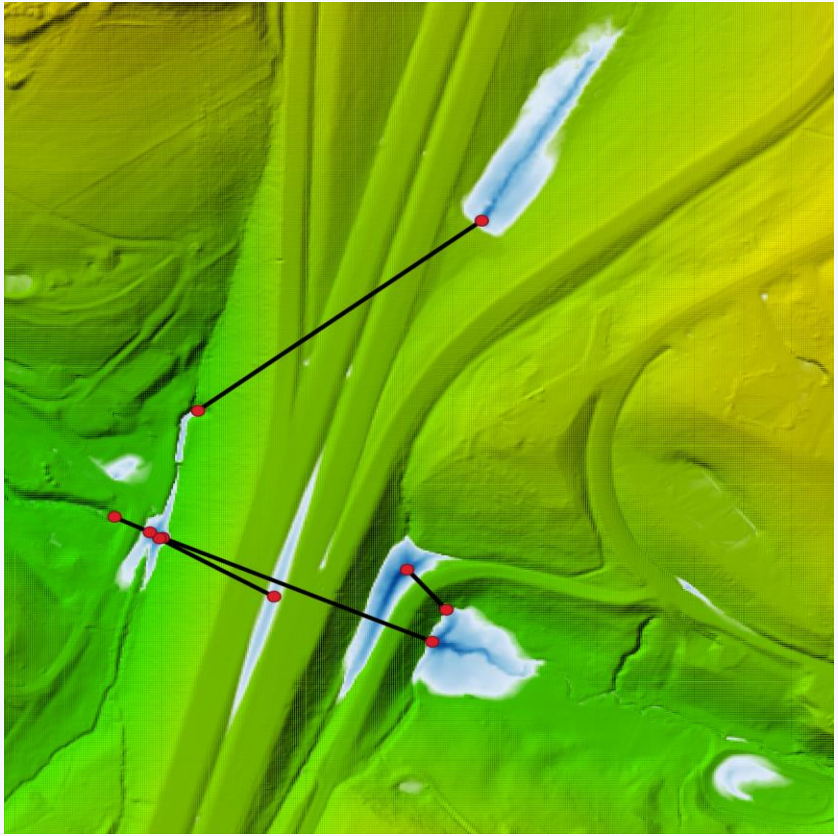
*Currently implemented in MATLAB script, with GIS support provided by QGIS

First Step: Apply some "Virtual Ponding" to the DEM using HydroFill

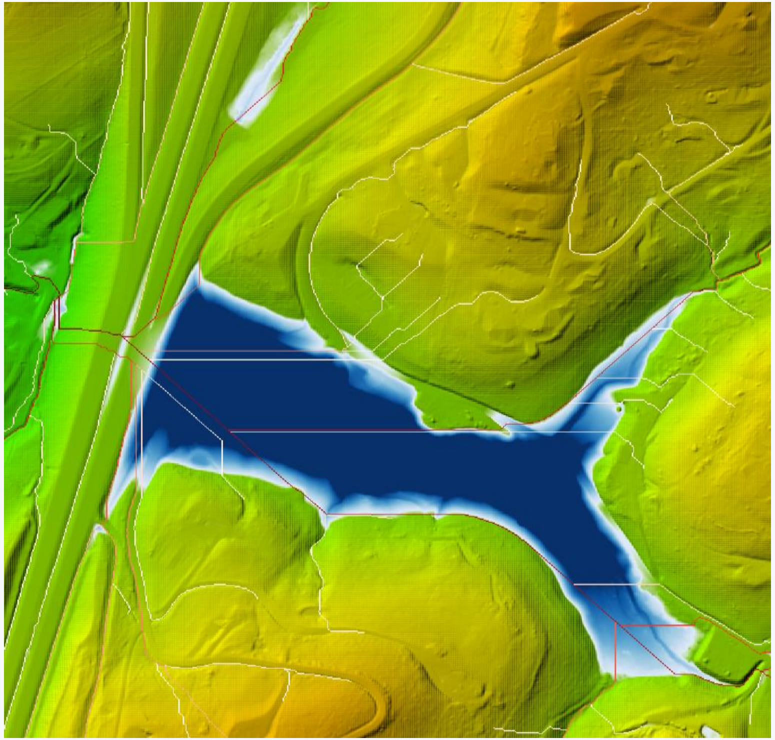


Second Step: Add culverts and drains via a vector layer in QGIS

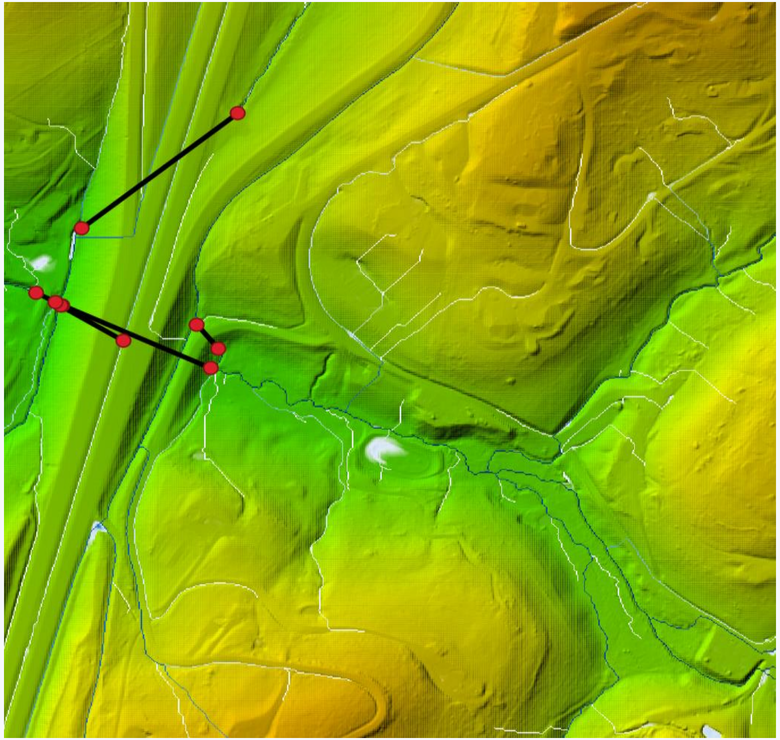




<u>Third Step</u>: Run HydroFill & HydroDrain to complete the drainage network

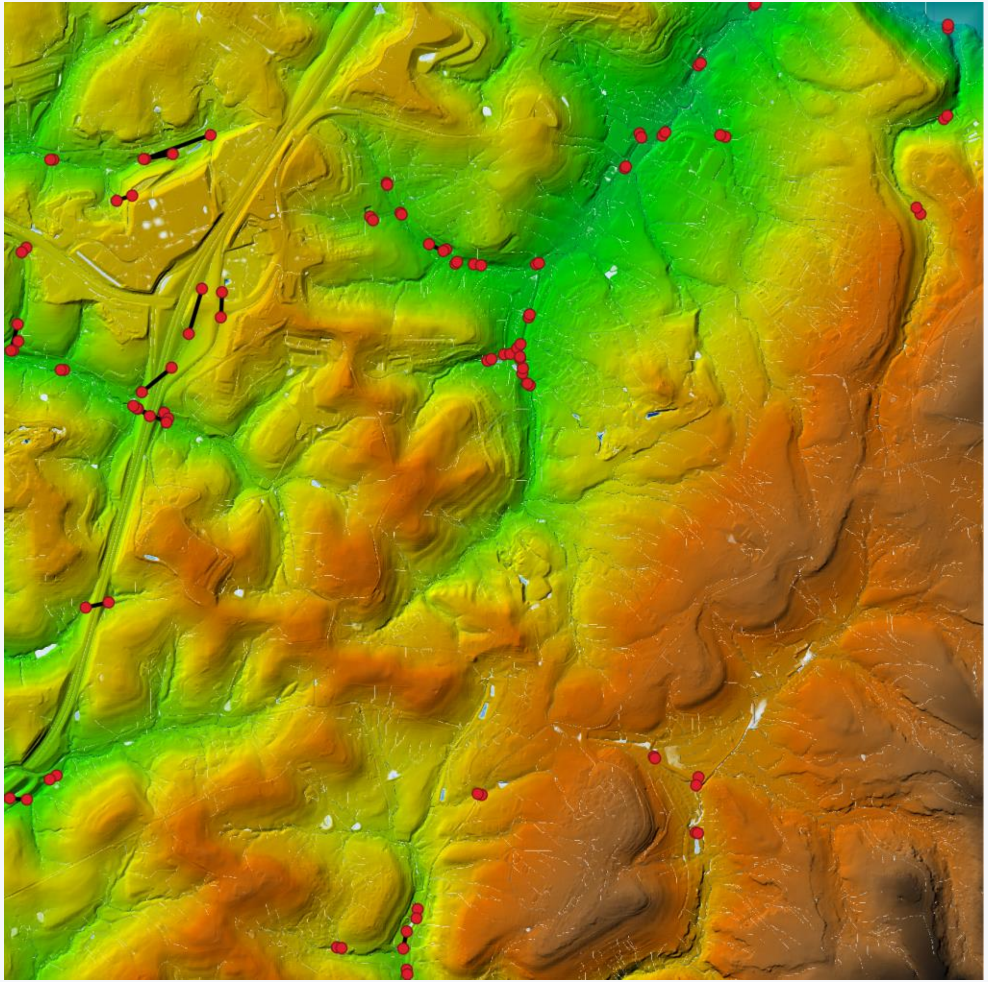


Without Culverts

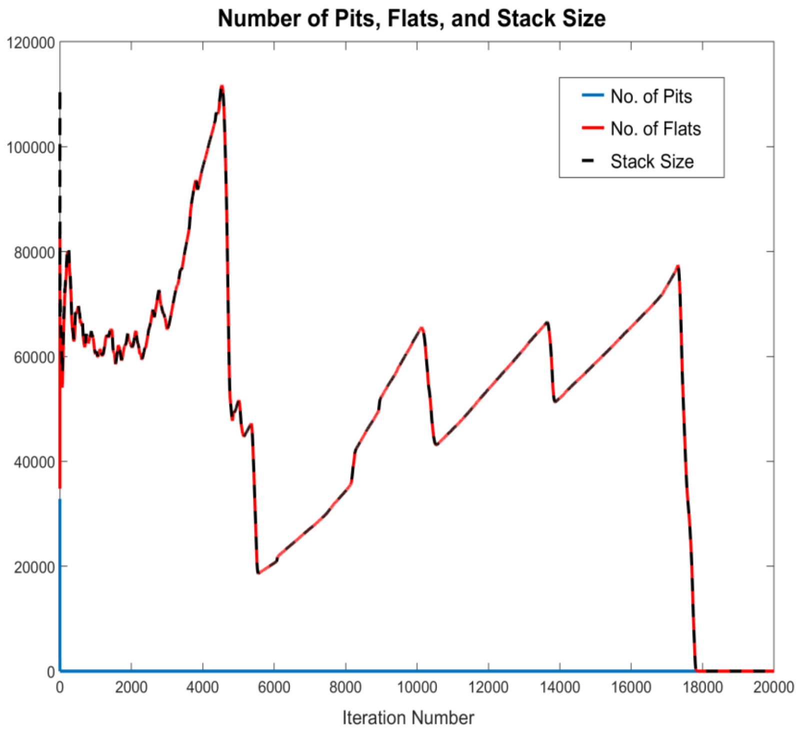


With Culverts

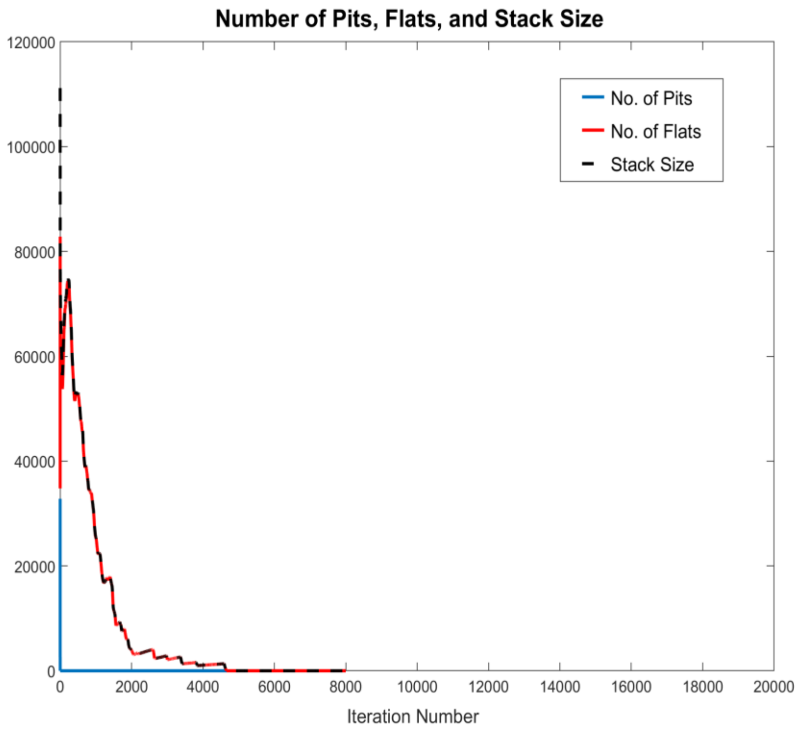
<u>50 culverts and drains</u> **were added to the Whites Run data set and HydroFill & HydroDrain were used to compare the resulting drainage path changes.**



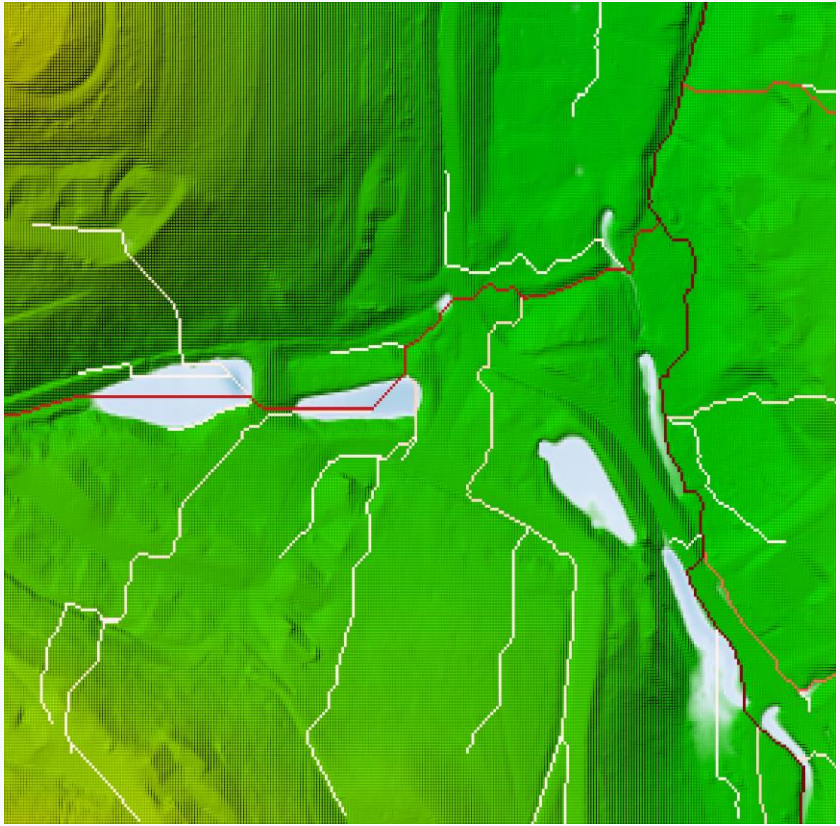
Without Culverts and Drains (compute time = 1184 seconds)

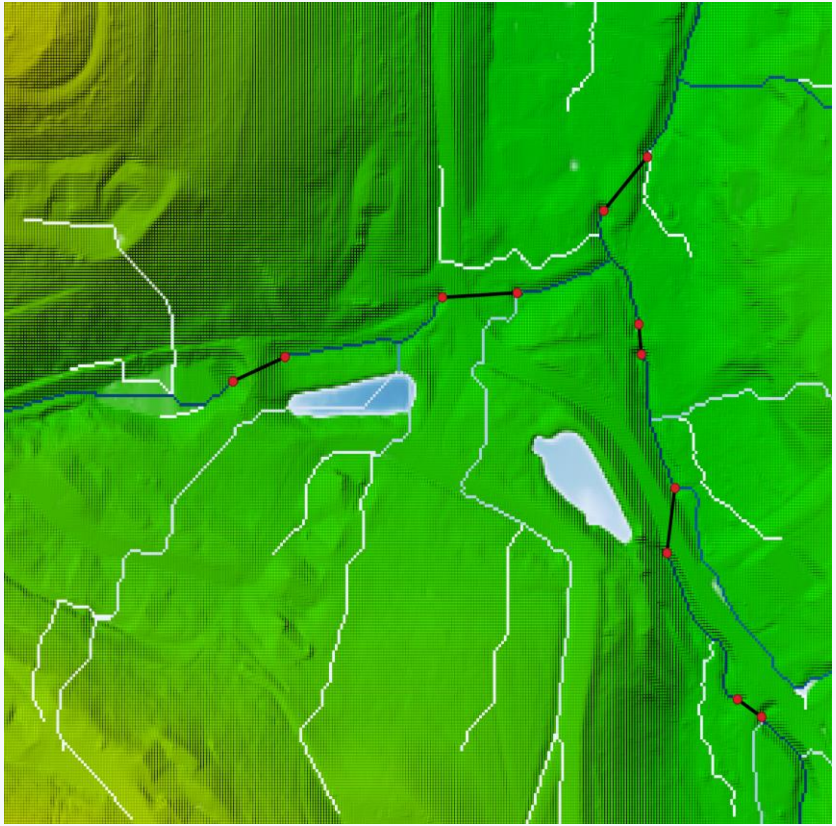


With Culverts and Drains (compute time = 128 seconds)

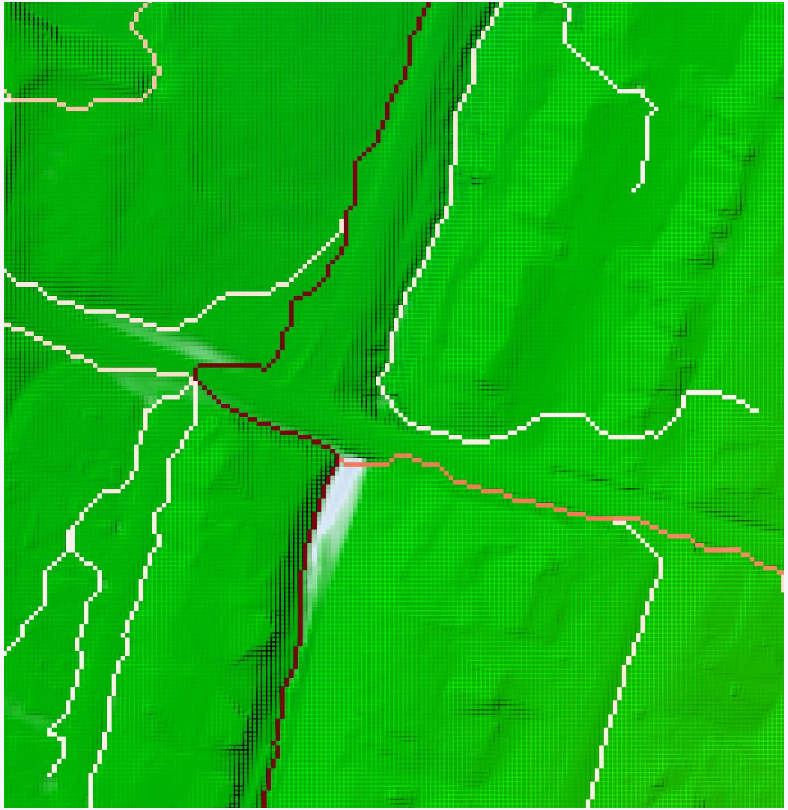


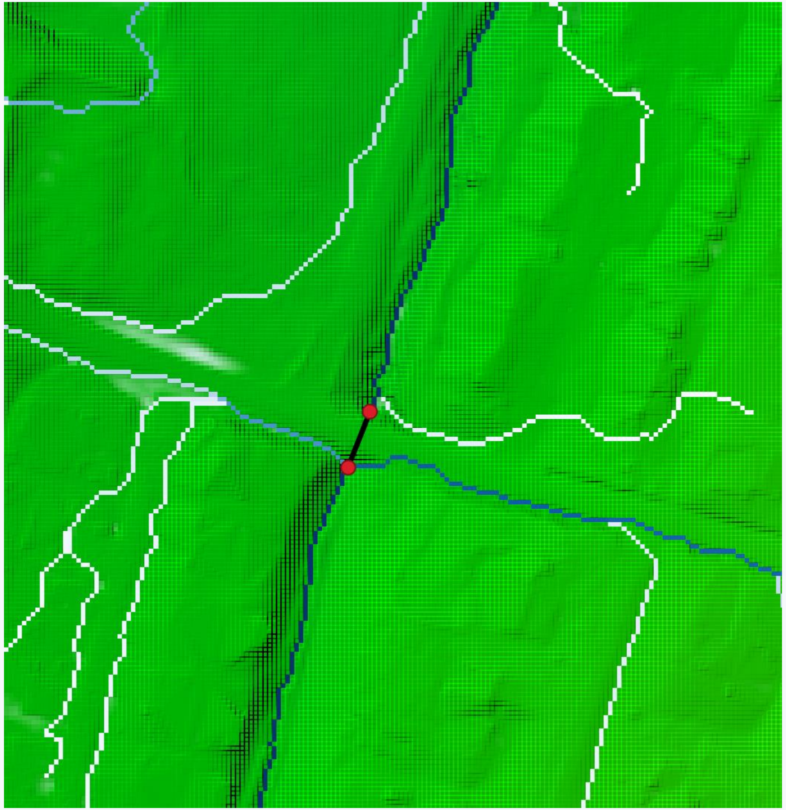
Pounds Hollow Ponds and Culverts – Upper Whites Run



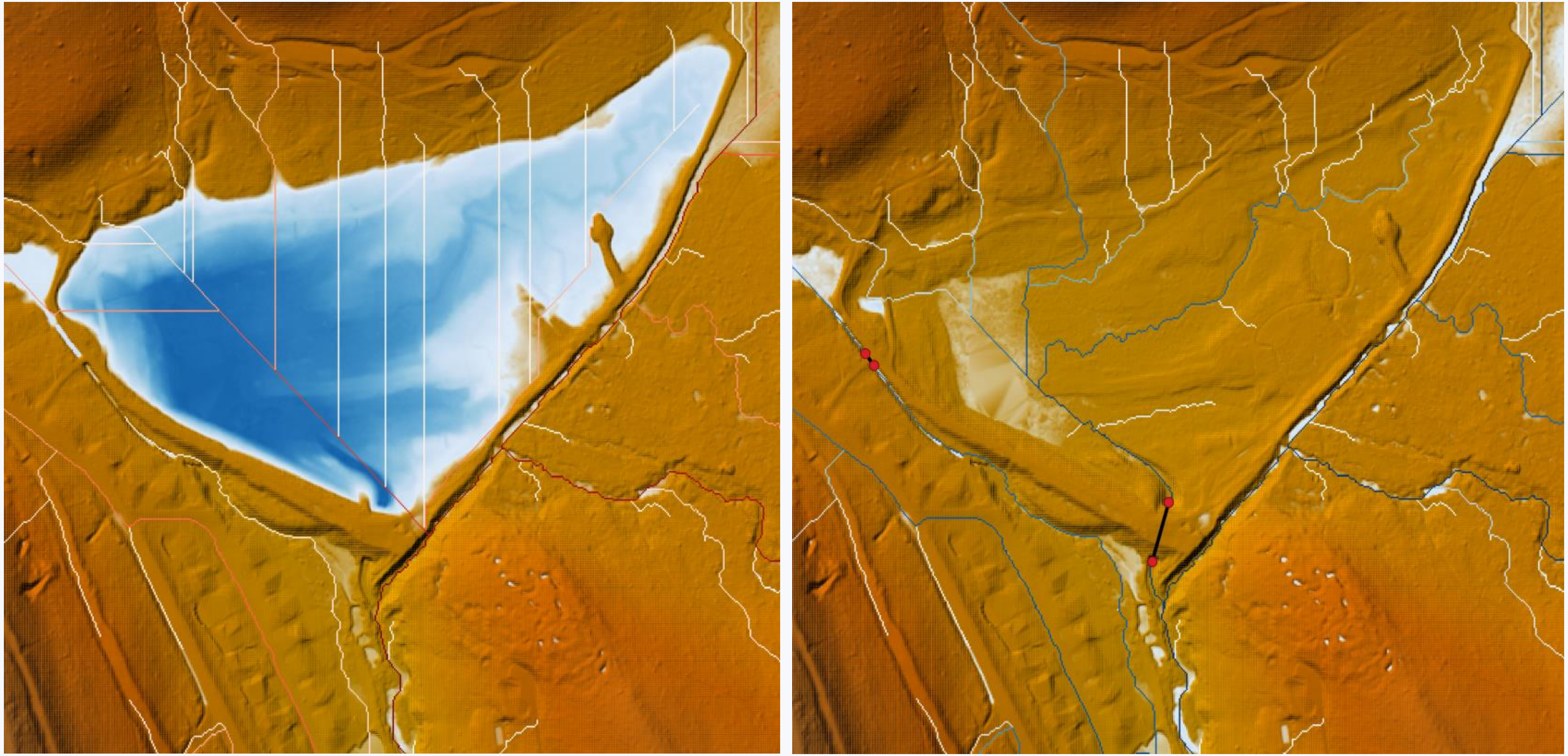


Tyrone-Avery Road Culvert at Whites Run

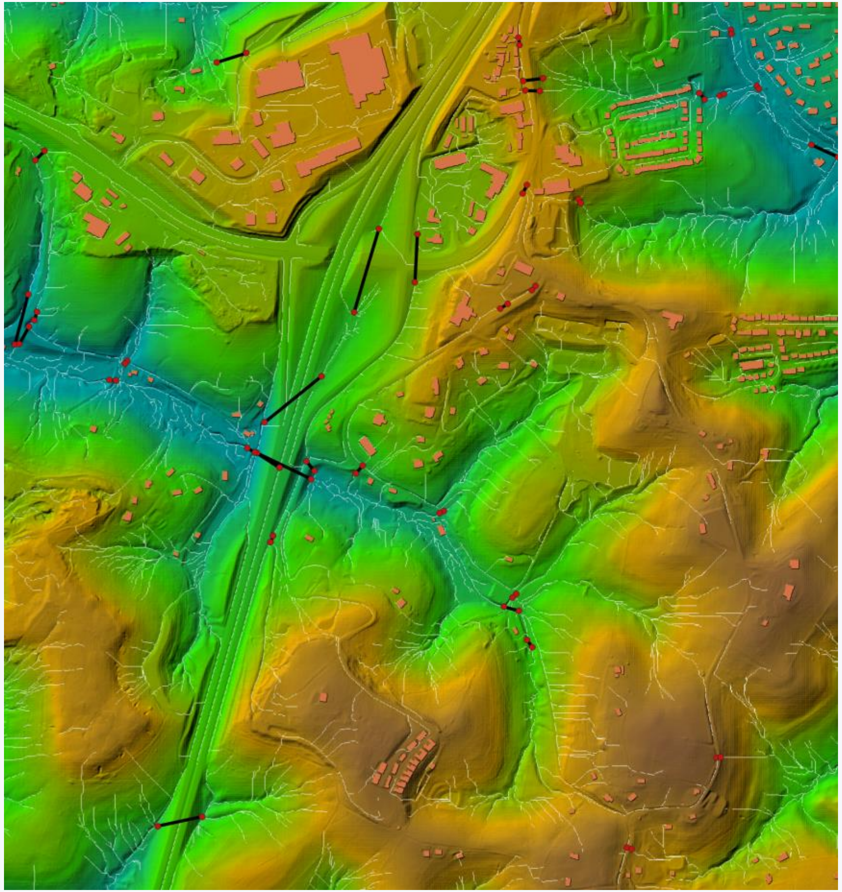




Tibbs Run Reservoir (Decommissioned)

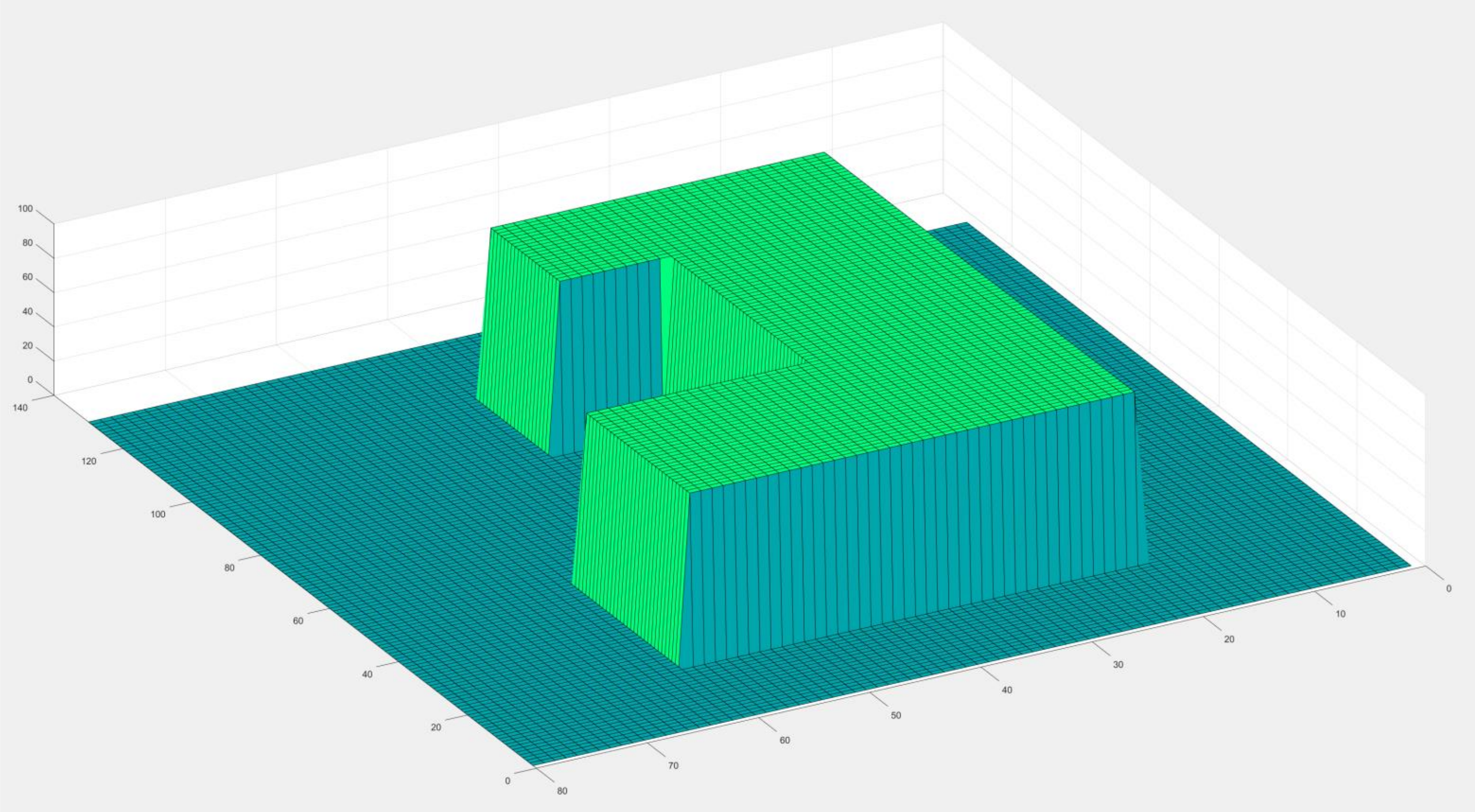


https://github.com/elirober/HydroFill-Example

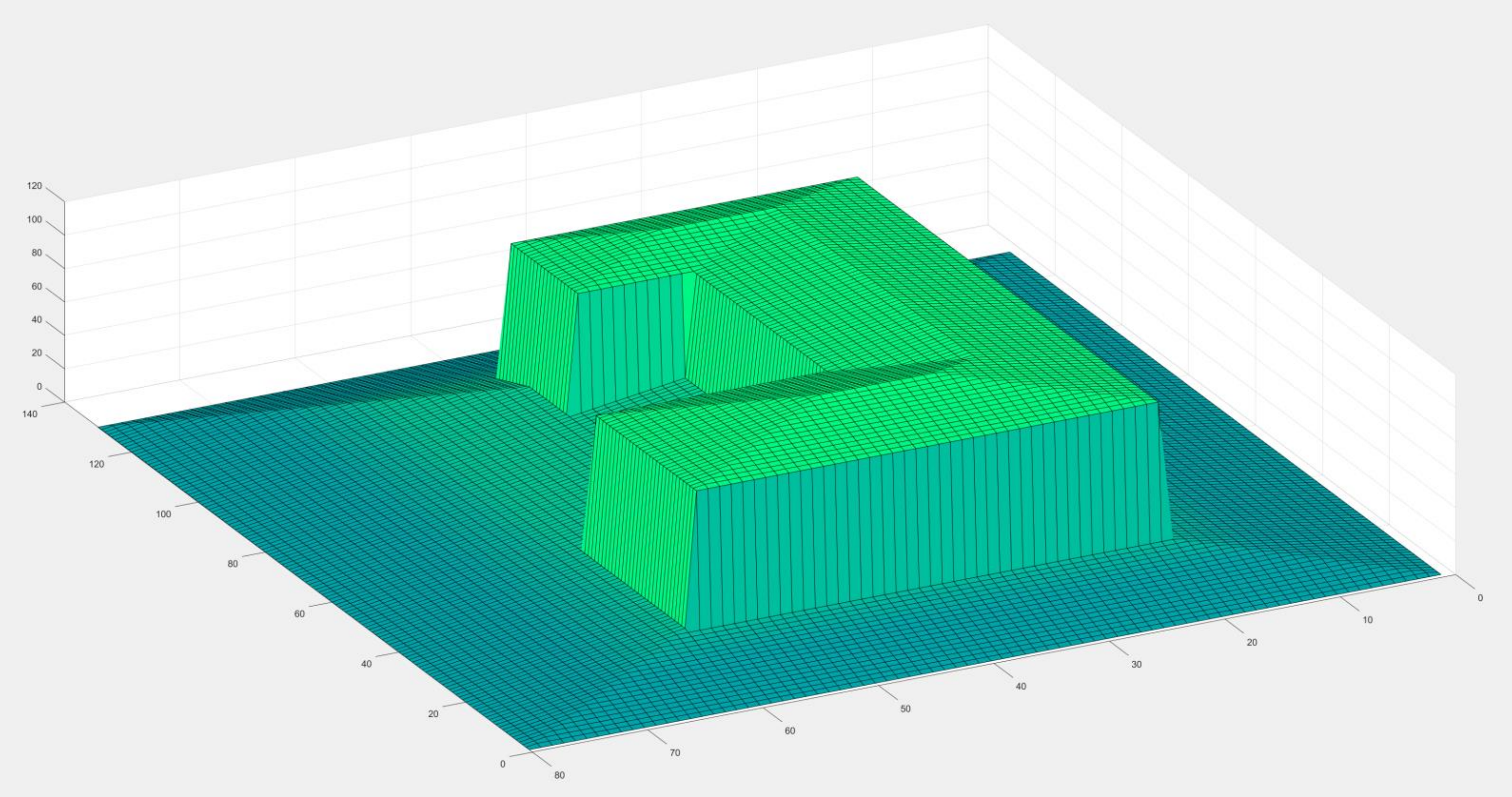


- MATLAB .m files
  - MIT License
- DEM subset
  - 2179 x 2015
- MS Buildings added
  - Flat-top roofs
- 35 culverts & drains
  - CIO table included

3D View of Flat Top Building on Flat Surface



3D View of Flat Top Building After HydroFill Processing



Summary and Conclusions:

- HydroFill can preprocess DEMs of any resolution.
  - Developed over a 20-year period using 10-m, 5-m, 3-m, 1-m, and 0.5-m DEMs.

- Subsurface culverts and drains can be added if DEM resolution is sufficient [<= (1-m)].

- Building structures (e.g., Microsoft Buildings datasets) can be added using a MATLAB .m algorithm to overwrite the DEM with a computed flat building roof elevation.

- All DEM flat surfaces, including building roofs, are given a minimal slope of 1 Unit-Depth/DEM grid spacing.

Thankyou for your attendance…

Questions?