# Concepts and Tools for Hydrologic Modeling with LiDAR Terrain Data

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USGS Upper Midwest Water Science Center

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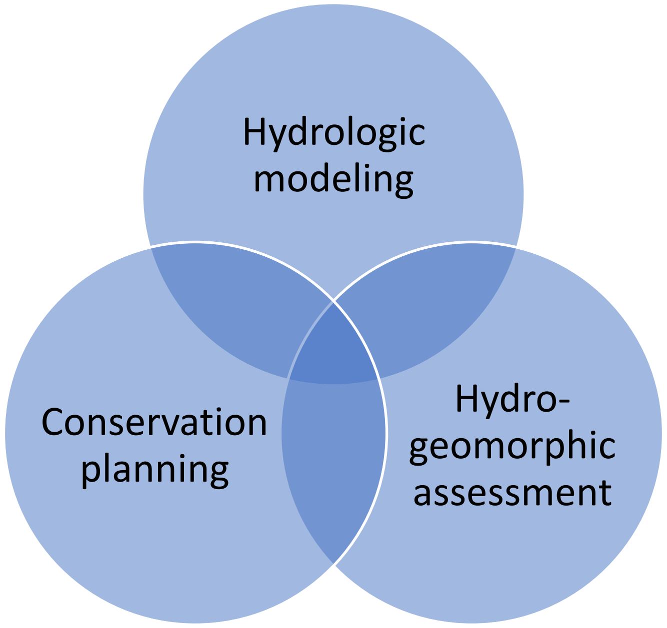
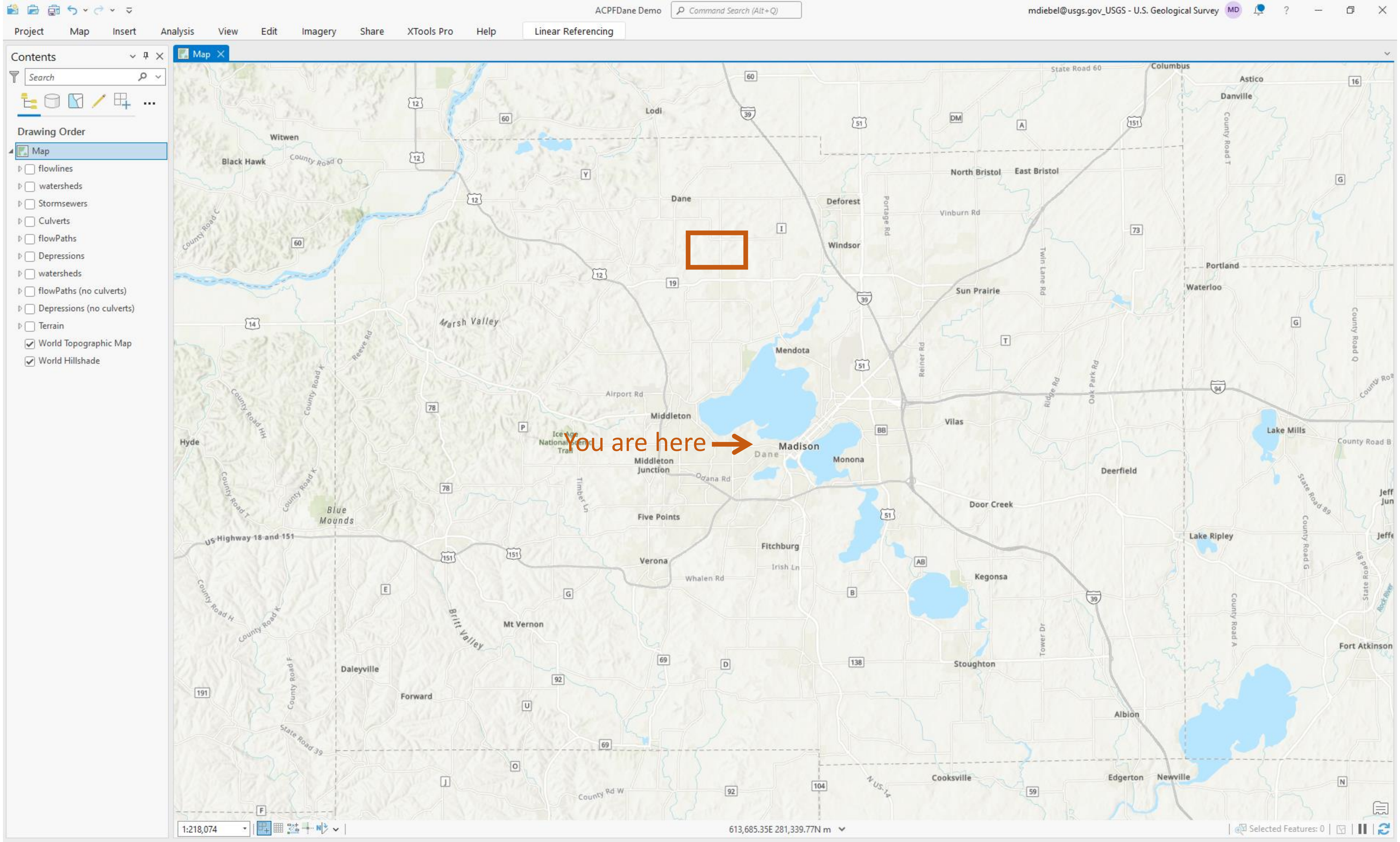
# Concepts

- To be useable for hydrologic modeling, most bare-earth LiDAR DEMs need to be “hydrologically conditioned”. This means mapping culverts and other sub-surface drainage structures.
- The high resolution of LiDAR DEMs allows modeling of “fill-and-spill” hydrology, which is common in glaciated terrain.



# Tools

- ArcGIS Hydrology Toolbox
- Agricultural Conservation Planning Framework (ACPF)
- ACPF Dane
- SWAT (DSF)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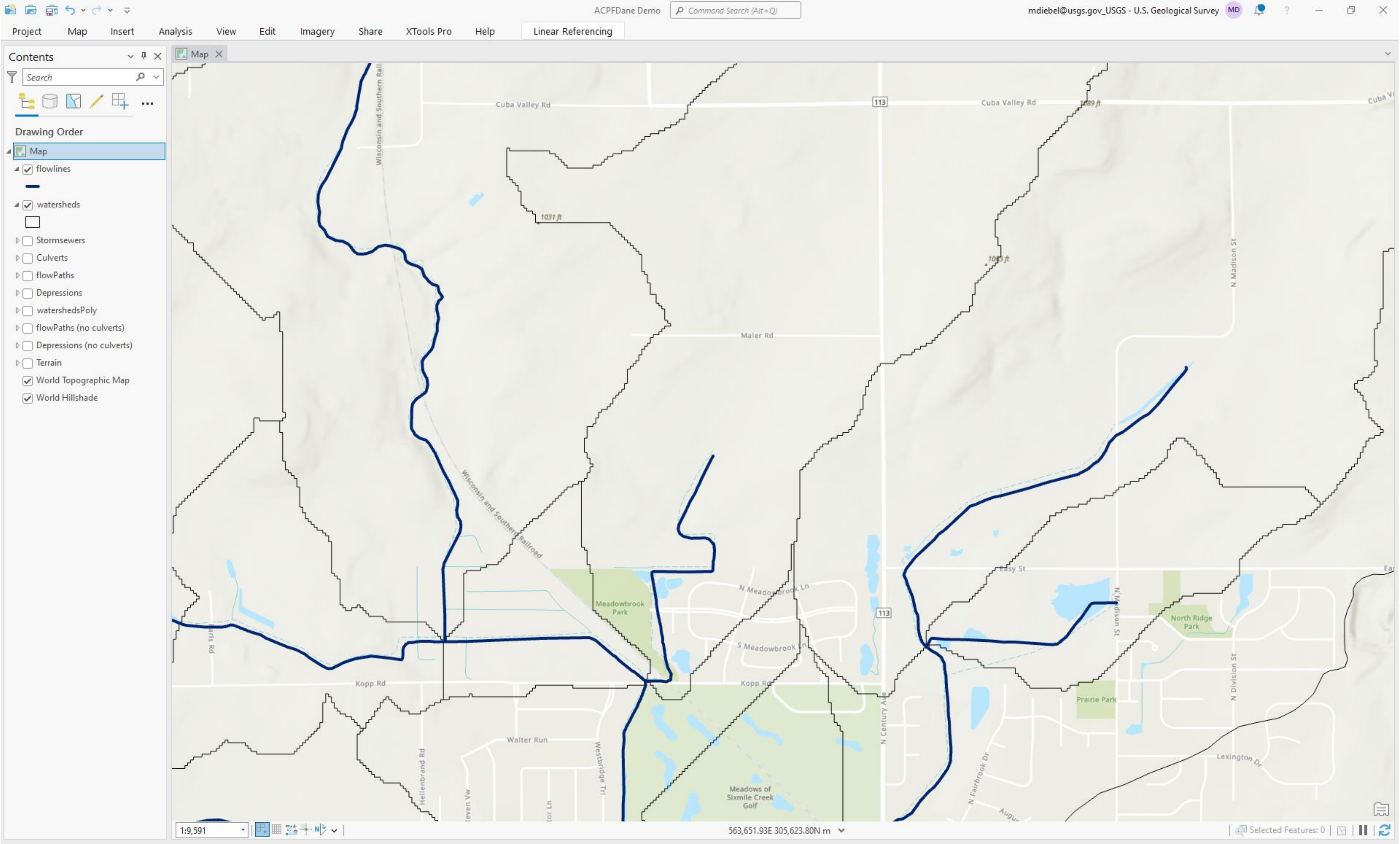
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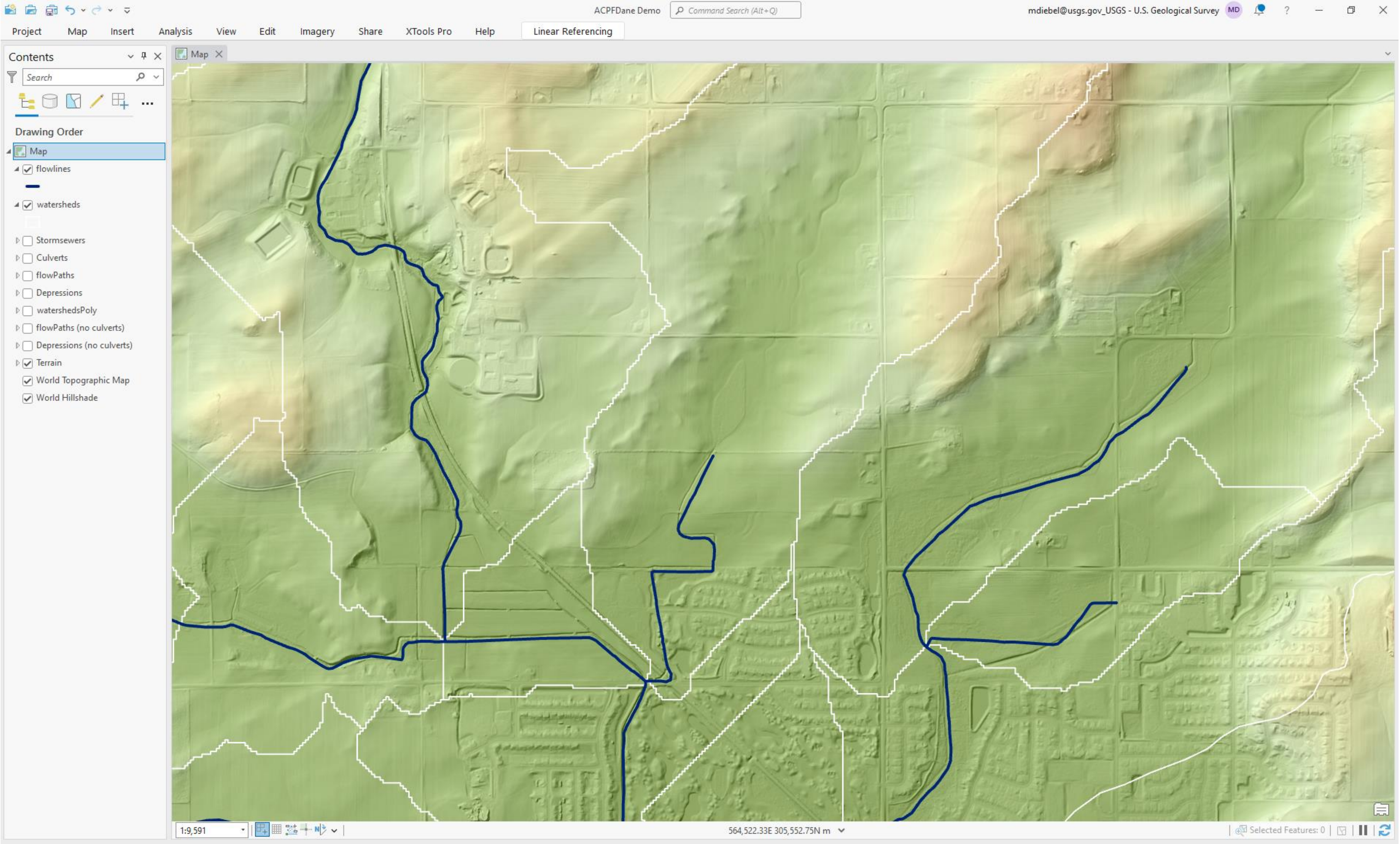
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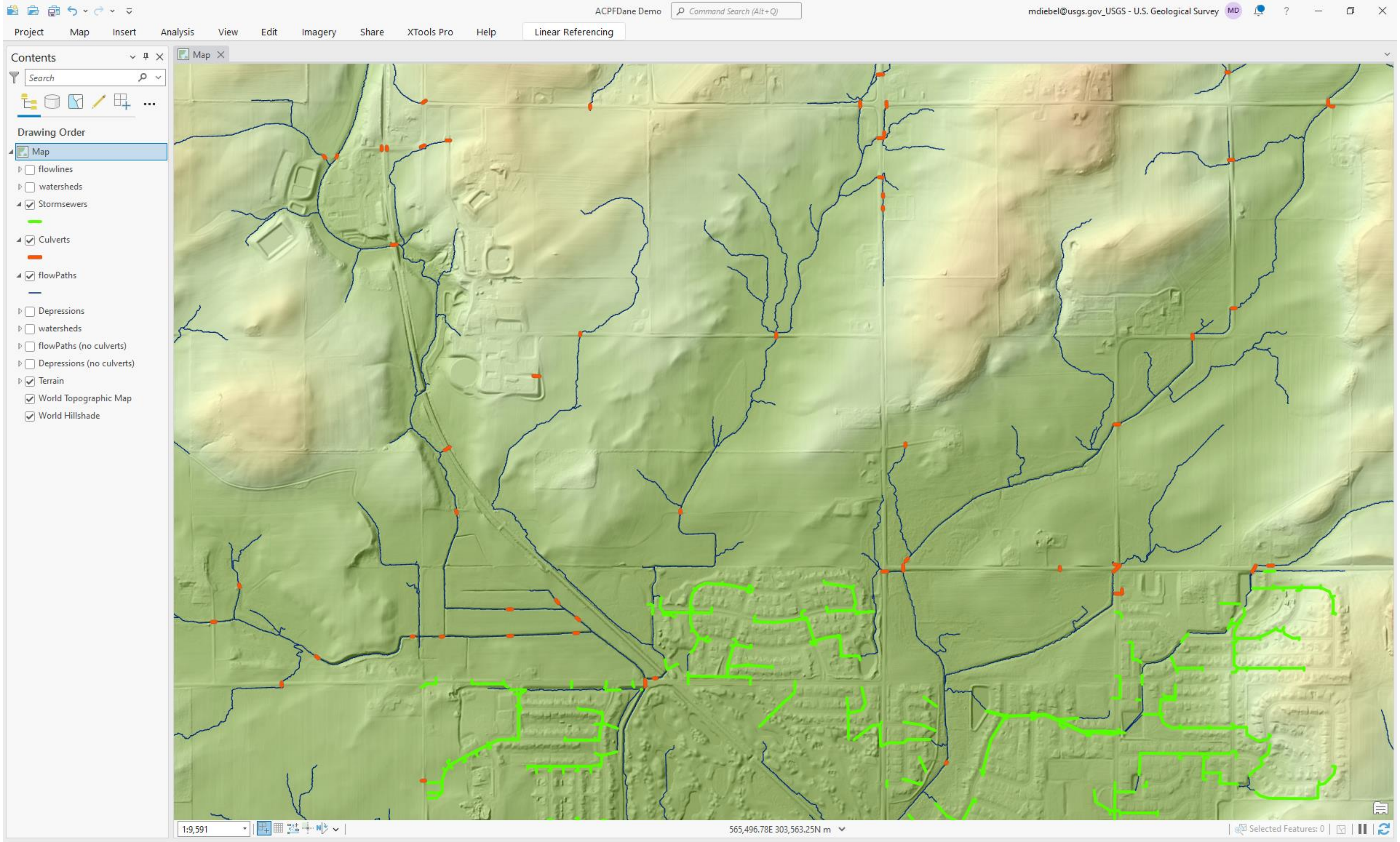
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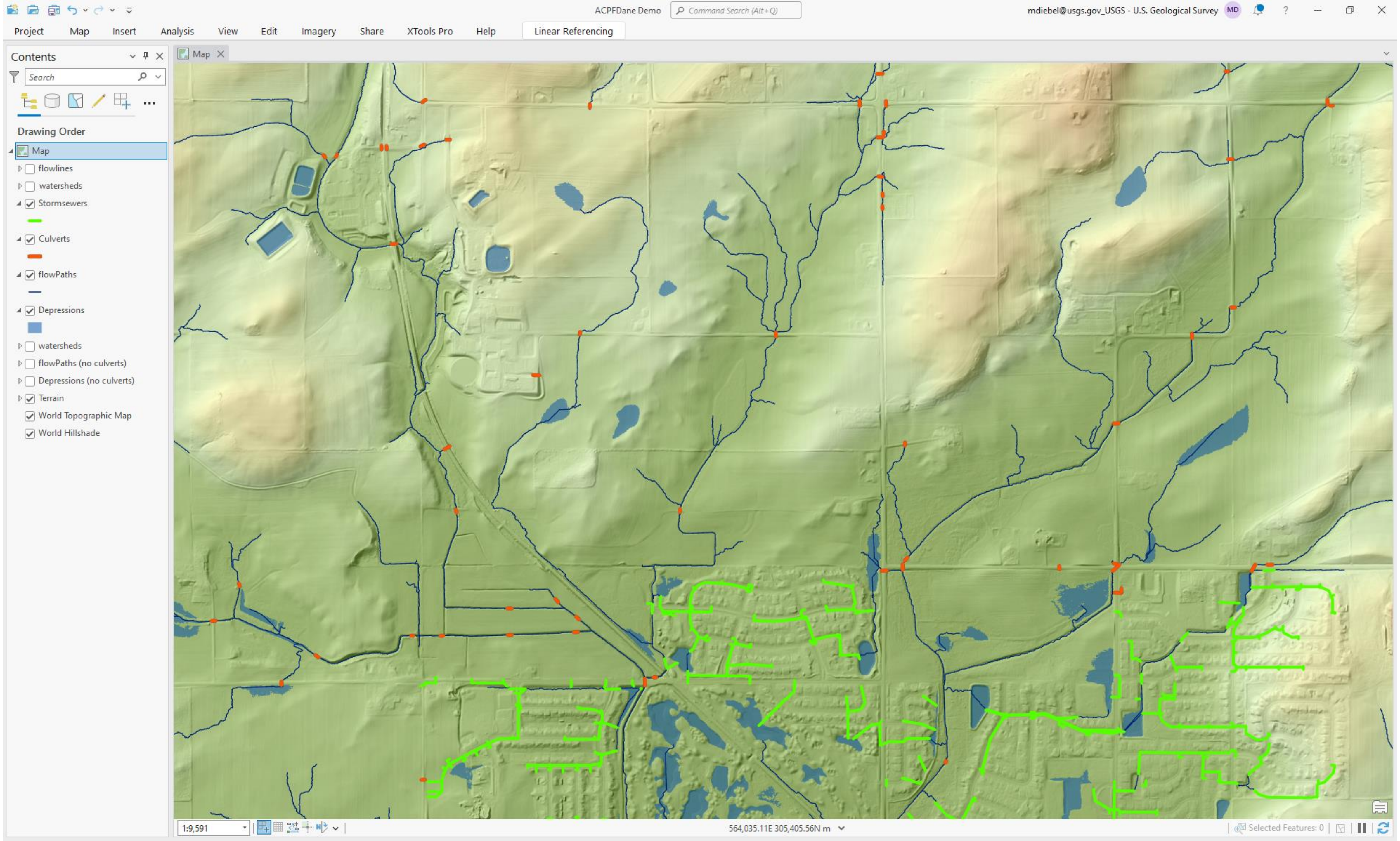
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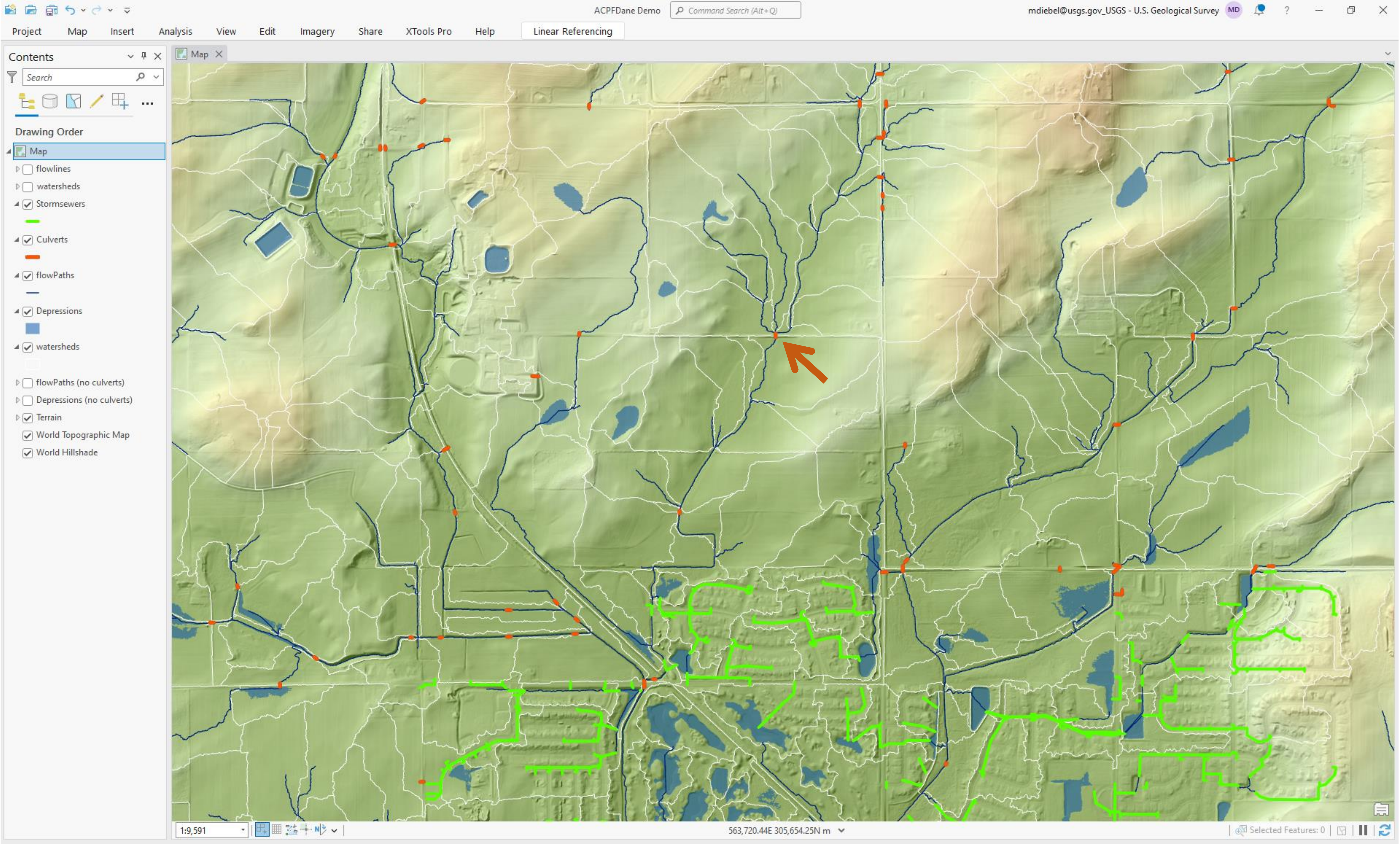
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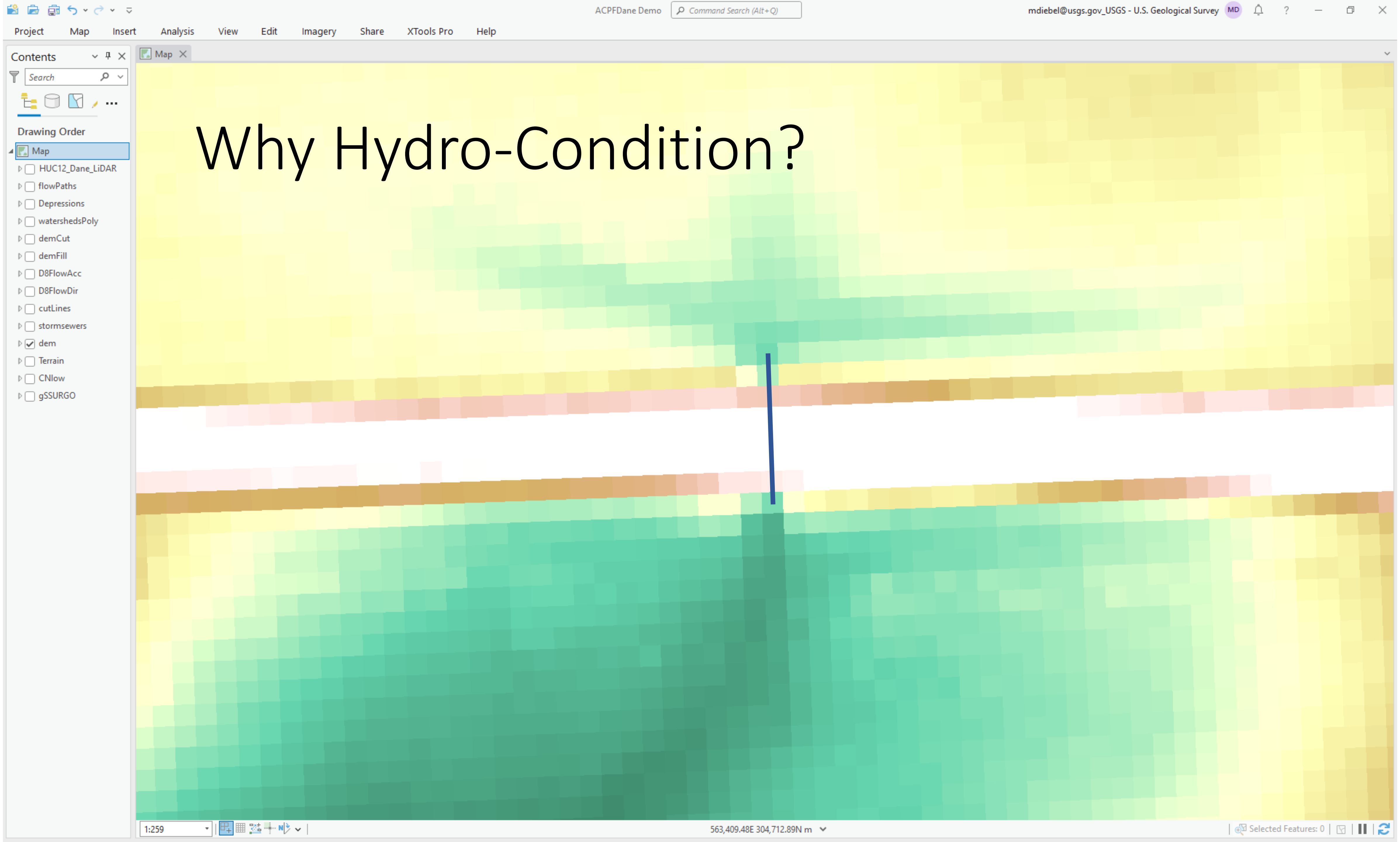

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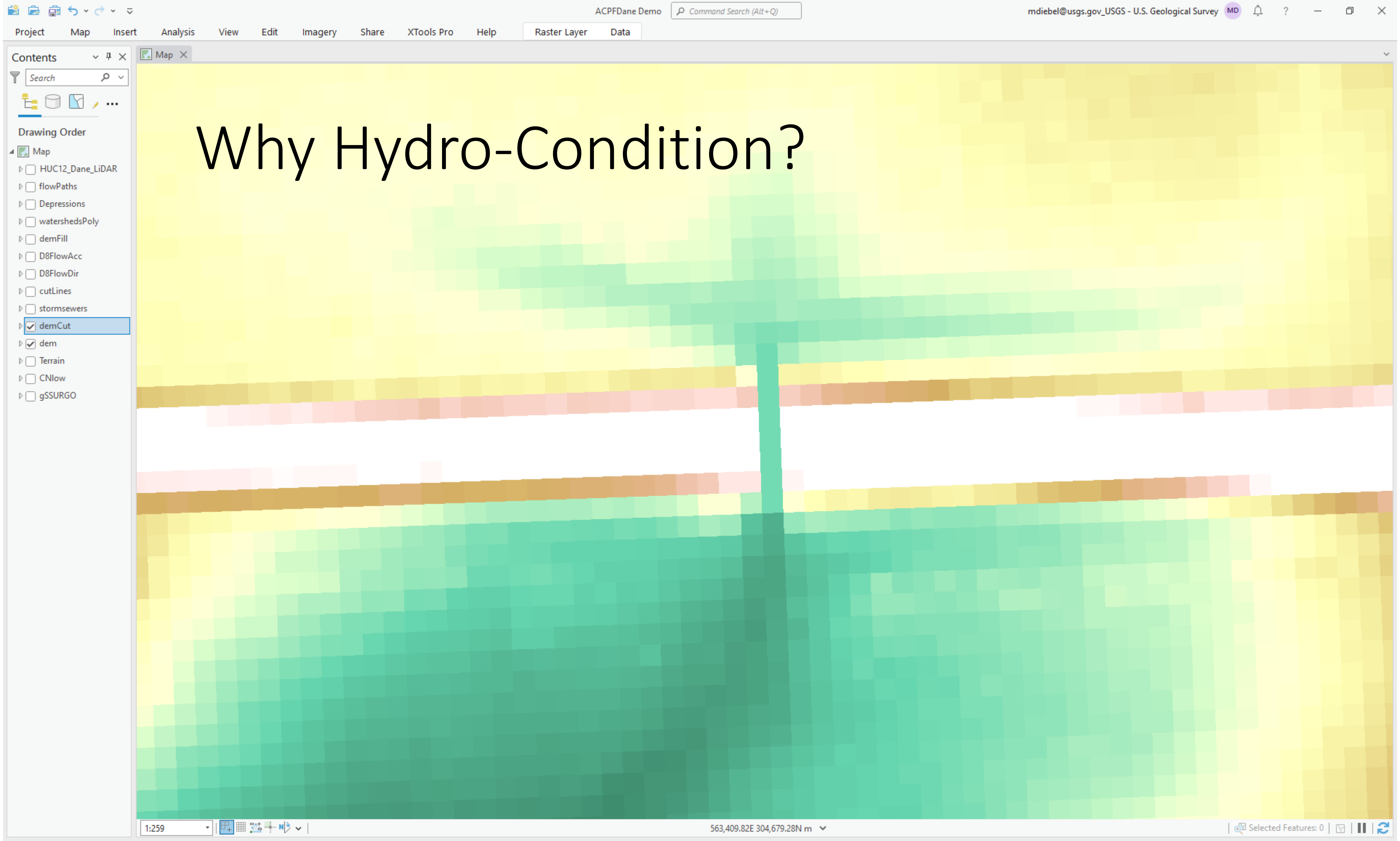

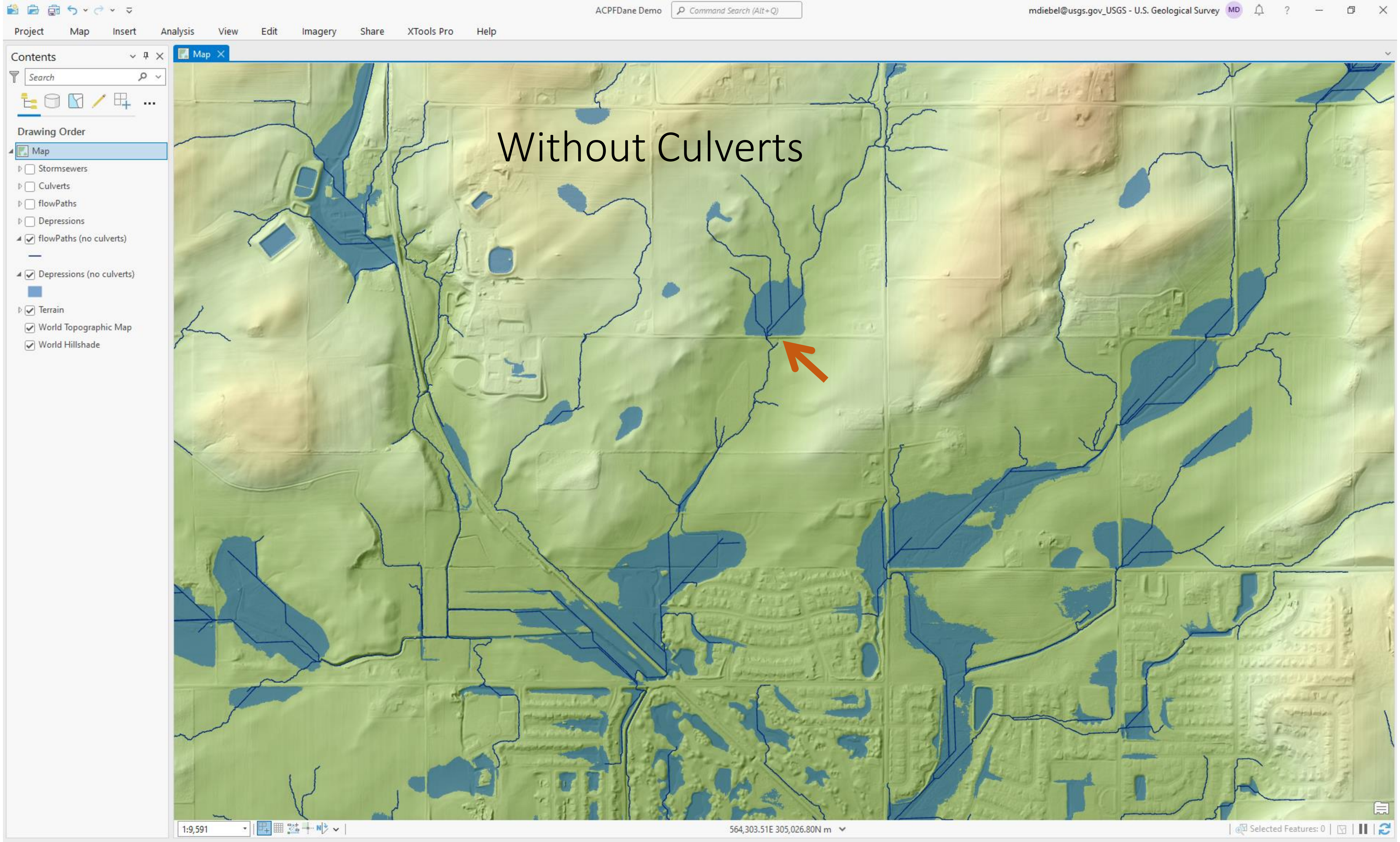
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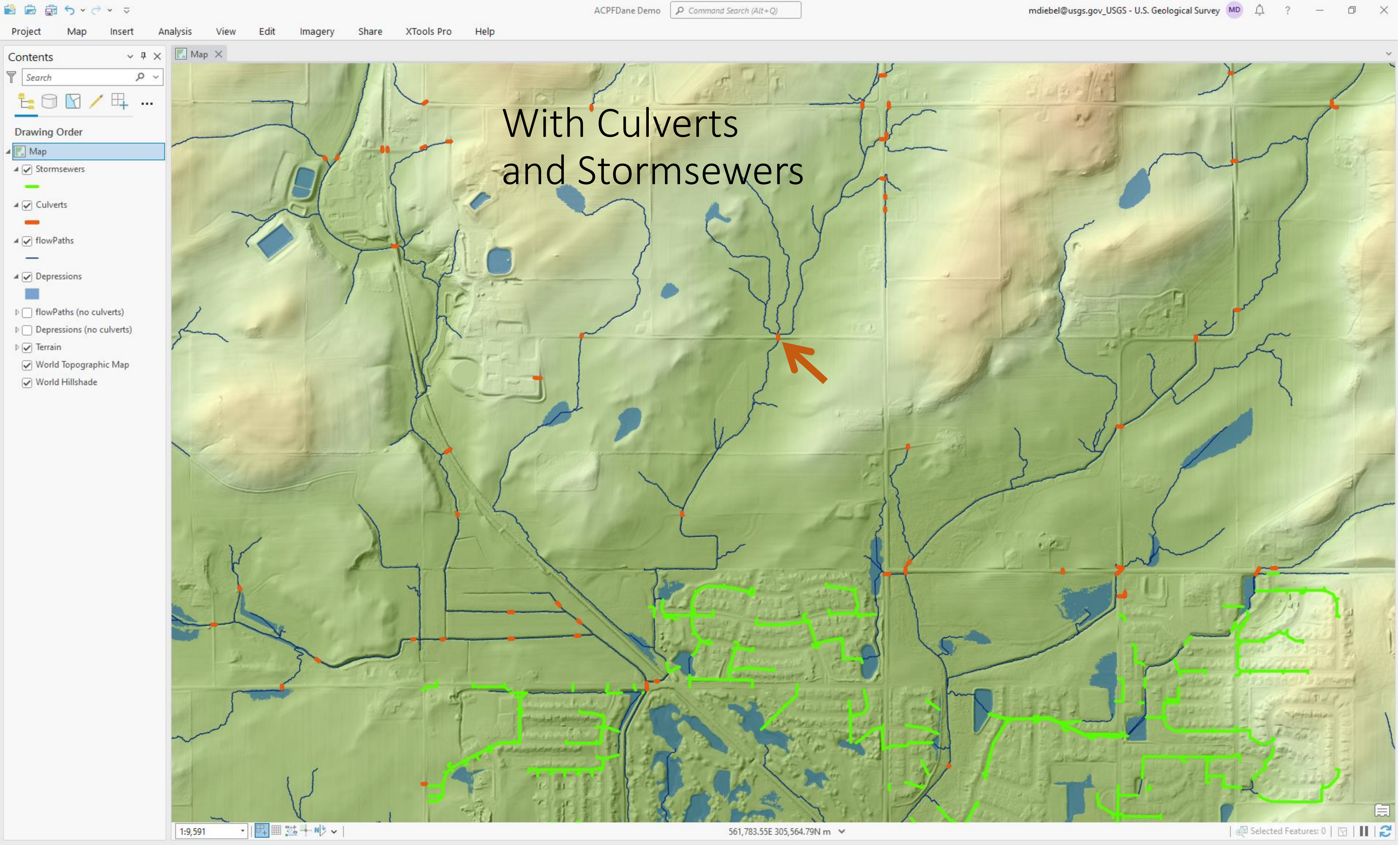
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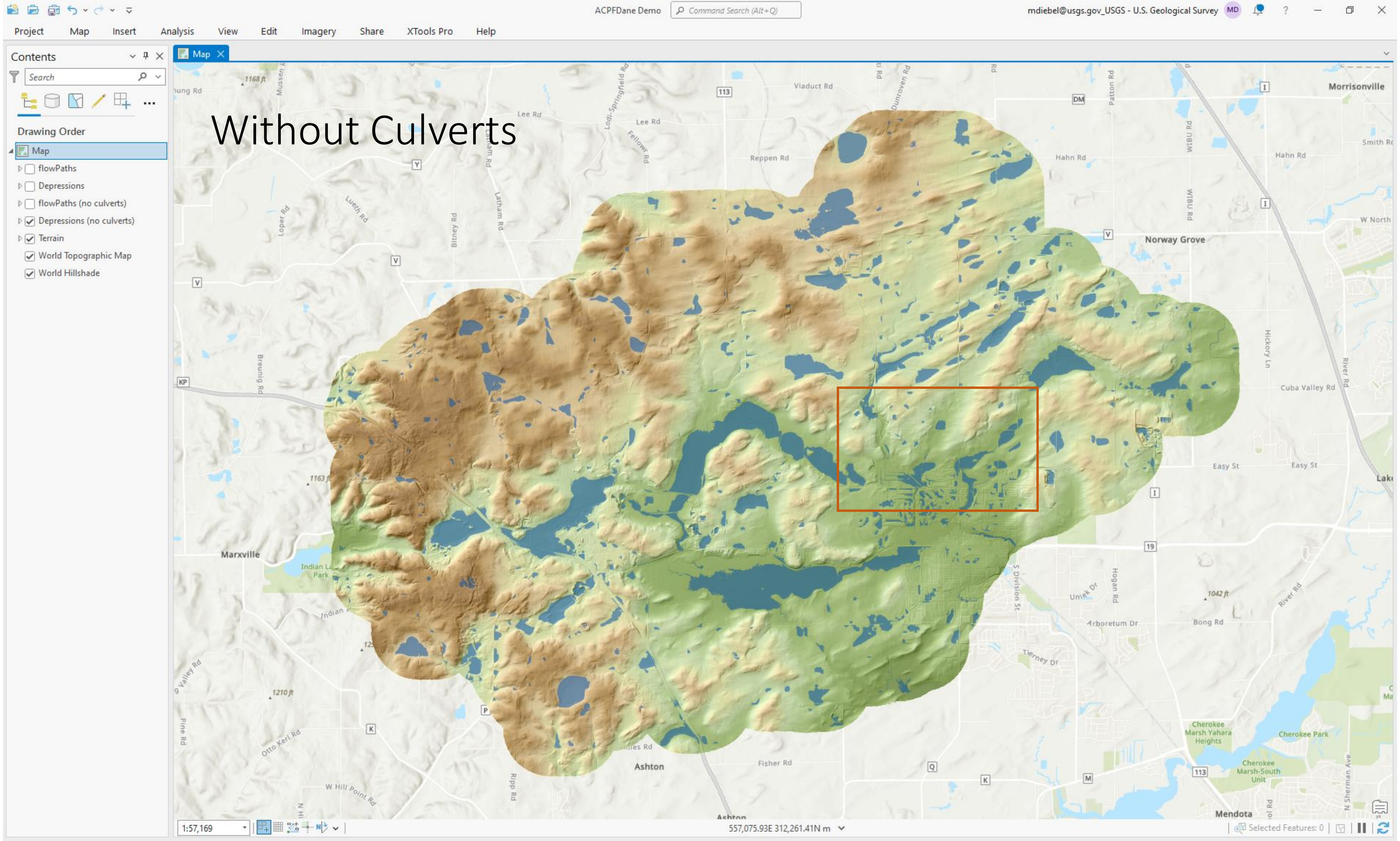
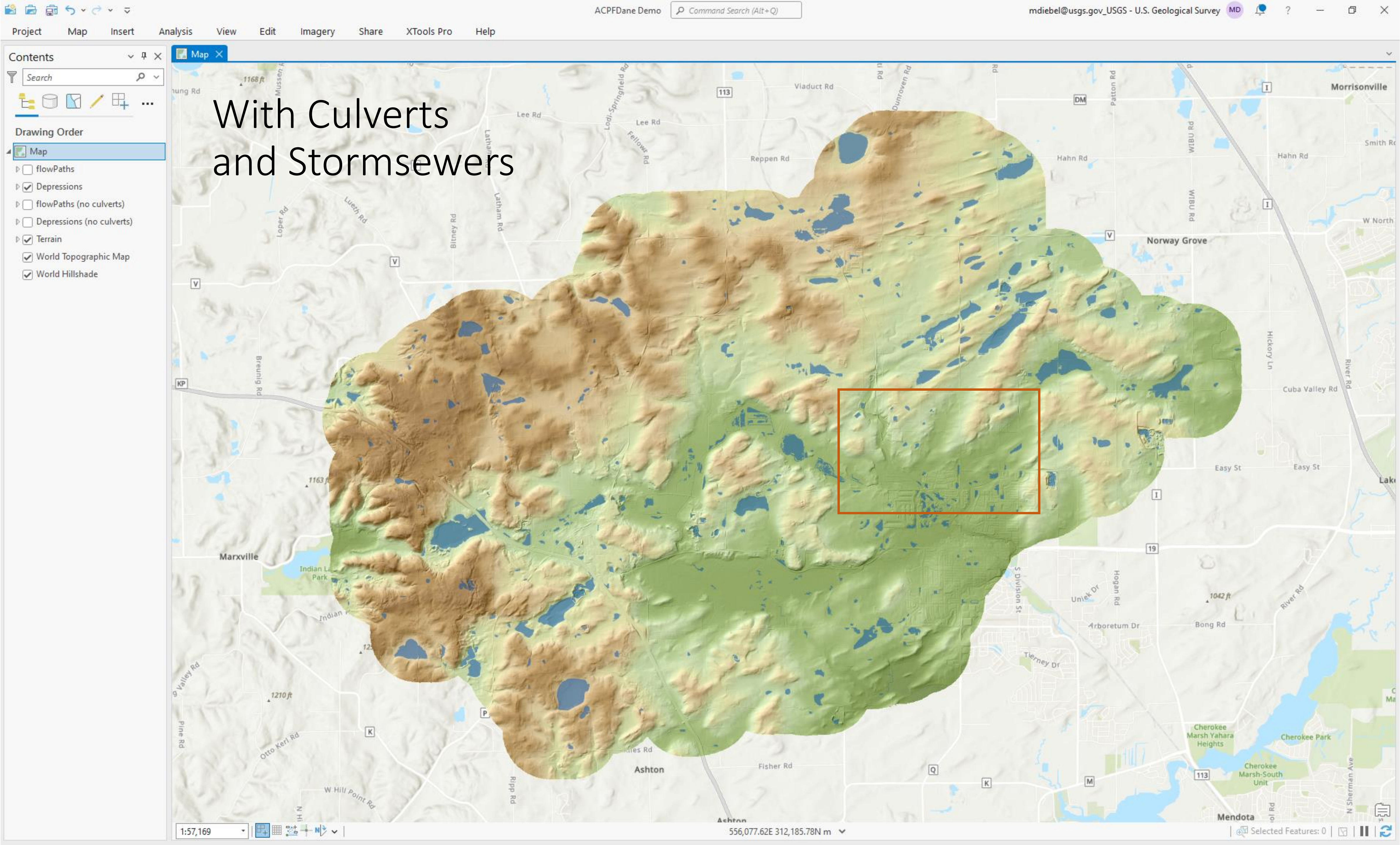
# Without Culverts

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# Mapping Culverts

## Manual digitization

1. Digitize at approximately 1:500 scale.
2. Use available road and stream datasets to identify likely culvert locations.
3. Create flowlines and depressions based on preliminary culverts.
4. Review locations where preliminary flowlines cross roads and where depressions are near roads; digitize additional culverts as needed.

We mapped a total of 17,452 culverts in 50 HUC12s in Dane County, WI in approximately 800 hours. This equates to an average of 350 culverts and 16 hours per HUC12.

# Mapping Culverts

## Automated methods

- Lindsay, J. B. and Dhun, K., 2015. Modelling surface drainage patterns in altered landscapes using LiDAR. *International Journal of Geographical Information Science*.
  - Does not retain real depressions
  - Method implemented in Whitebox Tools
- Gelder, B. K. 2015. Automation of DEM Cutting for Hydrologic/Hydraulic Modeling. In Trans Project Reports 103. http://lib.dr.iastate.edu/intrans_reports/103.
  - Designed to retain real depressions
  - Not implemented as a tool
- Wu, D., et al. 2023. Classification of drainage crossings on high-resolution digital elevation models: A deep learning approach. *GIScience & Remote Sensing.*
  - Trained on true and false culvert images
  - Not implemented as a tool


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# Fill-and-spill hydrology: Why?

## Simulation Accuracy ≠ Application Utility

- Lumped models, which implicitly *ignore how intra-watershed processes are distributed*, can predict integrated watershed responses like stream flow as well as models that simulate a fully distributed suite of intra-watershed processes.
- Watershed managers tasked with implementing strategies for controlling non-point source pollution need water quality models that *can correctly identify the locations* where runoff is generated in order to effectively place best management practices.

Easton, Z. M., et al., 2008. "Re-conceptualizing the soil and water assessment tool (SWAT) model to predict runoff from variable source areas." *Journal of Hydrology*.

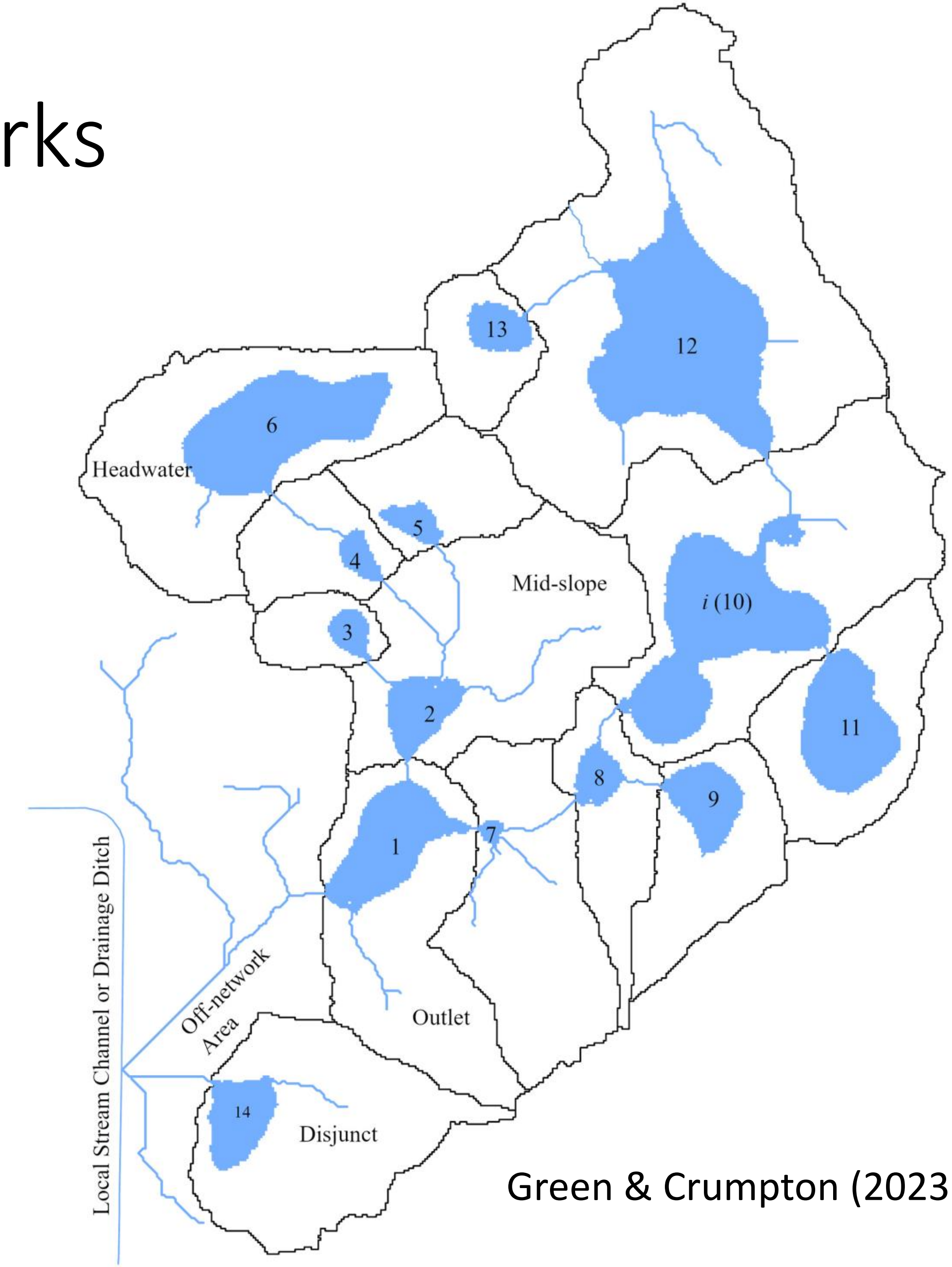
# Fill-and-spill hydrology: Key References


- Spence, C. 2010. A paradigm shift in hydrology: Storage thresholds across scales influence catchment runoff generation. *Geography Compass.*
- Evenson, G. R., et al. 2016. An improved representation of geographically isolated wetlands in a watershed-scale hydrologic model. *Hydrological Processes.*
- McDonnell, J. J., et al. 2021. Fill-and-spill: A process description of runoff generation at the scale of the beholder. *Water Resources Research.*
- Green, D. I., & Crumpton, W. G. 2023. Depressional runoff cascade networks of the Des Moines Lobe of Iowa. *Journal of the American Water Resources Association.*

# Depressional Cascade Networks

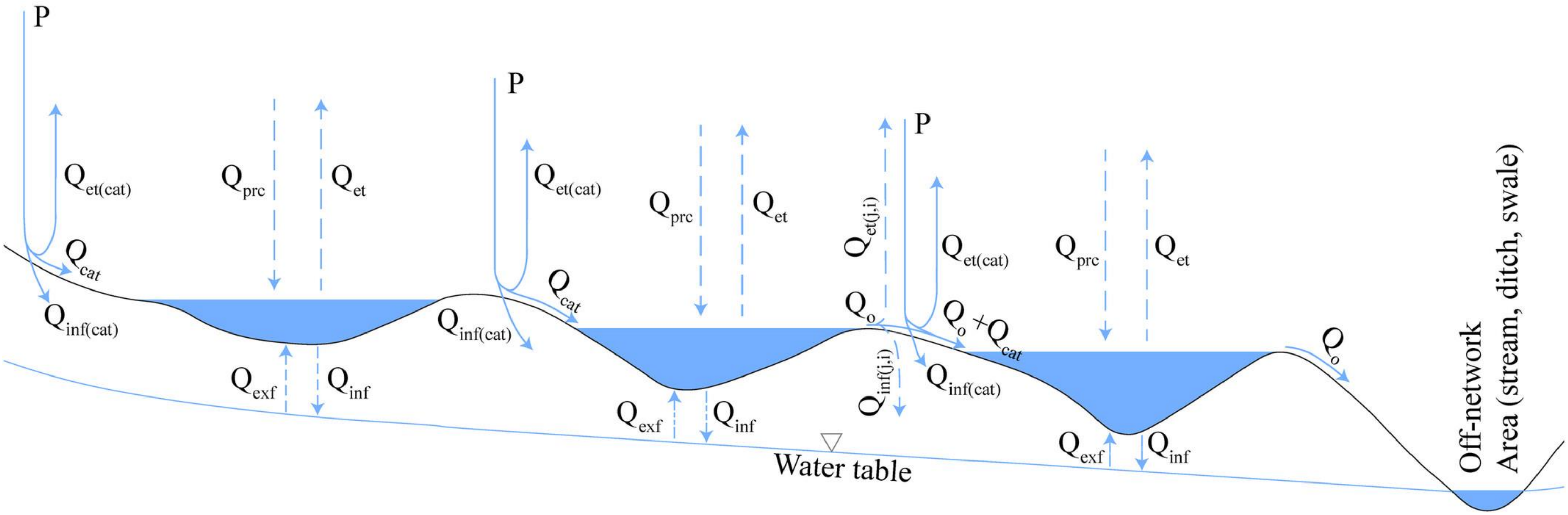
1. Runoff from a depression catchment (and overflow from any upslope depressions) enters the depression.
2. If the depression is filled, it spills to its directly neighboring downslope depression.

When evaluated over an entire network, the sequential filling and spilling of depressions gives rise to a nonlinear dependence between precipitation inputs and network runoff contributing area.




Green & Crumpton (2023)

# Depressional Cascade Networks




Green & Crumpton (2023)

# SWAT (DSF)

Soil and Water Assessment Tool (SWAT) modified to simulate depressional storage and flows (DSF)

- Fill-and-spill routing
- Subsurface water exchange
- Daily temporal resolution

Evenson, G.R., et al. 2018. A watershed-scale model for depressional wetland-rich landscapes. *Journal of Hydrology X*

# ArcGIS Hydrology Toolbox

- Hydrology
  - Basin
  - Derive Continuous Flow
  - Derive Stream As Line
  - Derive Stream As Raster
  - Fill
  - Flow Accumulation
  - Flow Direction
  - Flow Distance
  - Flow Length
  - Sink
  - Snap Pour Point
  - Storage Capacity
  - Stream Link
  - Stream Order
  - Stream to Feature
  - Watershed

# Agricultural Conservation PLANNING FRAMEWORK

The Agricultural Conservation Planning Framework (ACPF) is a free ArcGIS toolbox that leverages high-resolution geo-spatial data to help local farming communities better address their soil and water conservation needs.

https://acpf4watersheds.org/

ACPF training videos are an excellent way to learn the toolbox.

- acpf_V5_Pro.atbx
  - 1. DEM Preparation
  - 2. Develop Stream Network and Catchments
  - 3. Field Characterization
  - 4. Precision Conservation Practice Siting
  - 5. Impoundment Siting
  - 6. Riparian Assessment
  - 7. Soil Vulnerability Index
  - Utilities

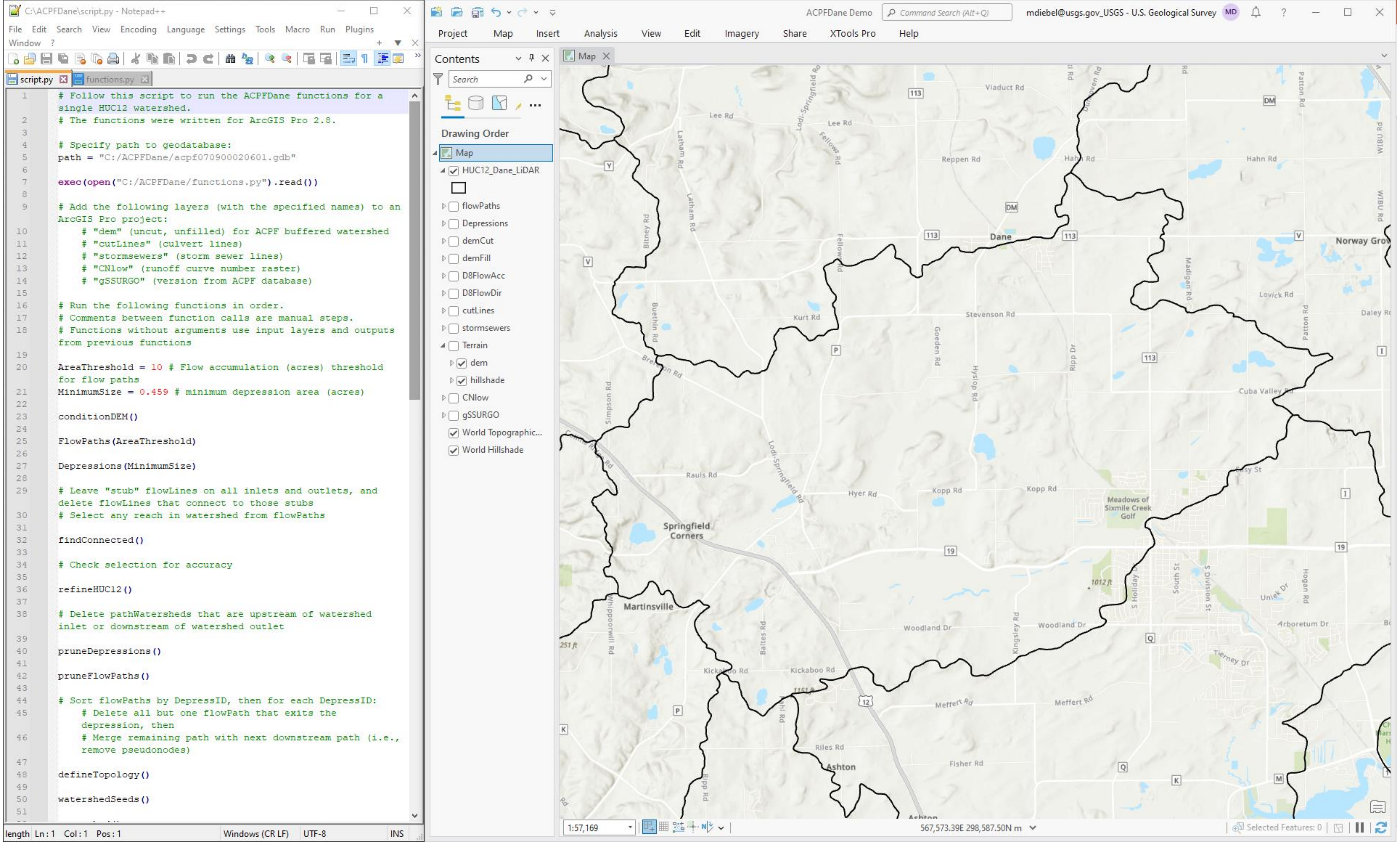
# ACPFDane

Modified version of the Agricultural Conservation Planning Framework for Dane County, Wisconsin

This script and set of functions takes a HUC12 LiDAR DEM as input and conducts the following analyses:

1. Condition DEM with culverts and storm sewers, fill depressions, calculate flow direction and accumulation.
2. Define flow paths and topographic depressions
3. Delineate flow path and depression watersheds
4. Define watershed topology from node intersections and LakeCat tool
5. Calculate runoff from a design storm with curve number hydrology
6. Calculate unit stream power of flow paths

https://github.com/mattdiebel/ACPFDane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script.py
functions.py
# Follow this script to run the ACPFDane functions for a single HUC12 watershed.
# The functions were written for ArcGIS Pro 2.8.
# Specify path to geodatabase:
path = "C:/ACPFDane/acpf070900020601.gdb"
exec(open("C:/ACPFDane/functions.py").read())
# Add the following layers (with the specified names) to an ArcGIS Pro project:
# "dem" (uncut, unfilled) for ACPF buffered watershed
# "cutLines" (culvert lines)
# "stormsewers" (storm sewer lines)
# "CNlow" (runoff curve number raster)
# "gSSURGO" (version from ACPF database)
# Run the following functions in order.
# Comments between function calls are manual steps.
# Functions without arguments use input layers and outputs from previous functions
AreaThreshold = 10 # Flow accumulation (acres) threshold for flow paths
MinimumSize = 0.459 # minimum depression area (acres)
conditionDEM()
FlowPaths(AreaThreshold)
Depressions(MinimumSize)
# Leave "stub" flowLines on all inlets and outlets, and delete flowLines that connect to those stubs
# Select any reach in watershed from flowPaths
findConnected()
# Check selection for accuracy
refineHUC12()
# Delete pathWatersheds that are upstream of watershed inlet or downstream of watershed outlet
pruneDepressions()
pruneFlowPaths()
# Sort flowPaths by DepressID, then for each DepressID:
# Delete all but one flowPath that exits the depression, then
# Merge remaining path with next downstream path (i.e., remove pseudonodes)
defineTopology()
watershedSeeds()
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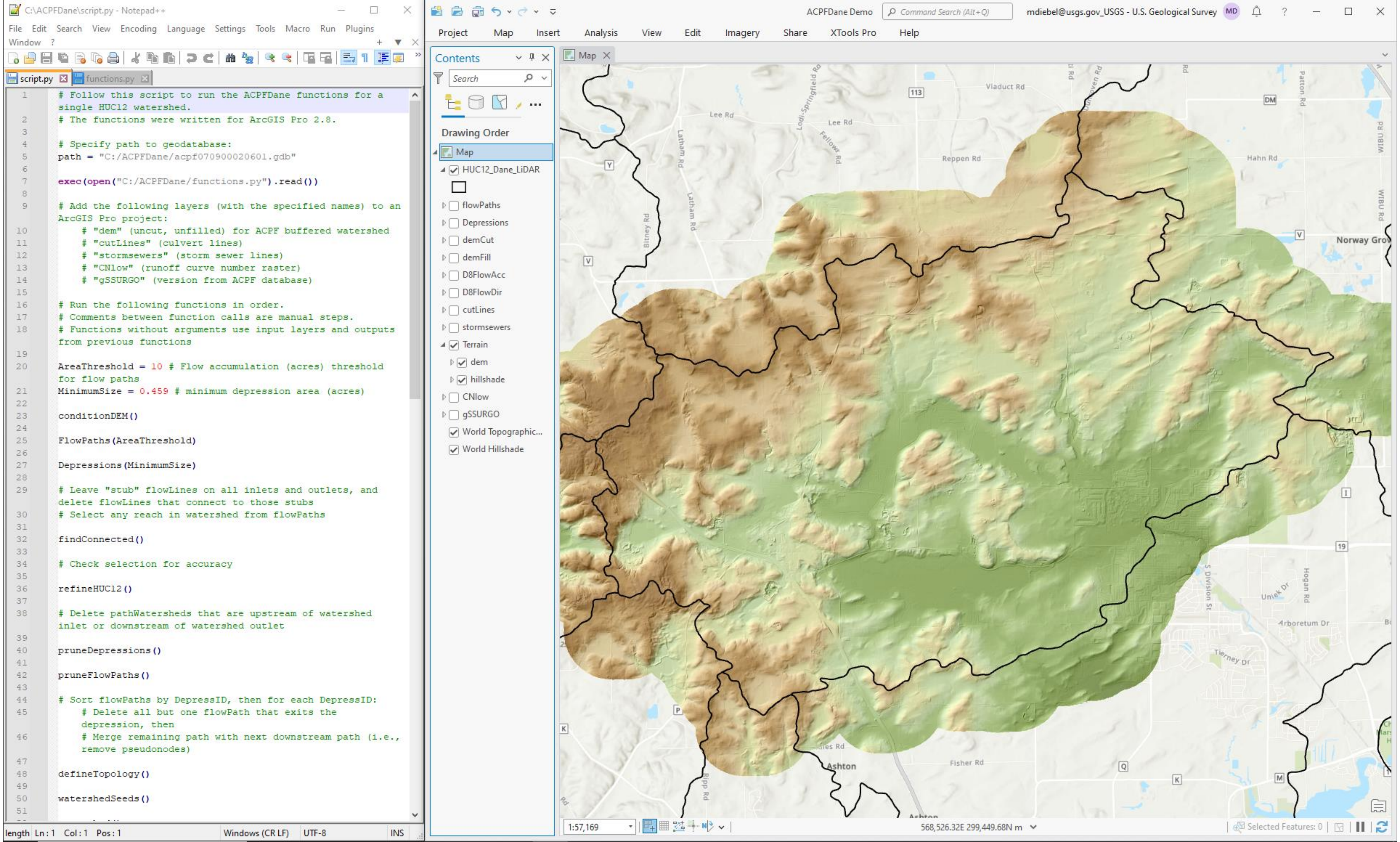
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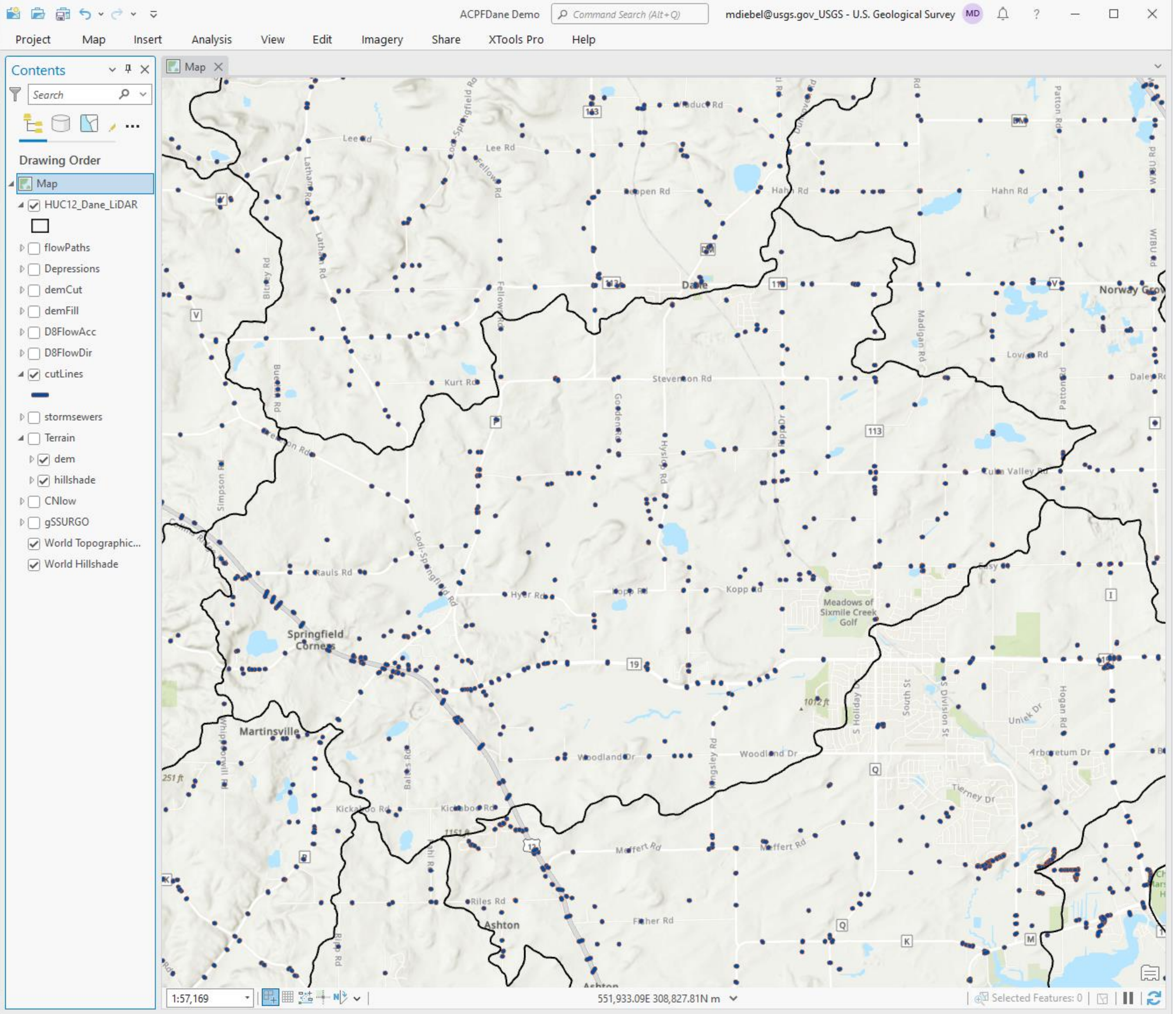

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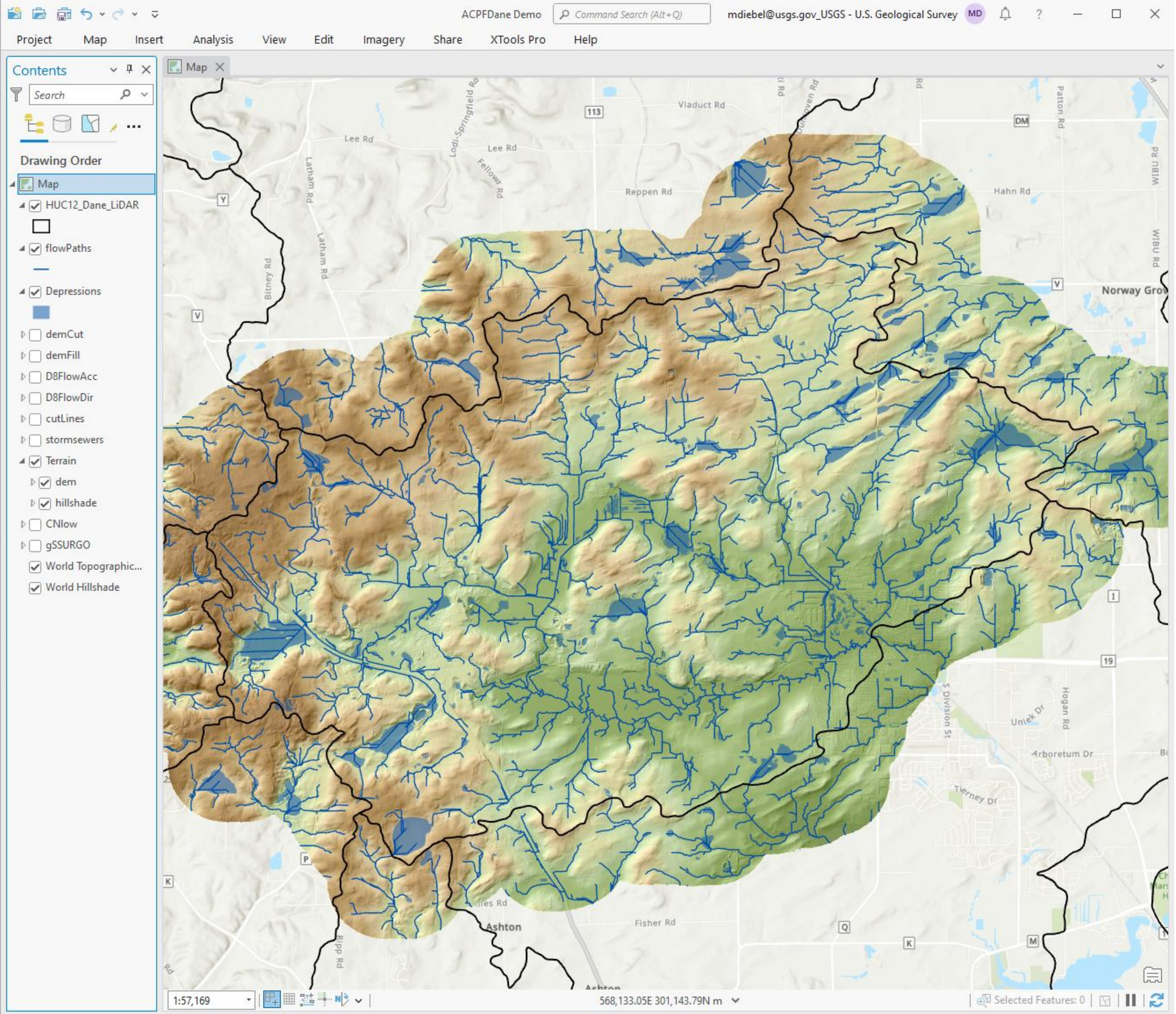

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# The functions were written for ArcGIS Pro 2.8.

# Specify path to geodatabase:
path = "C:/ACPFDane/acpf070900020601.gdb"

exec(open("C:/ACPFDane/functions.py").read())

# Add the following layers (with the specified names) to an ArcGIS Pro project:
    # "dem" (uncut, unfilled) for ACPF buffered watershed
    # "cutLines" (culvert lines)
    # "stormsewers" (storm sewer lines)
    # "CNlow" (runoff curve number raster)
    # "gSSURGO" (version from ACPF database)

# Run the following functions in order.
# Comments between function calls are manual steps.
# Functions without arguments use input layers and outputs from previous functions

AreaThreshold = 10 # Flow accumulation (acres) threshold for flow paths
MinimumSize = 0.459 # minimum depression area (acres)

conditionDEM()

FlowPaths(AreaThreshold)

Depressions(MinimumSize)

# Leave "stub" flowLines on all inlets and outlets, and delete flowLines that connect to those stubs
# Select any reach in watershed from flowPaths

findConnected()

# Check selection for accuracy

refineHUC12()

# Delete pathWatersheds that are upstream of watershed inlet or downstream of watershed outlet

pruneDepressions()

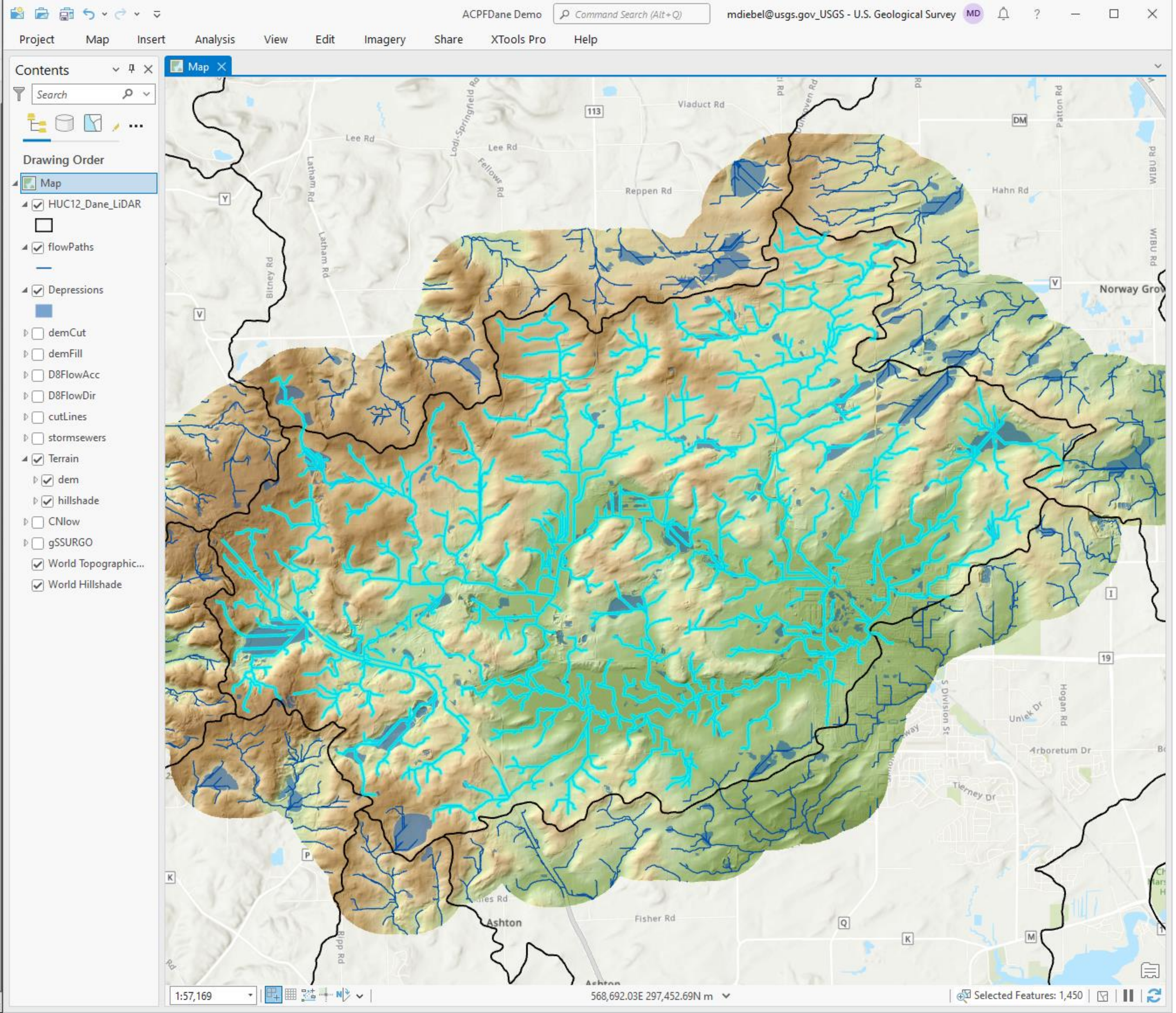
pruneFlowPaths()

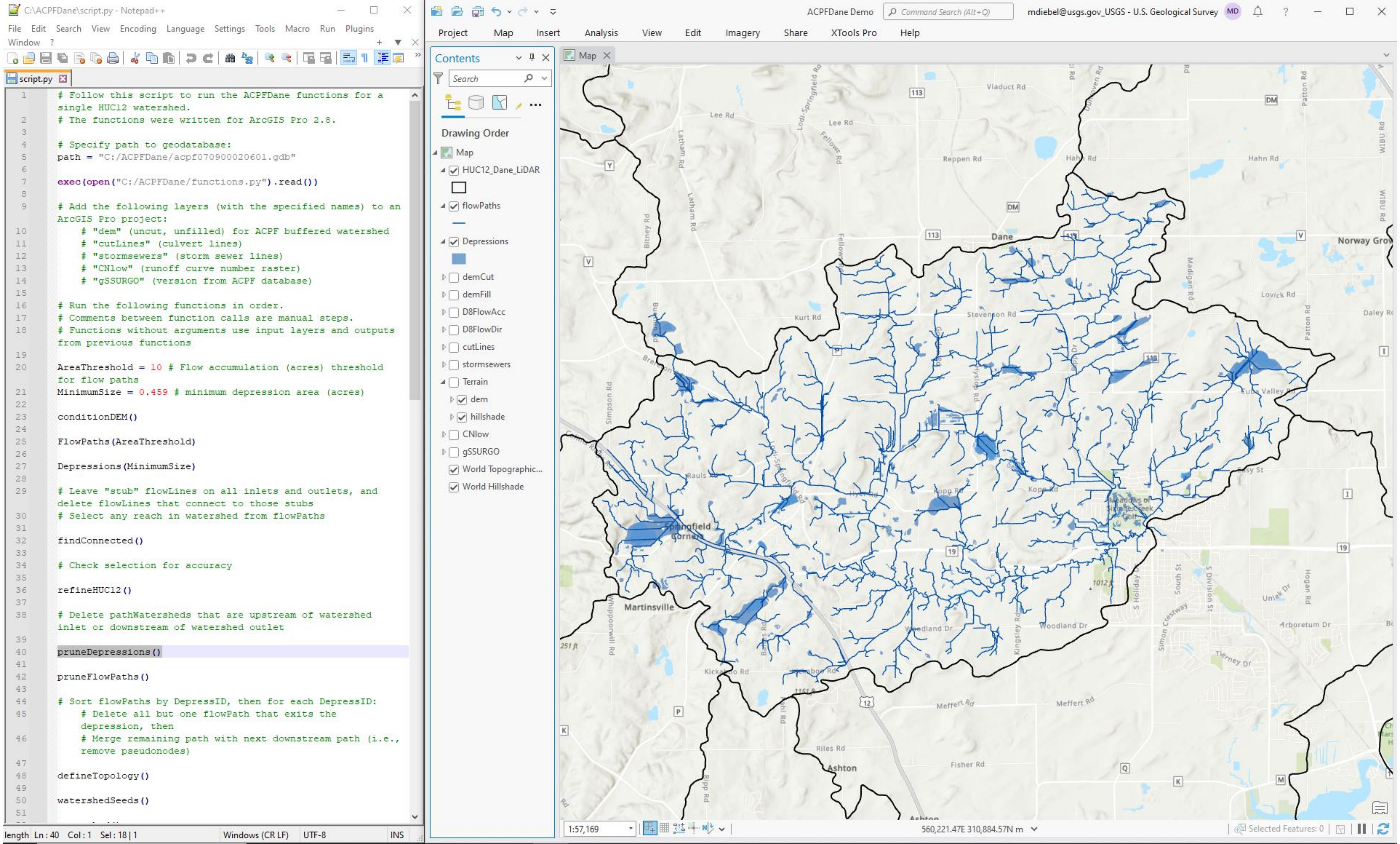
# Sort flowPaths by DepressID, then for each DepressID:
    # Delete all but one flowPath that exits the depression, then
    # Merge remaining path with next downstream path (i.e., remove pseudonodes)

defineTopology()

watershedSeeds()
```

length  Ln : 32  Col : 1  Sel : 15 | 1  Windows (CR LF)  UTF-8  INS




C:\ACPFDane\script.py - Notepad++
File Edit Search View Encoding Language Settings Tools Macro Run Plugins
Window ?
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watershedSeeds()
length Ln : 40 Col : 1 Sel : 18 | 1
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ACPFDane Demo
Command Search (Alt+Q)
mdiebel@usgs.gov_USGS - U.S. Geological Survey
Project Map Insert Analysis View Edit Imagery Share XTools Pro Help
Contents
Search
Drawing Order
Map
HUC12_Dane_LiDAR
flowPaths
Depressions
demCut
demFill
D8FlowAcc
D8FlowDir
cutLines
stormsewers
Terrain
dem
hillshade
CNlow
gSSURGO
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World Hillshade
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Dane
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Martinsville
Ashton
1:57,169
560,221.47E 310,884.57N m
Selected Features: 0

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    remove pseudonodes)

defineTopology()

watershedSeeds()
```

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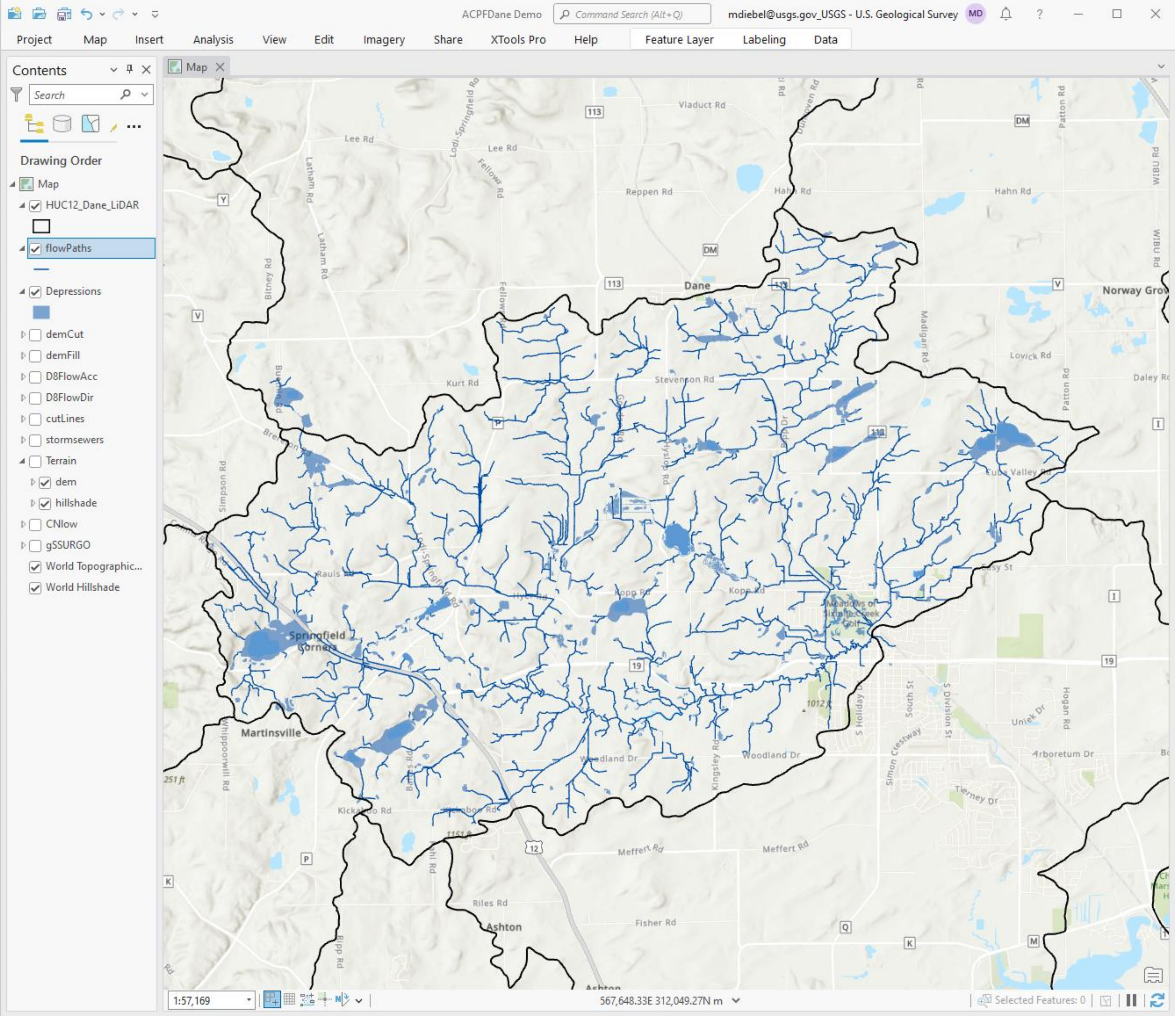

C:\ACPFDane\script.py - Notepad++

File Edit Search View Encoding Language Settings Tools Macro Run Plugins Window ?

script.py

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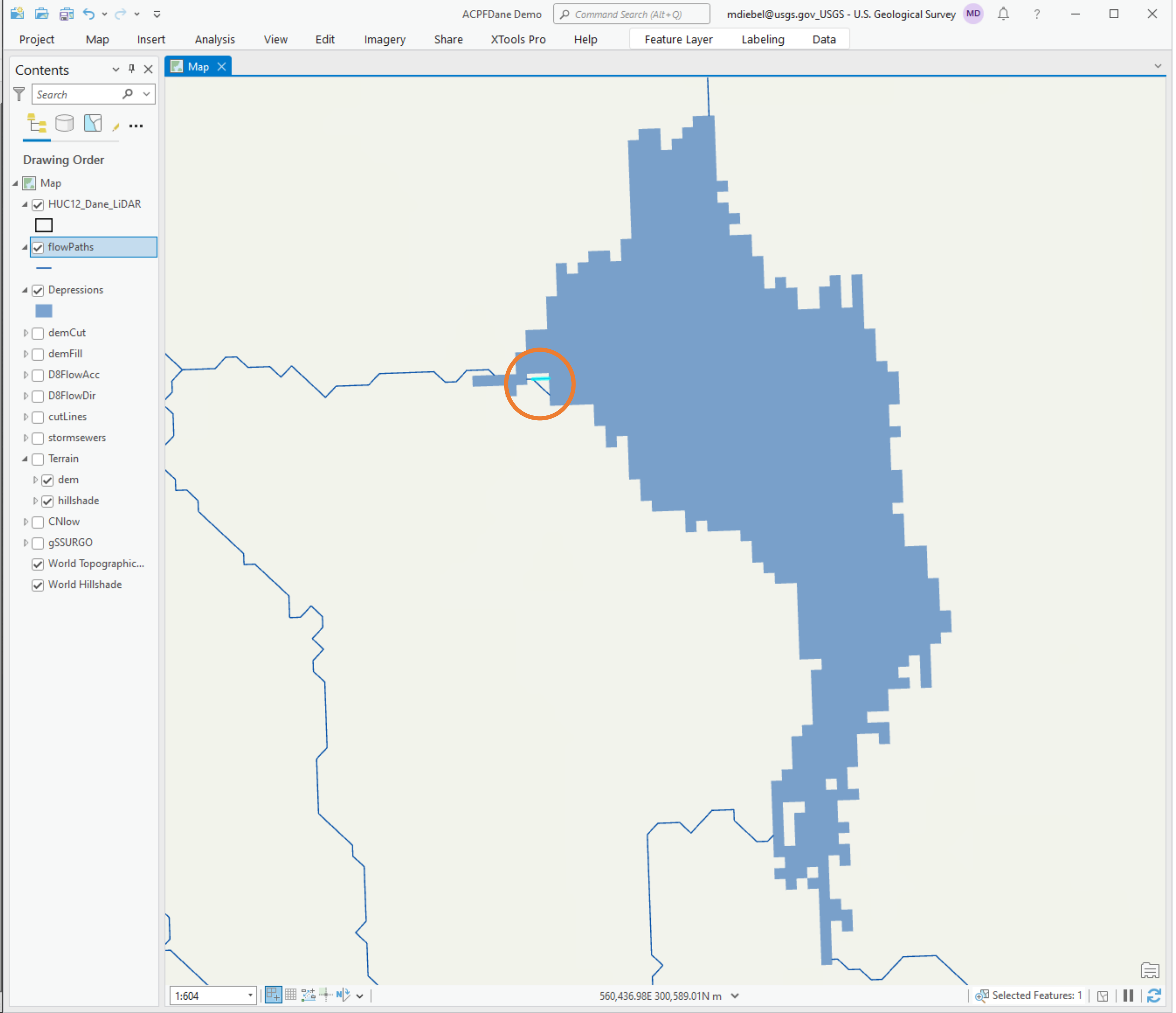
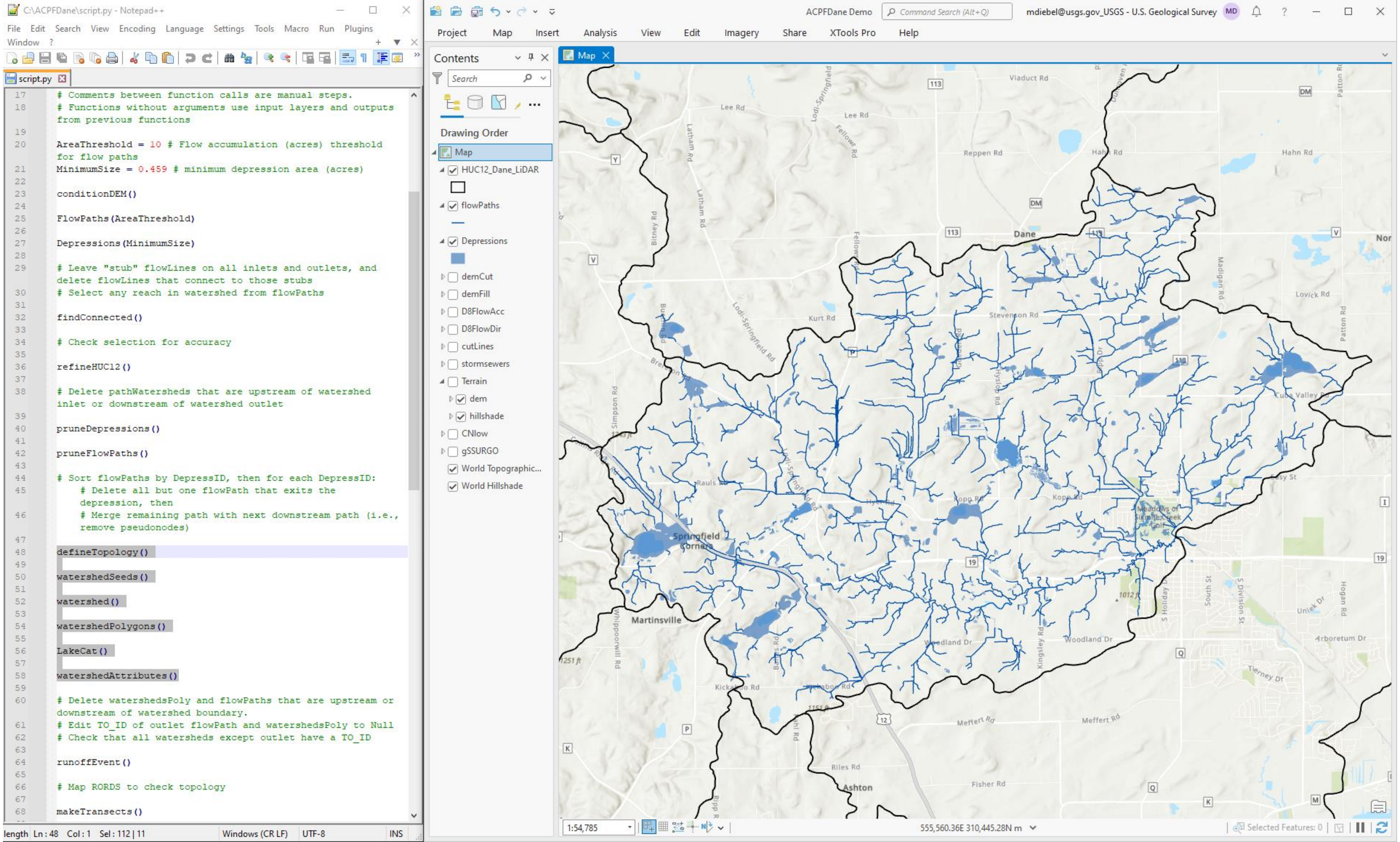
length Ln : 42 Col : 1 Sel : 18 | 1 Windows (CR LF) UTF-8 INS




C:\ACPFDane\script.py - Notepad++
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watershedPolygons()
LakeCat()
watershedAttributes()
# Delete watershedsPoly and flowPaths that are upstream or downstream of watershed boundary.
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runoffEvent()
# Map RORDS to check topology
makeTransects()
ACPFDane Demo
Contents
Drawing Order
Map
HUC12_Dane_LiDAR
flowPaths
Depressions
demCut
demFill
D8FlowAcc
D8FlowDir
cutLines
stormsewers
Terrain
dem
hillshade
CNlow
gSSURGO
World Topographic...
World Hillshade
Dane
Springfield Corners
Martinsville
Ashton
1:54,785
555,560.36E 310,445.28N m

C:\ACPFDane\script.py - Notepad++

File Edit Search View Encoding Language Settings Tools Macro Run Plugins Window ?

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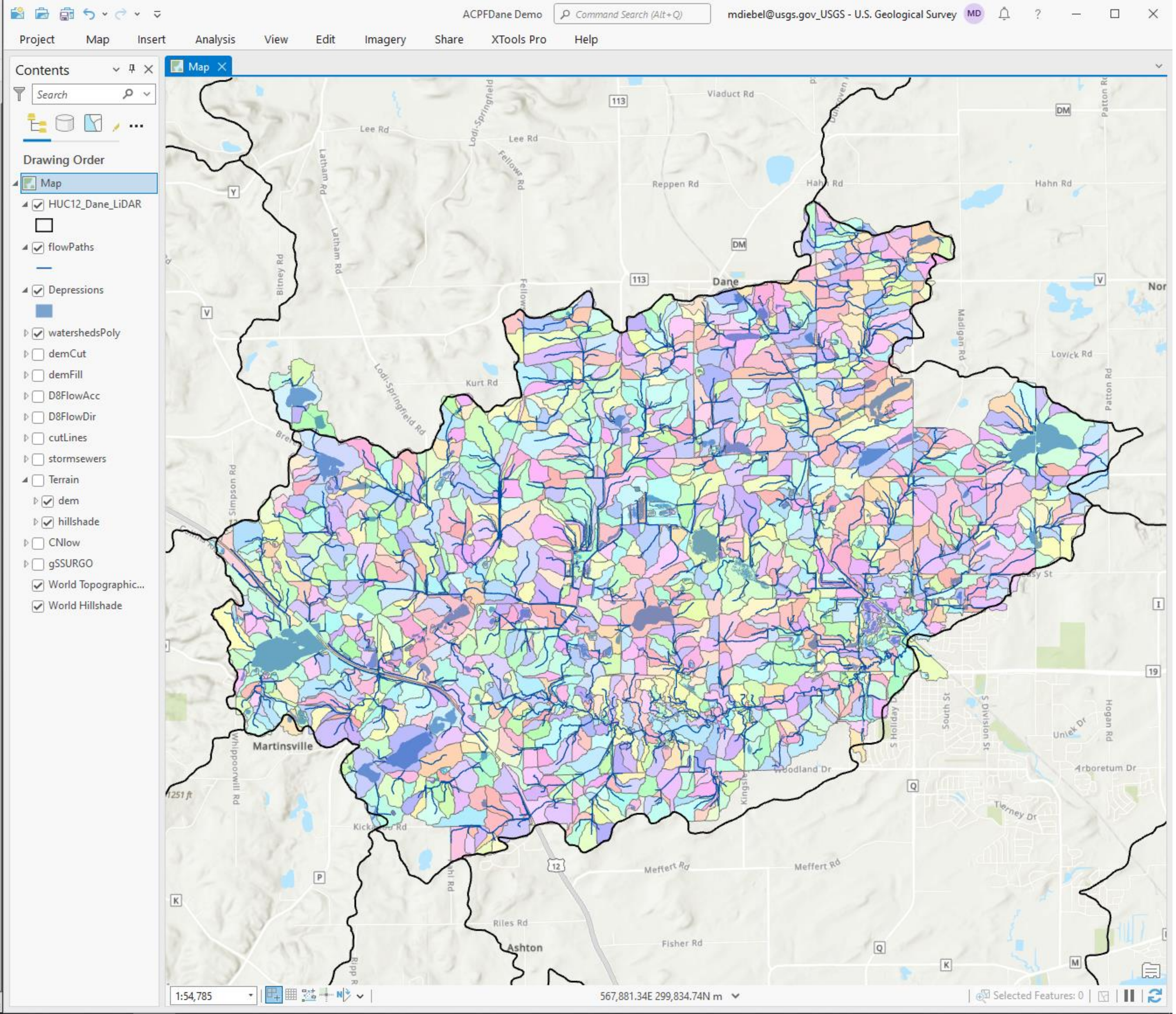
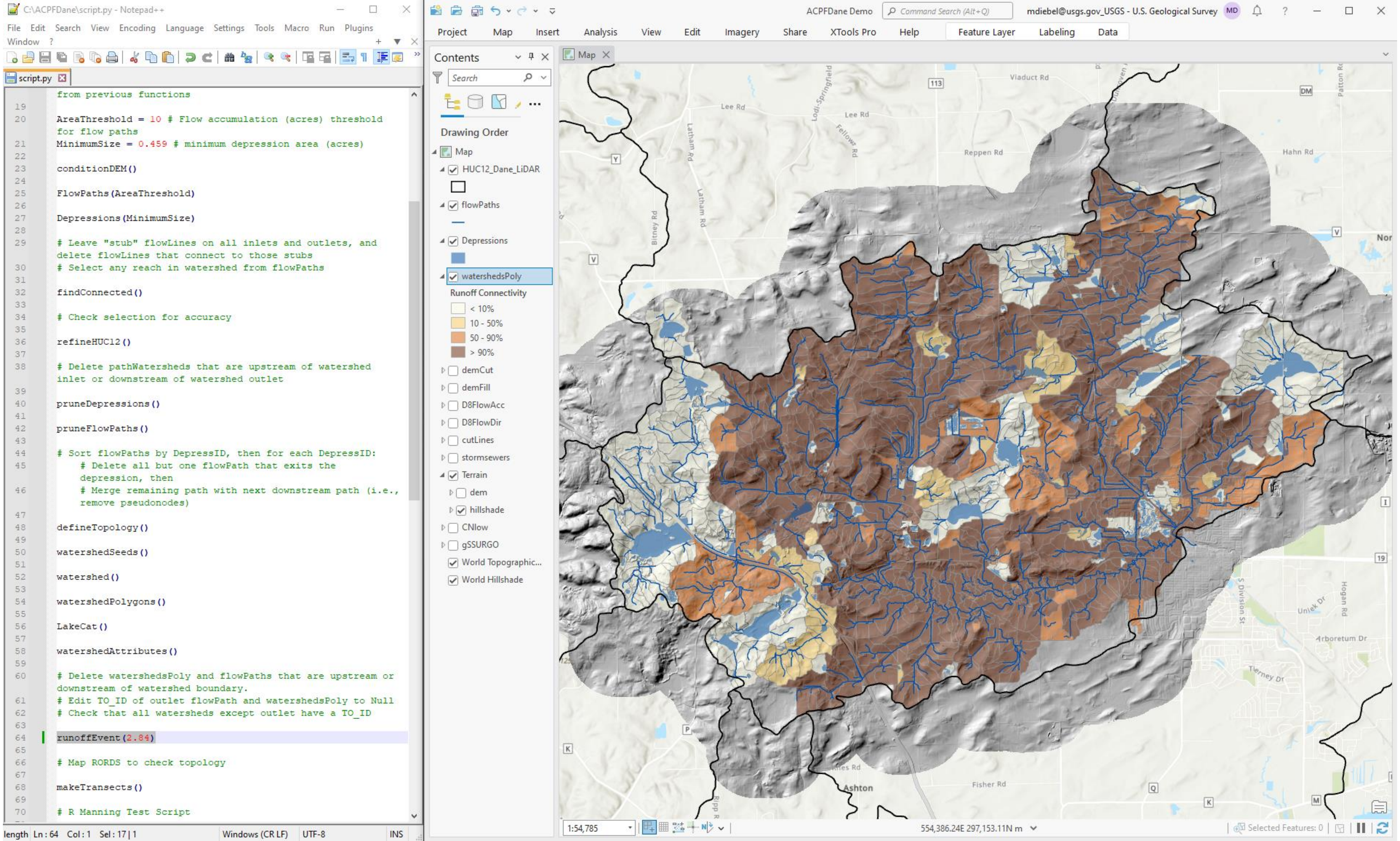
makeTransects()
```

length Ln : 59 Col : 1 Pos : 1,641 Windows (CR LF) UTF-8 INS




C:\ACPFDane\script.py - Notepad++
File Edit Search View Encoding Language Settings Tools Macro Run Plugins Window ?
script.py
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runoffEvent(2.84)
# Map RORDS to check topology
makeTransects()
# R Manning Test Script
length Ln : 64 Col : 1 Sel : 17 | 1 Windows (CR LF) UTF-8 INS
ACPFDane Demo
Command Search (Alt+Q)
mdiebel@usgs.gov_USGS - U.S. Geological Survey
Project Map Insert Analysis View Edit Imagery Share XTools Pro Help Feature Layer Labeling Data
Contents
Search
Drawing Order
Map
HUC12_Dane_LiDAR
flowPaths
Depressions
watershedsPoly
Runoff Connectivity
< 10%
10 - 50%
50 - 90%
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D8FlowAcc
D8FlowDir
cutLines
stormsewers
Terrain
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hillshade
CNlow
gSSURGO
World Topographic...
World Hillshade
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Viaduct Rd
Lee Rd
Reppen Rd
Hahn Rd
Fisher Rd
Ashton
Arboretum Dr
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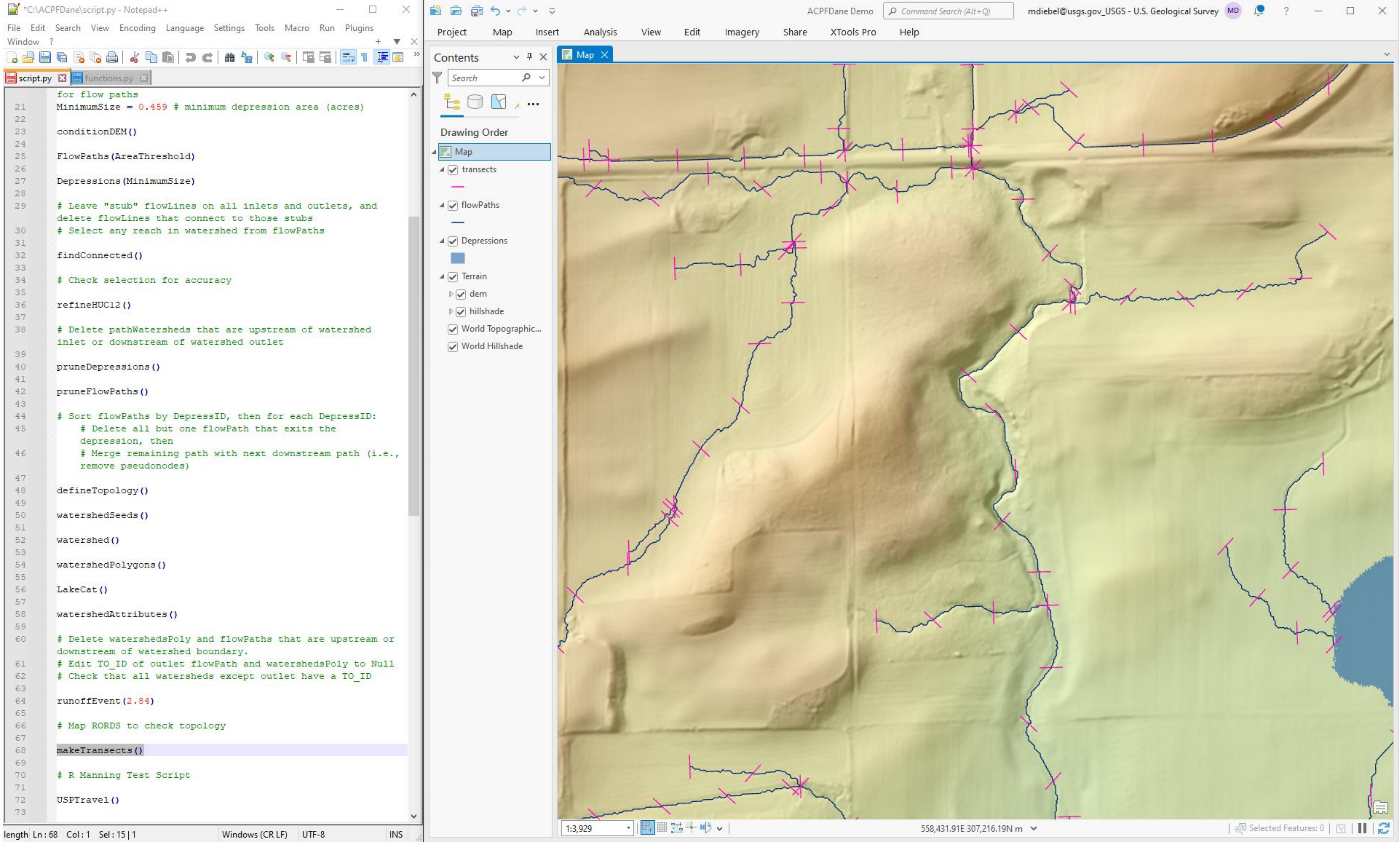
554,386.24E 297,153.11N m
Selected Features: 0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File Edit Search View Encoding Language Settings Tools Macro Run Plugins
Window ?
script.py
functions.py
for flow paths
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runoffEvent(2.84)
# Map RORDS to check topology
makeTransects()
# R Manning Test Script
USPTravel()
length Ln : 68 Col : 1 Sel : 15 | 1
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ACPFDane Demo
Command Search (Alt+Q)
mdiebel@usgs.gov_USGS - U.S. Geological Survey
Project Map Insert Analysis View Edit Imagery Share XTools Pro Help
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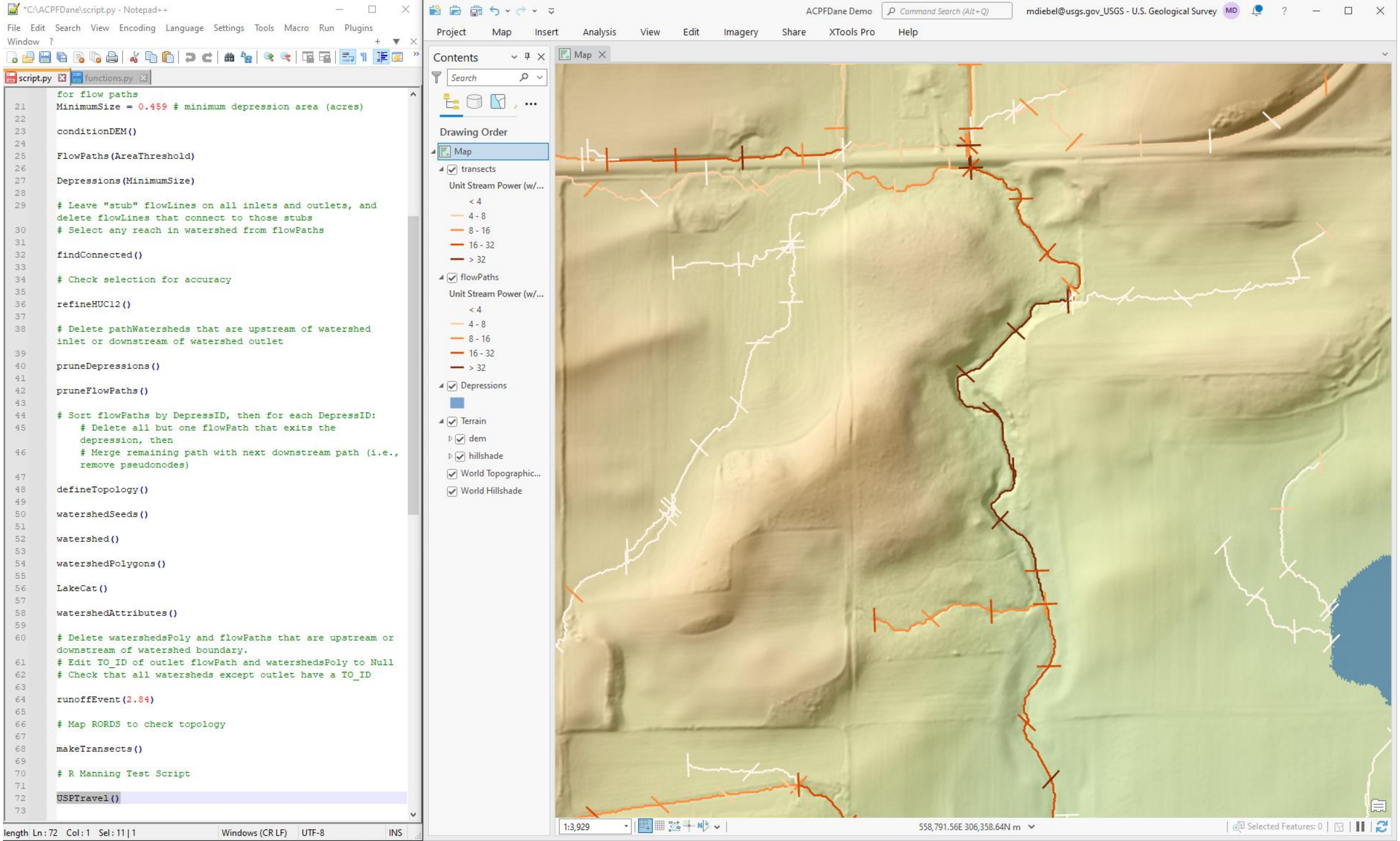
Search
Drawing Order
Map
transects
flowPaths
Depressions
Terrain
dem
hillshade
World Topographic...
World Hillshade
1:3,929
558,431.91E 307,216.19N m
Selected Features: 0


*C:\ACPFDane\script.py - Notepad++
File Edit Search View Encoding Language Settings Tools Macro Run Plugins
Window ?
script.py
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runoffEvent(2.84)
# Map RORDS to check topology
makeTransects()
# R Manning Test Script
USPTravel()
length Ln : 72 Col : 1 Sel : 11 | 1
Windows (CR LF)
UTF-8
INS
ACPFDane Demo
Command Search (Alt+Q)
mdiebel@usgs.gov_USGS - U.S. Geological Survey
Project Map Insert Analysis View Edit Imagery Share XTools Pro Help
Contents
Search
Drawing Order
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Unit Stream Power (w/...
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8 - 16
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> 32
flowPaths
Unit Stream Power (w/...
< 4
4 - 8
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16 - 32
> 32
Depressions
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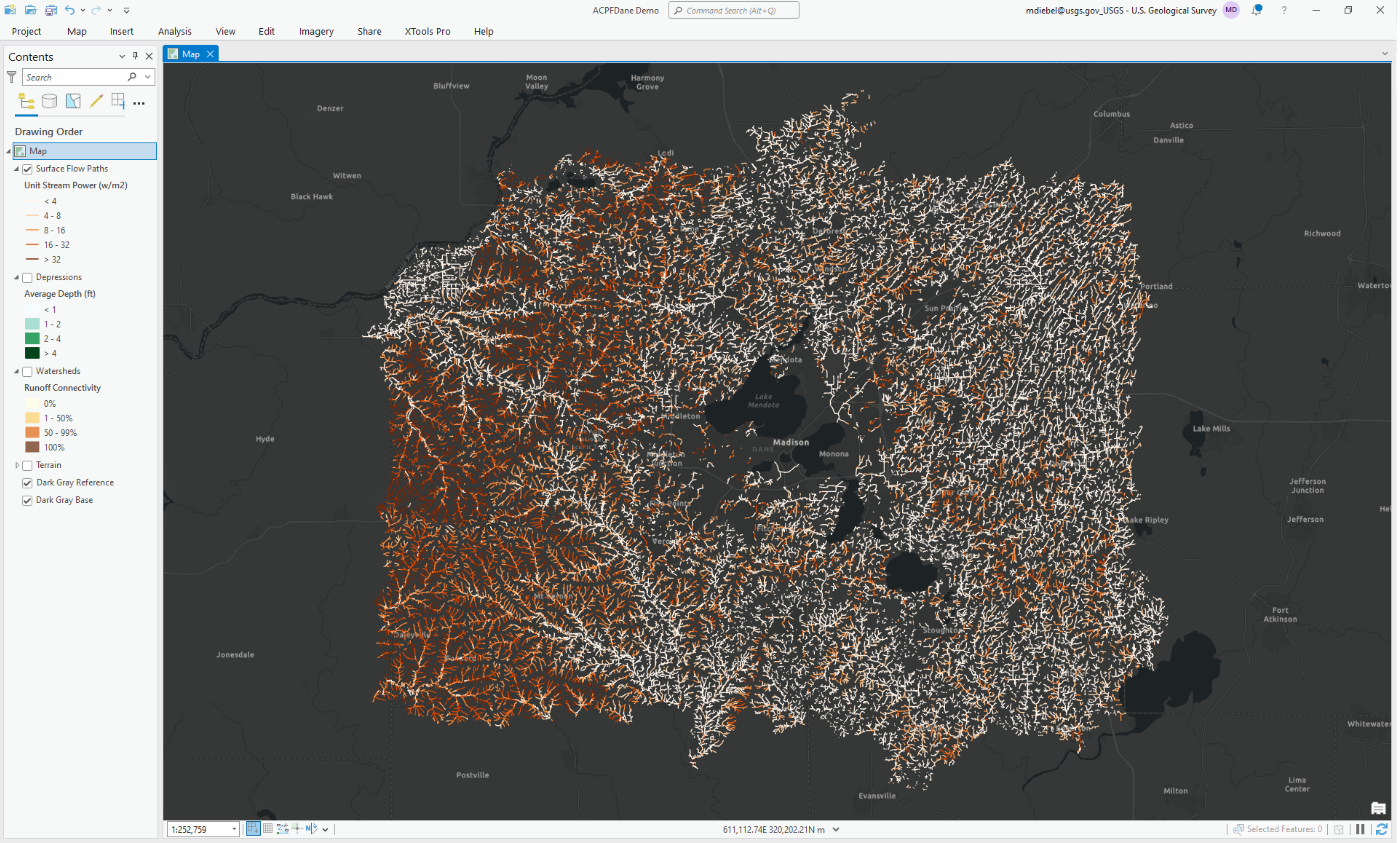
hillshade
World Topographic...
World Hillshade
1:3,929
558,791.56E 306,358.64N m
Selected Features: 0


ACPFDane Demo
Command Search (Alt+Q)
mdiebel@usgs.gov_USGS - U.S. Geological Survey
Project
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Analysis
View
Edit
Imagery
Share
XTools Pro
Help
Contents
Search
Drawing Order
Map
Surface Flow Paths
Unit Stream Power (w/m2)
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4 - 8
8 - 16
16 - 32
> 32
Depressions
Average Depth (ft)
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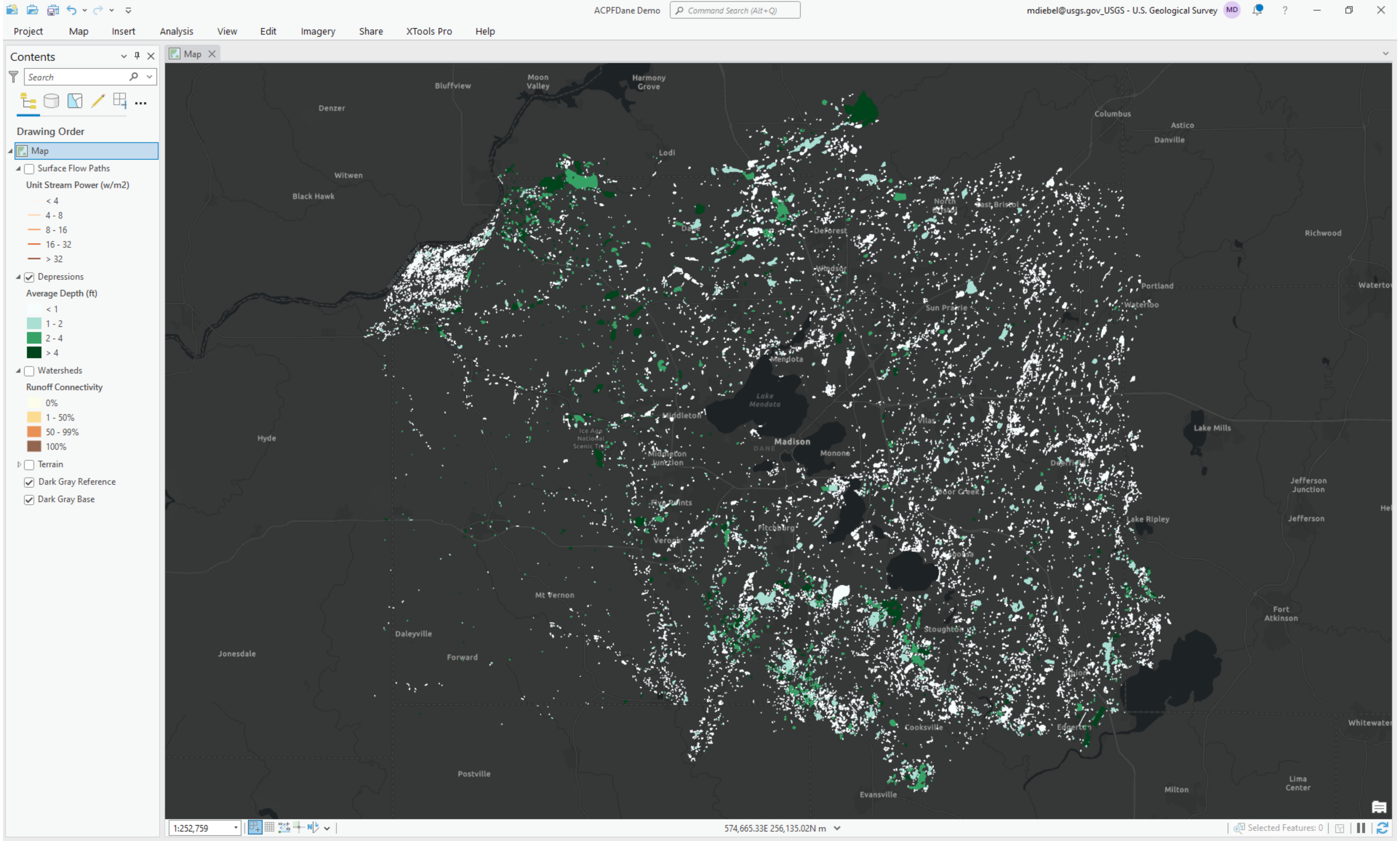
1 - 2
2 - 4
> 4
Watersheds
Runoff Connectivity
0%
1 - 50%
50 - 99%
100%
Terrain
Dark Gray Reference
Dark Gray Base
Map
Bluffview
Moon Valley
Harmony Grove
Denzer
Columbus
Astico
Danville
Lodi
Witwen
Black Hawk
Richwood
Portland
Waterto
Sun Prairie
Lake Mendota
Middleton
Madison
DANE
Monona
Lake Mills
Hyde
Jefferson Junction
Lake Ripley
Jefferson
Fort Atkinson
Jonesdale
Stoughton
Whitewater
Postville
Lima Center
Milton
Evansville
1:252,759
611,112.74E 320,202.21N m
Selected Features: 0


ACPFDane Demo
Command Search (Alt+Q)
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8 - 16
16 - 32
> 32
Depressions
Average Depth (ft)
< 1
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Portland
Waterloo
Sun Prairie
Mendota
Lake Mendota
Middleton
Madison
Monona
Hyde
Lake Mills
Middleton Junction
Jefferson Junction
Jefferson
Five Points
Fitchburg
Verona
Lake Ripley
Mt Vernon
Fort Atkinson
Daleyville
Stoughton
Jonesdale
Forward
Cooksville
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Milton
Lima Center
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574,665.33E 256,135.02N m
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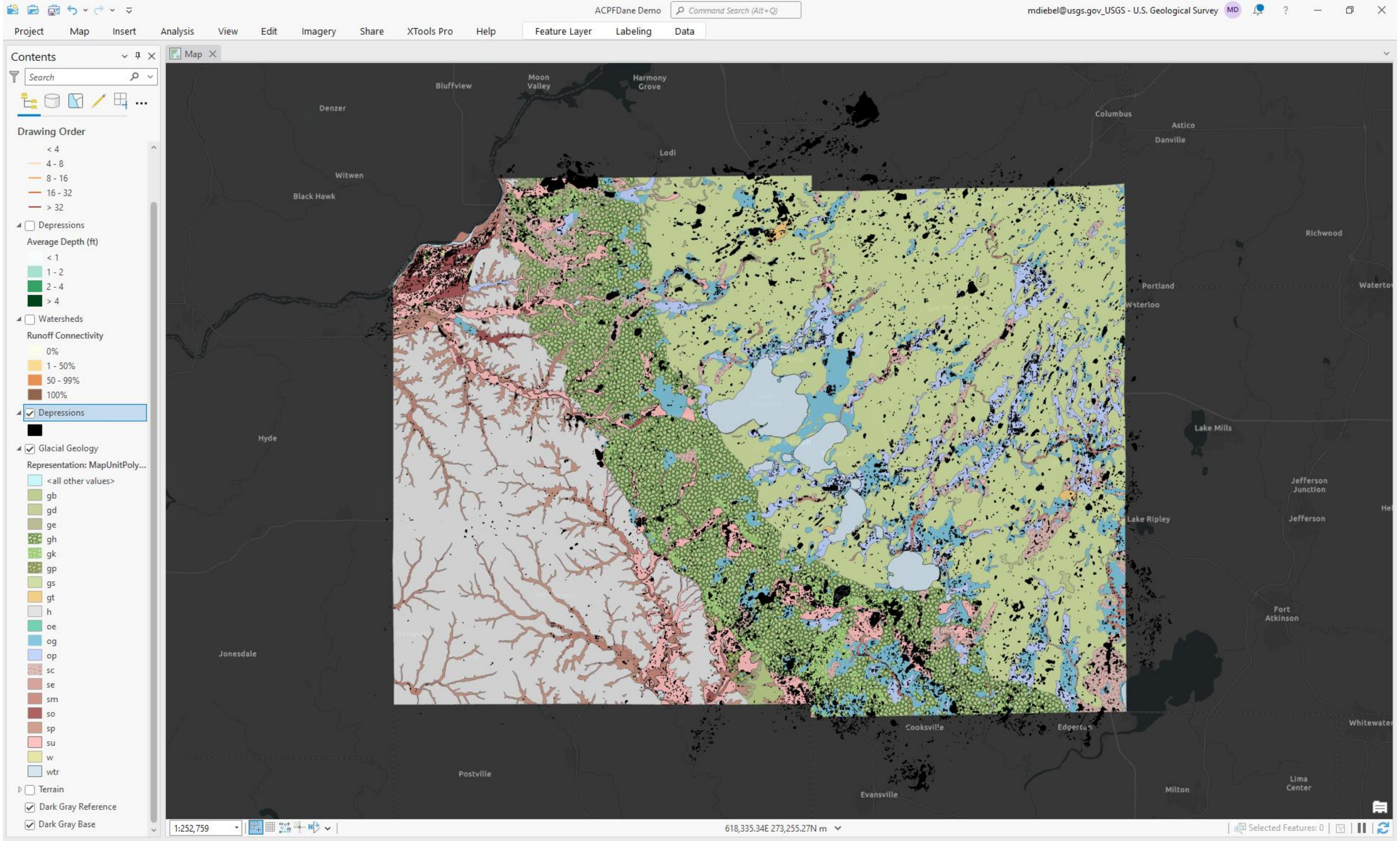
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XTools Pro
Help
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Labeling
Data
Contents
Search
Map
Drawing Order
< 4
4 - 8
8 - 16
16 - 32
> 32
Depressions
Average Depth (ft)
< 1
1 - 2
2 - 4
> 4
Watersheds
Runoff Connectivity
0%
1 - 50%
50 - 99%
100%
Depressions
Glacial Geology
Representation: MapUnitPoly...
<all other values>
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oe
og
op
sc
se
sm
so
sp
su
w
wtr
Terrain
Dark Gray Reference
Dark Gray Base
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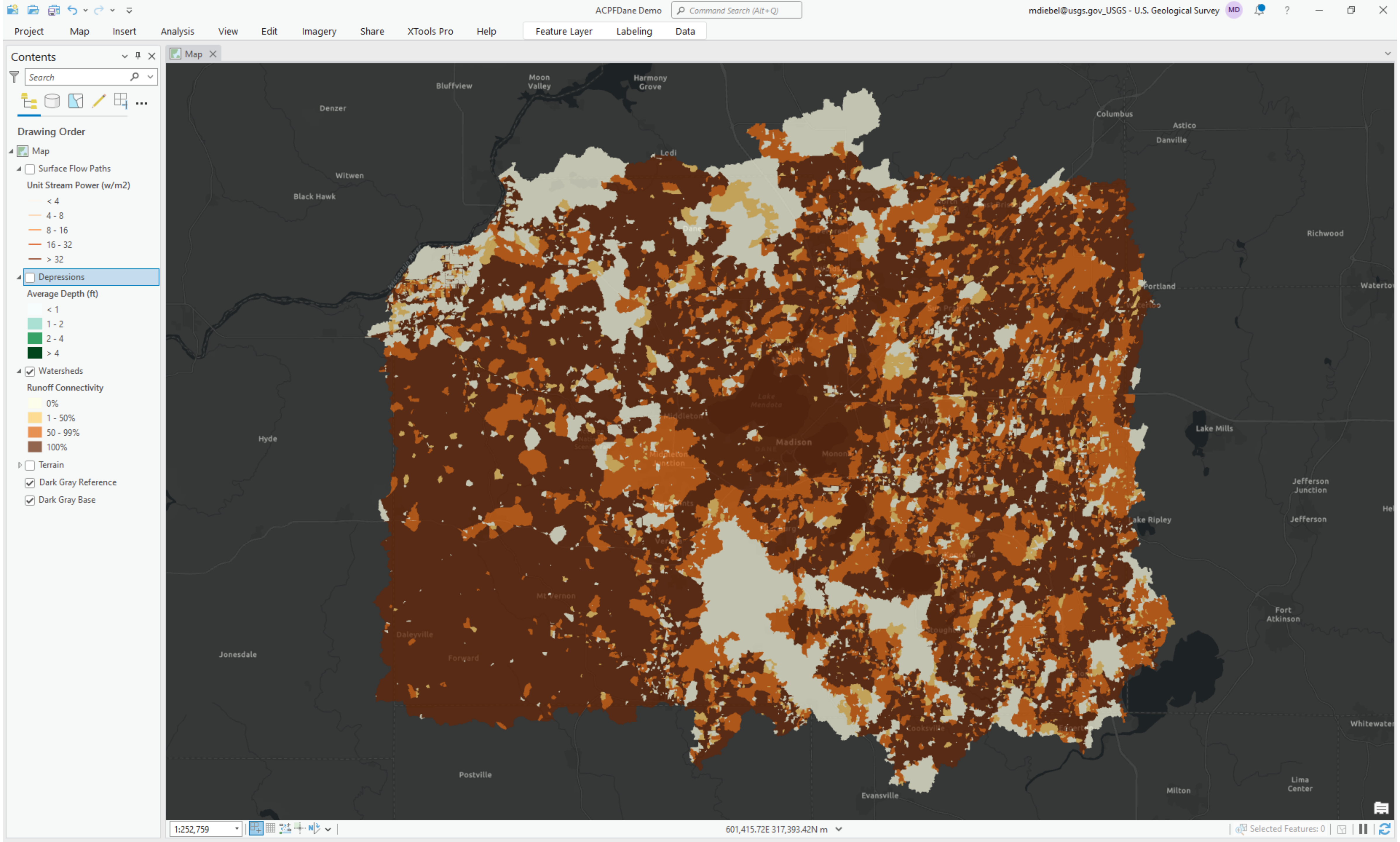
Milton
Lima Center
1:252,759
618,335.34E 273,255.27N m
Selected Features: 0


ACPFDane Demo
Command Search (Alt+Q)
mdiebel@usgs.gov_USGS - U.S. Geological Survey
Project
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Surface Flow Paths
Unit Stream Power (w/m2)
< 4
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Average Depth (ft)
< 1
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Watersheds
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Jefferson
Fort Atkinson
Jonesdale
Whitewater
Postville
Evansville
Milton
Lima Center
1:252,759
601,415.72E 317,393.42N m
Selected Features: 0

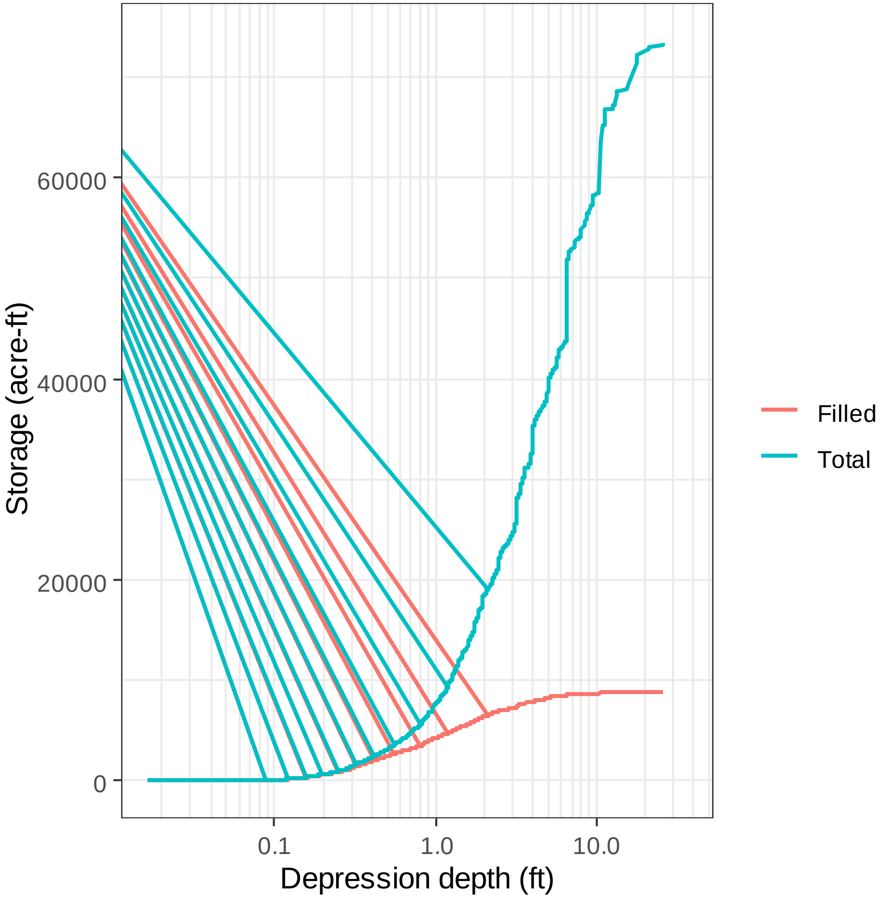
# Study Area Summary Statistics

## Depressions

- n = 12,009
- Total area = 36,800 acres (4% of land area)
- Median depth = 1.0 ft

## Runoff Connectivity (2.84-inch rainfall event)

- No off-site runoff from 19% of land area
- Partial storage of runoff from 39% of land area
- 52% of filled storage in non-wetland depressions
- 50% of filled storage in depressions < 1 ft deep



# Fields

Watershed ID
ID of next downstream watershed
Watersheds area (acres)
Hydric soil (percent of depression area)
Maximum depression depth (cm)
Depression volume (acre-feet)
Runoff curve number (low estimate assuming good hydrologic condition from EVAAL)
Downstream sort order (0 is watershed outlet)
Runoff volume generated in watershed (acre-feet)
Runoff volume generated in watershed and flowing into watershed from upstream (acre-feet)
Runoff volume leaving watershed (acre-feet)
Upstream runoff connectivity
Incremental runoff connectivity
Downstream runoff connectivity
Travel time of bankfull flow through watershed (hours)
Travel time of bankfull flow to HUC12 outlet (hours)

# Applications

## Agricultural conservation planning

- Prioritize financial and technical assistance in areas with high runoff connectivity
- Use unit stream power map to identify areas with high potential for gully erosion

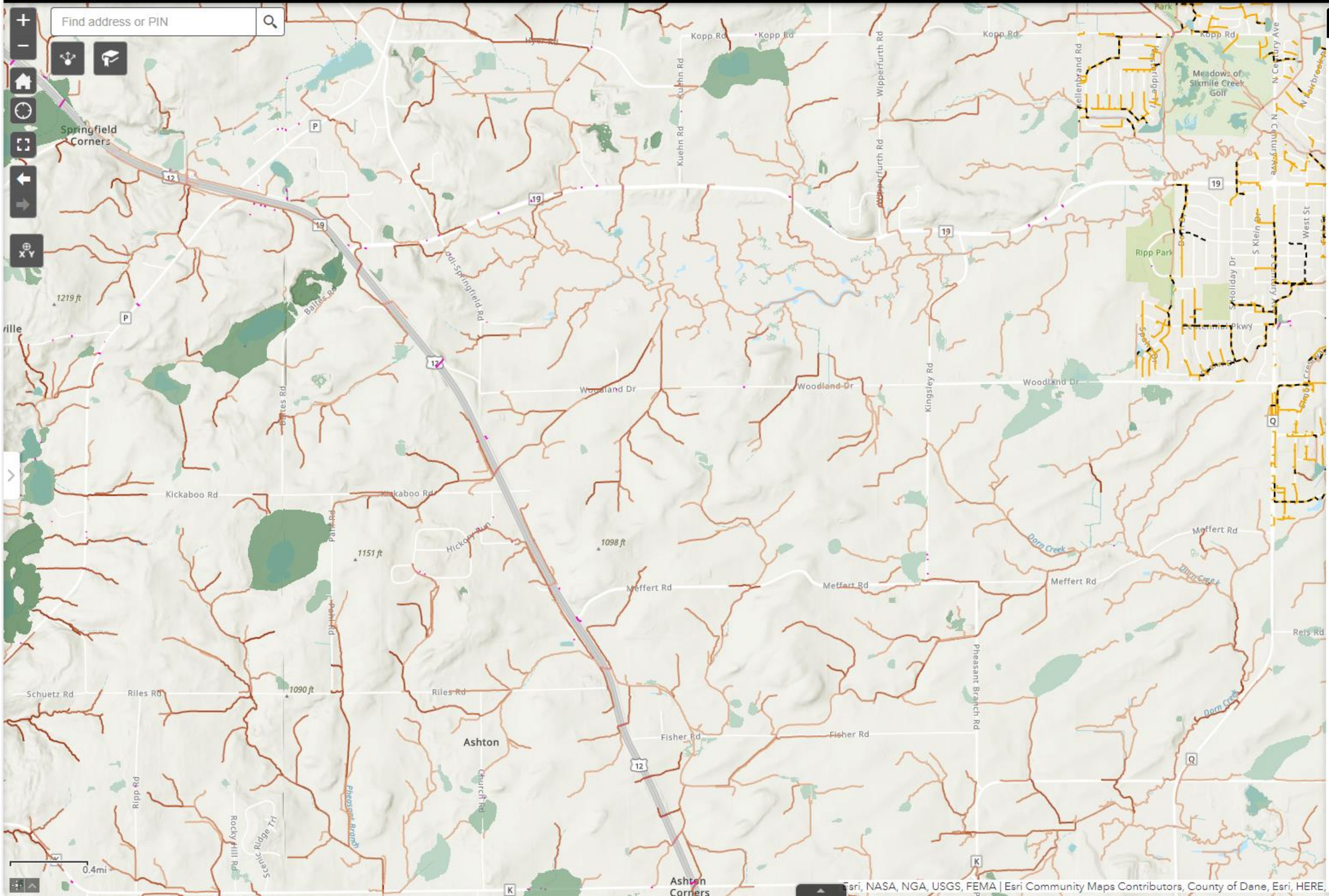
## Stormwater management

- Identifying areas of Dane County where certain stormwater management requirements apply

## Foundational dataset for characterizing the hydrology of Dane County

https://dcimapapps.countyofdane.com/lwrviewer/

Land and Water Resources Viewer Version 3.2




**Water Resources**

Layers

- [ ] Rivers and Streams
- [ ] Lakes and Ponds
- [x] Depressions
- [ ] Well Drilling
- [ ] Internally Drained Areas
- [x] Drainage Networks
  - [x] Surface Drainage Network
  - [x] Storm Sewer Drainage Network
- [ ] Shoreland Zone
- [ ] Thermal Stream Data
- [x] Culverts & Storm Sewers
  - [x] Culverts
  - [x] Storm Sewers
- [ ] Hydrologic Units
  - [ ] Watershed Boundaries (NRCS)
  - [x] Watershed Boundaries (ACPF HUC12)
  - [x] Hydrologic Units
  - [x] Runoff Delivery
- [ ] DNR Wetland Indicators
- [ ] DNR Wetlands
- [ ] FEMA Floodplain
- [ ] Groundwater Recharge