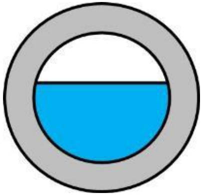
GIS Enabled Automated Culvert Design



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ASCE
AMERICAN SOCIETY OF CIVIL ENGINEERS

Outline

- Culvert Background
- Research Project Objectives
- Methodology
- Tool Validation
- Tuscaloosa Case Study
- Results & Conclusions

Background

- Culverts are the most common method of transporting water beneath roadways
- Often managed and maintained by municipalities & DOTs
- Design requires time-consuming spatial analysis

Objectives

- Demonstrate that culverts can be designed within GIS
- Decrease amount of time spent designing culverts by hand
- Eliminate need to use multiple types of software (HEC-RAS, HY-8, etc.)

Rational Method for Peak Flow Determination

$$Q = CiA$$

Q = peak flow, cfs
C = rational method land cover coefficient, dimensionless
i = rainfall intensity, in/hr
A = drainage area, acres

- Introduced to the US in 1889
- Most widely used peak flow method
- For watersheds < 200 acres
- Requires multiple spatial inputs

Kirpich Method for Time of Concentration

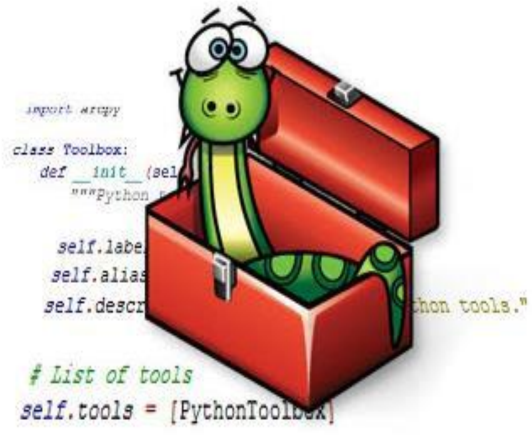
$$T_c = 0.0078L^{0.88}S^{-0.385}$$

T_c = Time of concentration, minutes
L = Channel length, ft
s = basin slope, ft/ft

- Occurs when water from most distant point reaches watershed outlet
- Developed for small basins in Tennessee
- Adjustment factors for different terrain

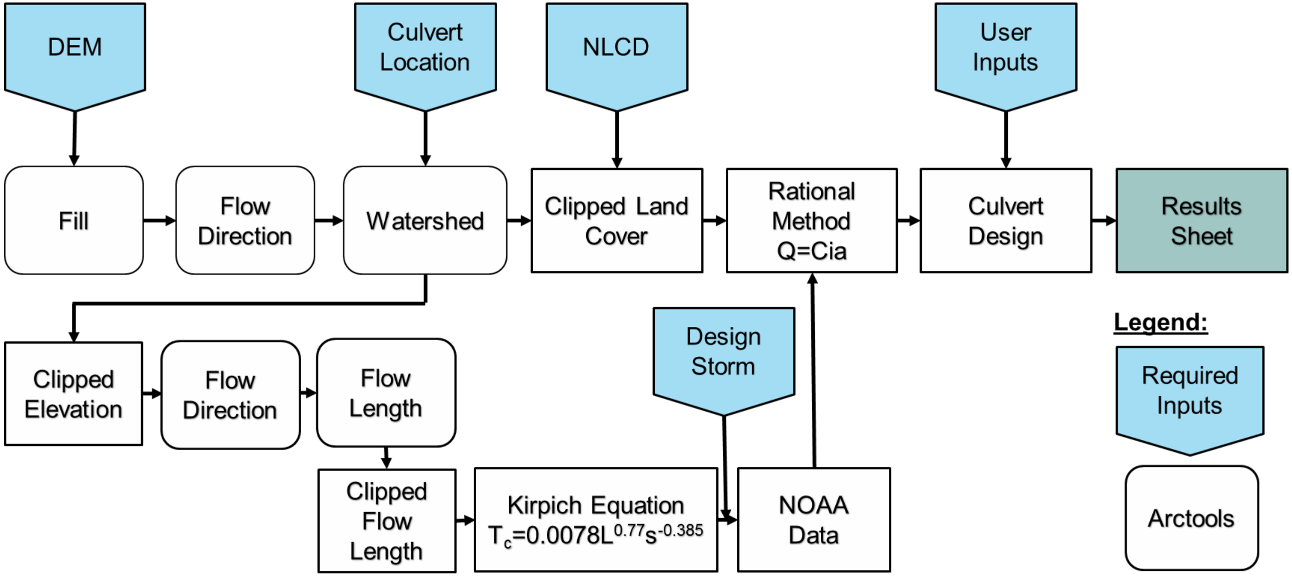
Methodology

- Tool developed as Python add-in for ArcMap 10.4
  - Customization that plugs into ArcGIS Desktop application
- Utilizes ArcPy geoprocessing functions
  - Automates actions in response to an event

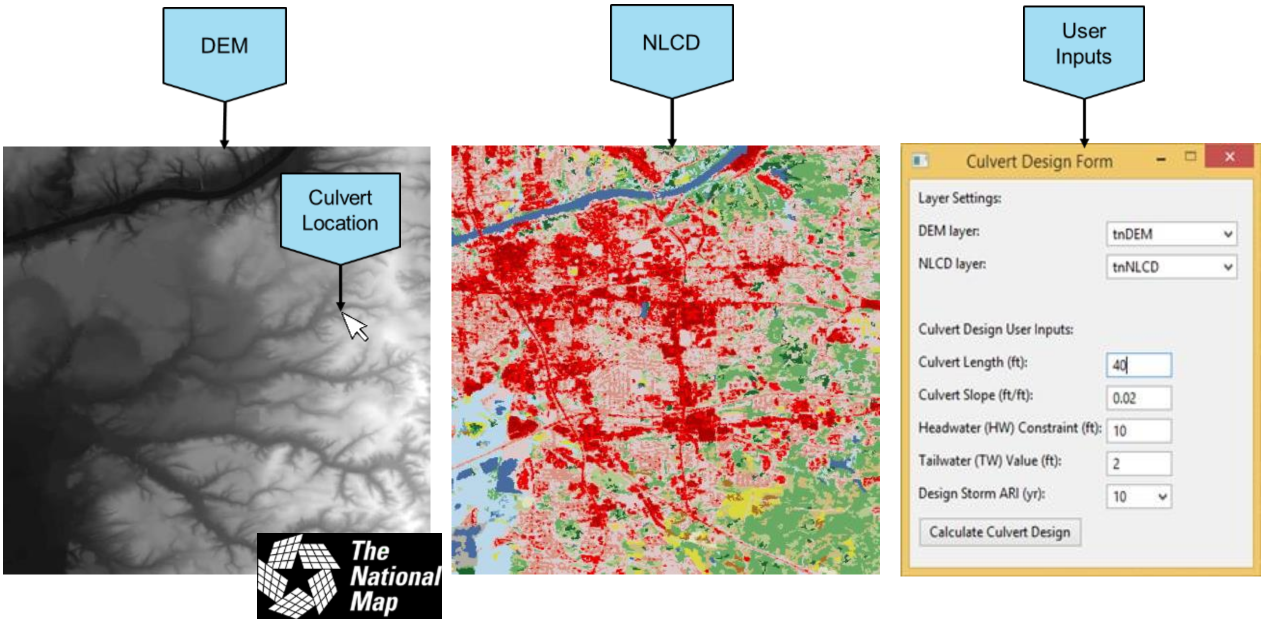


Methodology

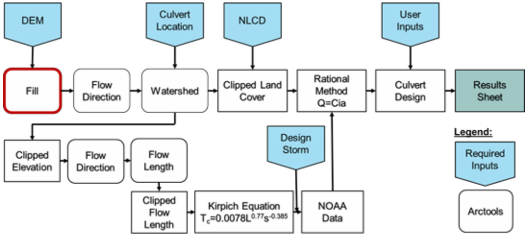
- Three categories: Landscape Analysis, Hydrologic Parameter Determination, Design Calculations

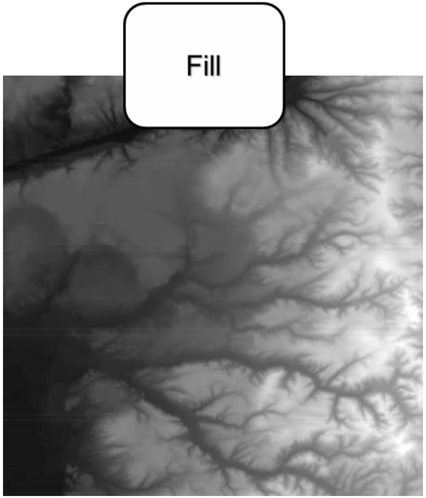


Required Inputs

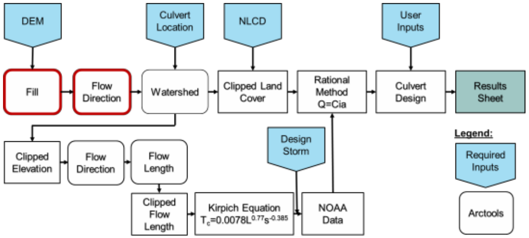


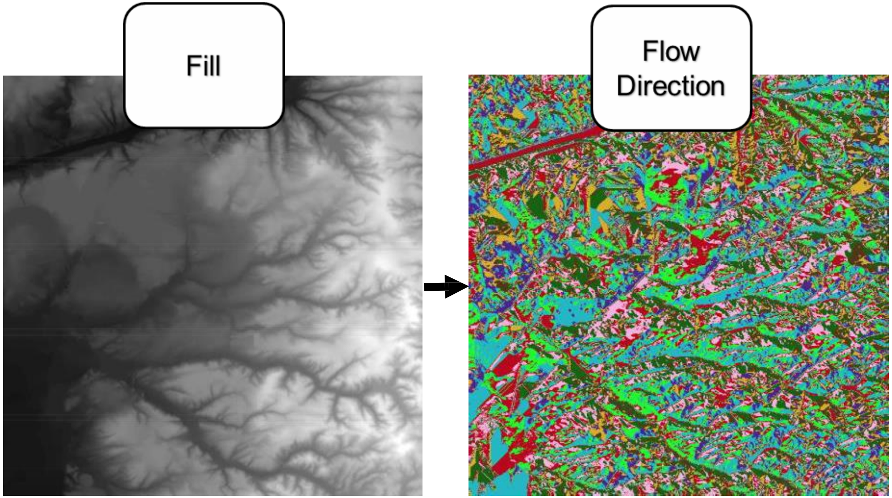
Landscape Analysis





Landscape Analysis





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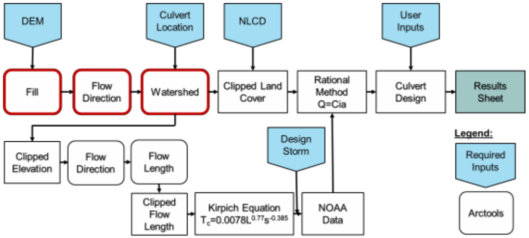
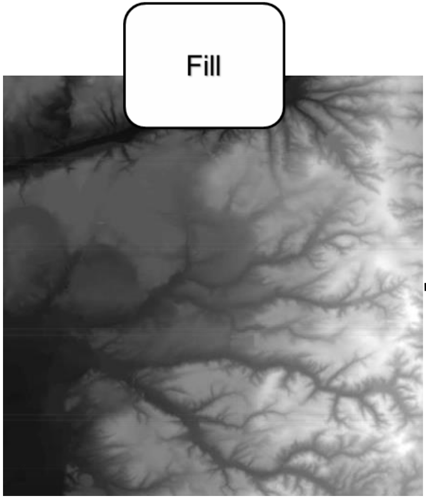
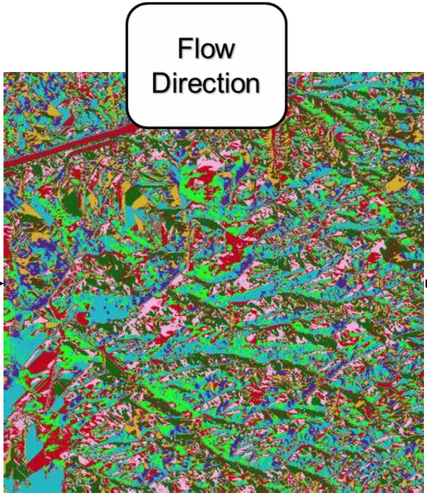
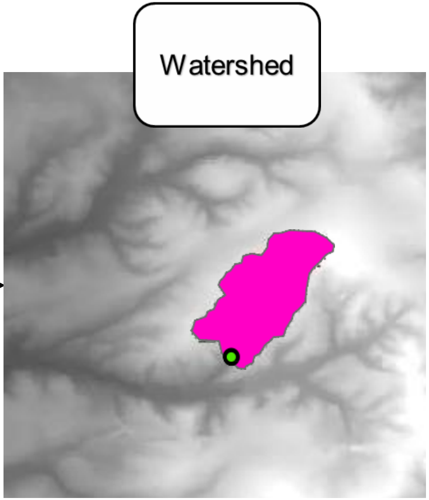
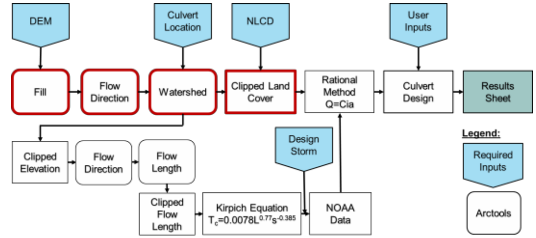




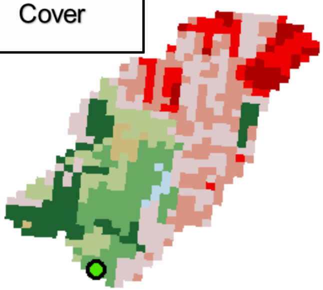




Landscape Analysis



Clipped Land Cover



Rational method coefficient, *C*

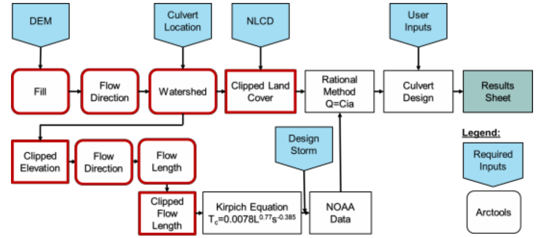
NLCD Value	Land Cover Class	C_Value
11	Open Water	1
21	Developed, Open Space	0.8
22	Developed, Low Intensity	0.85
23	Developed, Medium Intensity	0.9
24	Developed, High Intensity	0.95
31	Barren Land	0.6
41	Deciduous Forest	0.3
42	Evergreen Forest	0.2
43	Mixed Forest	0.25
52	Shrub/Scrub	0.7
71	Herbaceous	0.65
81	Hay/Pasture	0.4
82	Cultivated Crops	0.45
90	Woody Wetlands	0.9
95	Emergent Herbaceous Wetlands	0.95

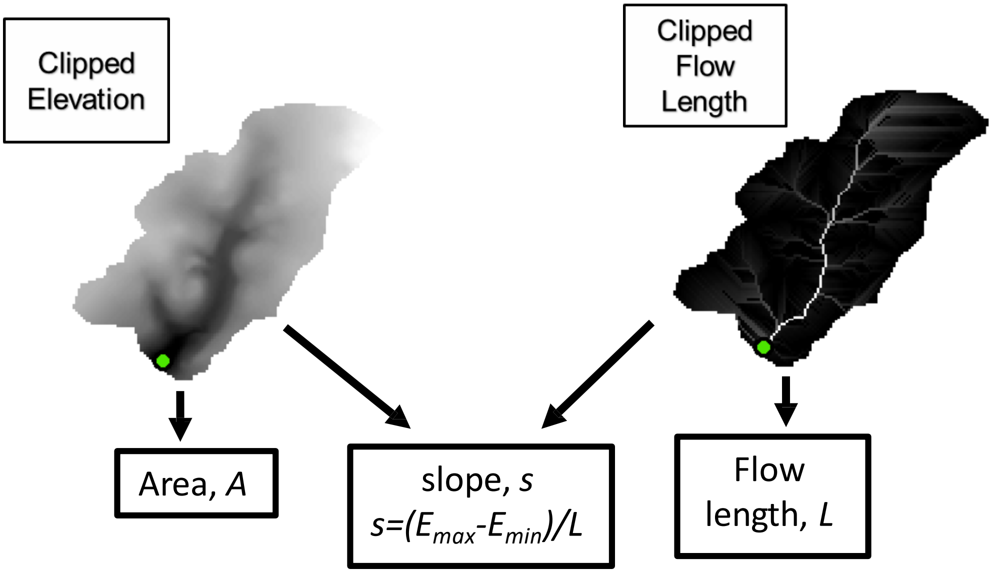
Overall weighted C calculation:

$$C = \frac{\sum_{j=1}^{n}(C_j * A_j)}{\sum_{j=1}^{n} A_j}$$

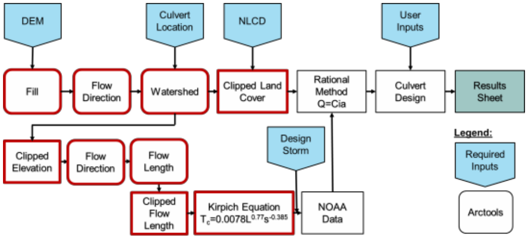
$\boldsymbol{A_j}$= area for land cover *j*
$\boldsymbol{C_j}$ = C value for j
n = distinct landcover categeories within watershed

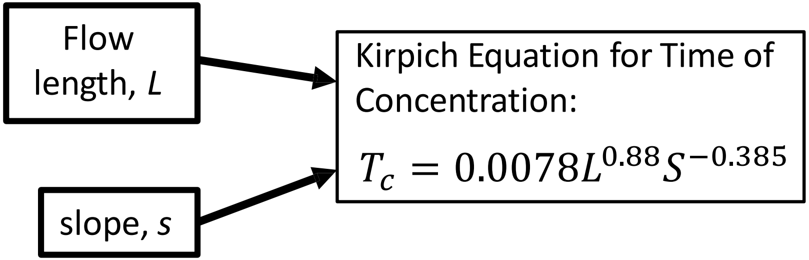
Landscape Analysis





Hydrologic Parameter Calculations:





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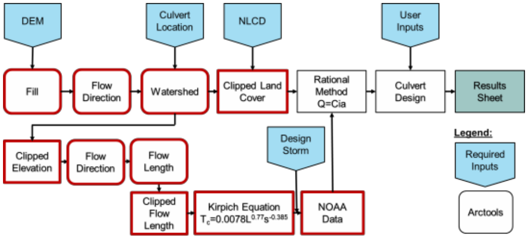


NOAA's National Weather Service

Hydrometeorological Design Studies Center

Precipitation Frequency Data Server (PFDS)

Storm Return Period

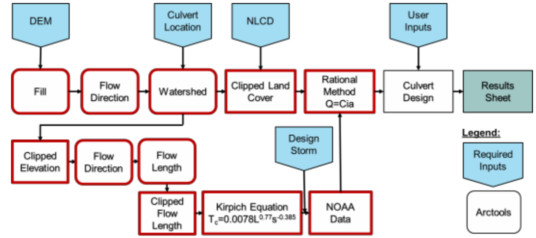
Time of Concentration, T_c

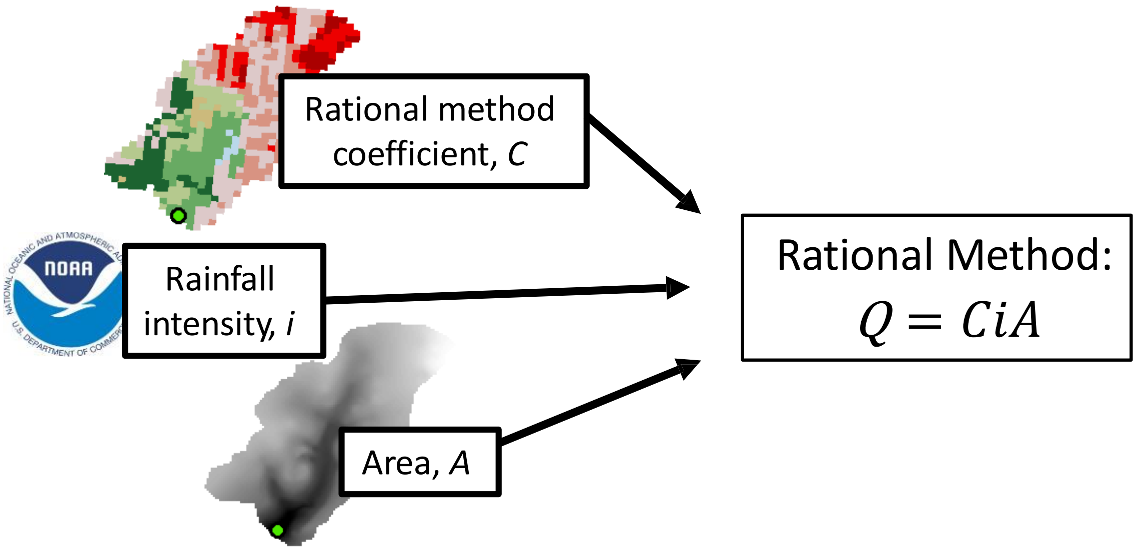
Rainfall intensity, i

PDS-based precipitation frequency estimates with 90% confidence intervals (in inches/hour)[1]

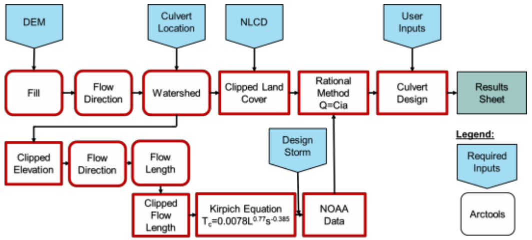
Duration	Average recurrence interval (years)									
	1	2	5	10	25	50	100	200	500	1000
5-min	5.09 (4.38-5.95)	5.89 (5.08-6.91)	7.18 (6.16-8.44)	8.21 (7.00-9.70)	9.58 (7.81-11.6)	10.6 (8.42-13.0)	11.6 (8.84-14.6)	12.5 (9.13-16.2)	13.7 (9.58-18.3)	14.6 (9.92-19.9)
10-min	3.72 (3.21-4.36)	4.31 (3.71-5.06)	5.26 (4.51-6.18)	6.01 (5.12-7.10)	7.01 (5.72-8.48)	7.75 (6.17-9.53)	8.47 (6.48-10.7)	9.17 (6.68-11.9)	10.1 (7.01-13.4)	10.7 (7.27-14.6)
15-min	3.02 (2.61-3.54)	3.51 (3.02-4.11)	4.27 (3.66-5.02)	4.88 (4.16-5.77)	5.70 (4.65-6.90)	6.30 (5.02-7.75)	6.88 (5.27-8.68)	7.45 (5.44-9.67)	8.17 (5.70-10.9)	8.69 (5.90-11.9)
30-min	2.23 (1.93-2.62)	2.60 (2.24-3.05)	3.18 (2.72-3.73)	3.63 (3.10-4.29)	4.23 (3.45-5.11)	4.67 (3.71-5.74)	5.09 (3.89-6.41)	5.49 (4.00-7.11)	5.99 (4.18-7.99)	6.34 (4.31-8.65)
60-min	1.48 (1.27-1.73)	1.71 (1.48-2.01)	2.09 (1.79-2.46)	2.40 (2.04-2.83)	2.80 (2.29-3.40)	3.11 (2.47-3.82)	3.40 (2.60-4.29)	3.69 (2.69-4.79)	4.06 (2.83-5.42)	4.33 (2.94-5.91)
2-hr	0.917 (0.796-1.07)	1.06 (0.920-1.24)	1.30 (1.12-1.51)	1.49 (1.28-1.75)	1.75 (1.43-2.10)	1.94 (1.55-2.37)	2.13 (1.64-2.67)	2.32 (1.70-2.99)	2.56 (1.80-3.41)	2.75 (1.88-3.72)
3-hr	0.686 (0.597-0.796)	0.792 (0.688-0.919)	0.965 (0.835-1.12)	1.11 (0.954-1.30)	1.31 (1.08-1.58)	1.47 (1.18-1.79)	1.62 (1.26-2.03)	1.78 (1.31-2.30)	[illegible]	[illegible]
6-hr	0.418 (0.366-0.481)	0.479 (0.418-0.551)	0.583 (0.508-0.673)	0.674 (0.583-0.782)	0.806 (0.674-0.973)	0.914 (0.743-1.12)	1.03 (0.802-1.29)	1.15 (0.854-1.48)	[illegible]	[illegible]
12-hr	0.251 (0.221-0.287)	0.286 (0.251-0.327)	0.349 (0.305-0.400)	0.406 (0.353-0.468)	0.493 (0.417-0.595)	0.566 (0.465-0.691)	0.644 (0.508-0.807)	0.730 (0.549-0.938)	[illegible]	[illegible]
24-hr	0.150 (0.133-0.170)	0.171 (0.151-0.194)	0.209 (0.184-0.238)	0.245 (0.214-0.280)	0.300 (0.256-0.361)	0.347 (0.287-0.422)	0.398 (0.316-0.496)	0.454 (0.344-0.582)	[illegible]	[illegible]
2-day	0.087 (0.077-0.098)	0.099 (0.088-0.112)	0.122 (0.108-0.138)	0.143 (0.126-0.162)	0.175 (0.150-0.209)	0.203 (0.169-0.245)	0.233 (0.186-0.289)	0.266 (0.203-0.338)	[illegible]	[illegible]

Hydrologic Parameter Calculations:





Culvert Design



$$\frac{Q}{AD^{0.5}g^{0.5}} \geq 0.70 \quad \text{(Submerged)}$$

$$HW = D\left[C\left(\frac{Q}{A\sqrt{gD}}\right)^2 + Y + K_s S_o\right] \quad \text{(Inlet Control)}$$

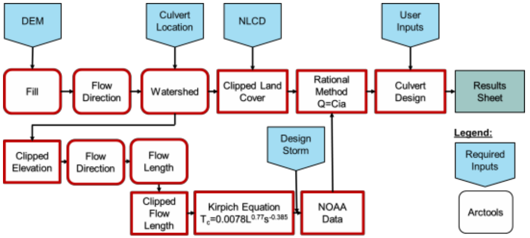
$$HW = TW - S_o L + \left(1 + K_e + \frac{2gn^s L}{K_n^2 R^{\left(\frac{4}{3}\right)}}\right)\frac{Q^2}{2gA^2} \quad \text{(Outlet Control)}$$

$$V = \frac{M}{n} R^{2/3} S_o^{1/2} \quad \text{(Flow Velocity)}$$

Q = peak flow rate, cfs
A = Cross-sectional culvert area, ft
D = Culvert diameter, ft
R = Hydraulic radius, ft
g= Gravitational constant, ft/s2
HW = Headwater, ft
TW = Tailwater, ft

S_o= Culvert slope, ft/ft
L = Culvert Length, ft
n = Manning's coefficient
M = conversion constant (1.00)
C, Y, K-values = Constants for circular, concrete pipes

Culvert Design



- Each equation must be satisfied
- Loop iterates through a list of different diameters until conditions are met
- If conditions cannot be met, user will be notified that an error has occurred

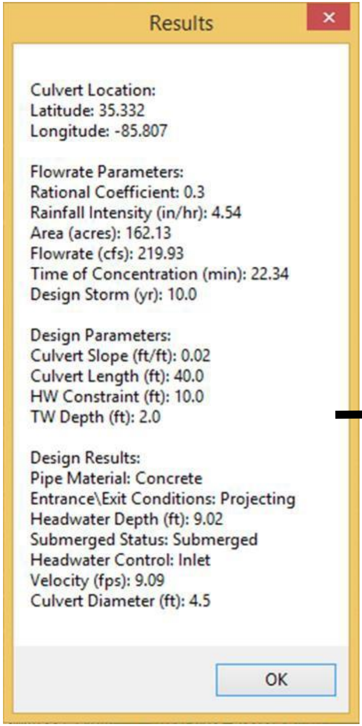
$$\frac{Q}{AD^{0.5}g^{0.5}} \geq 0.70 \quad \text{(Submerged)}$$

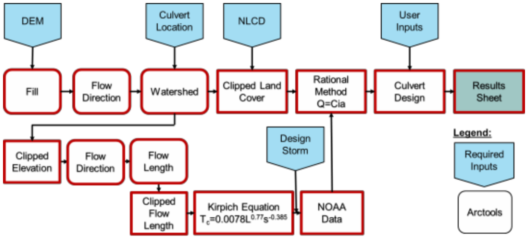
$$\frac{HW}{D} = C\left(\frac{Q}{A\sqrt{gD}}\right)^2 + Y + K_s S_o \quad \text{(Inlet Control)}$$

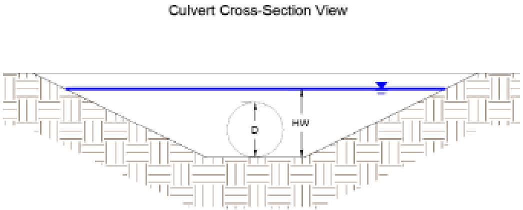
$$HW = TW - S_o L + \left(1 + K_e + \frac{2gn^s L}{K_n^2 R^{\left(\frac{4}{3}\right)}}\right)\frac{Q^2}{2gA^2} \quad \text{(Outlet Control)}$$

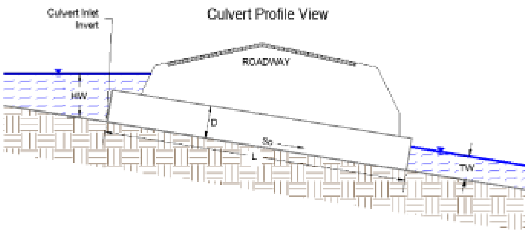
Results

- ArcMap dialog box shows results
- Results correspond to drawings located in user guide



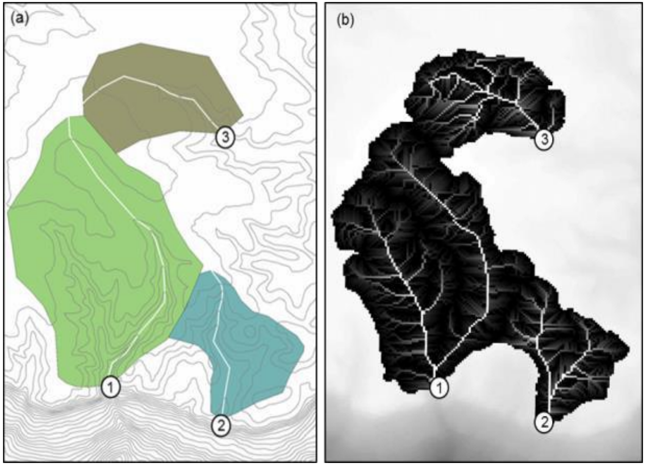






Tool Validation

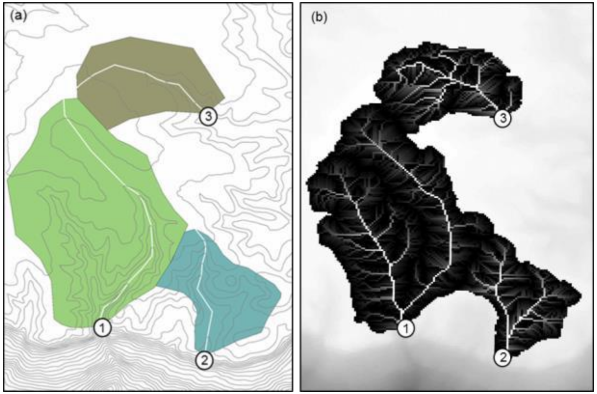
- Three rural Tennessee drainage basins were analyzed by hand (left) and with culvert tool (right)
- Peak flows were within ~ 5 %



Culvert ID	C	Slope (m/m)	Flow Length (m)	T_c (min)	i, 10 yr event (cm/hr)	Area (km^2)	$Q_{hand\ calc}$ (m^3/s)	$Q_{GIS,\ auto}$ (m^3/s)	Percent Diff. (%)
1	0.30	0.03	1506	21.75	10.5	0.684	5.918	6.172	4.29
2	0.32	0.05	747	9.91	15.9	0.215	3.003	2.837	-5.53
3	0.33	0.03	750	16.99	12.9	0.251	2.932	2.946	0.46
								Average	3.4

Tool Validation

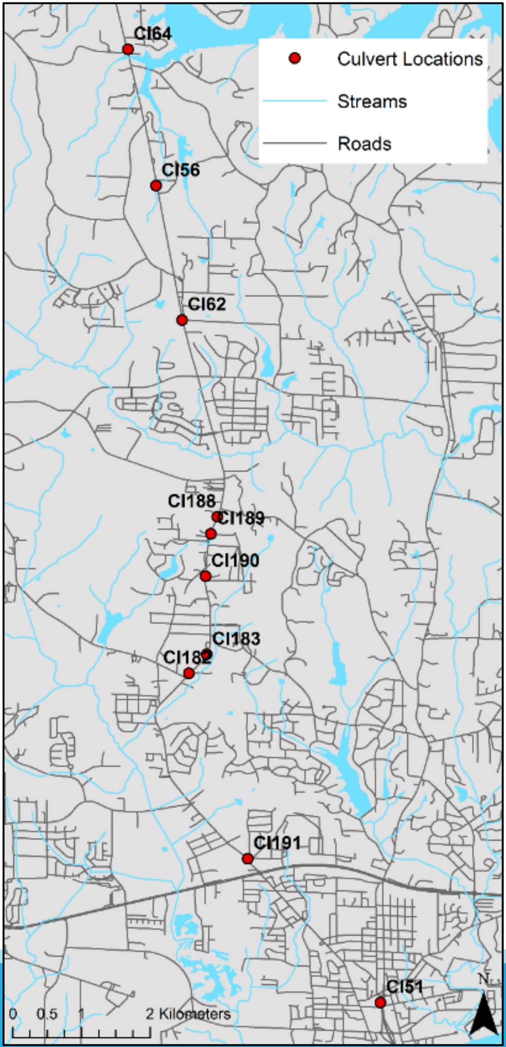
- Culverts were designed with culvert tool and designed with HY-8 for verification



Culvert ID	$Q_{GIS, Auto}$ (m^3/s)	Slope (m/m)	Length (m)	Headwater Constraint (m)	Tailwater Value (m)	$D_{GIS, auto}$ (m)	HY-8 Verification (m)	
1	6.172	0.02	12.2	3.05	0.610	1.372	1.372	✓
2	2.837	0.02	12.2	3.05	0.610	0.914	0.914	✓
3	2.946	0.02	12.2	3.05	0.610	0.914	0.914	✓

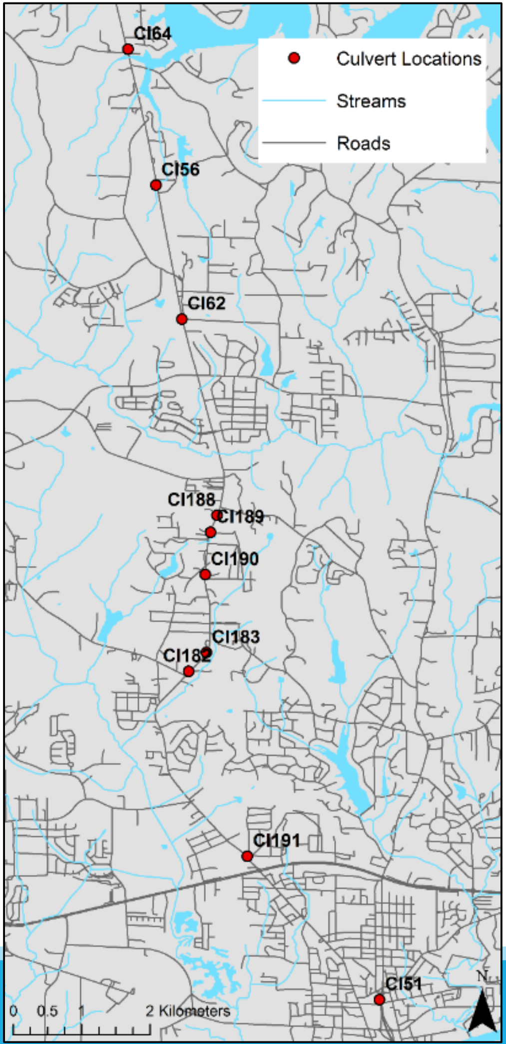
Case Study

- Data was collected for 10 culverts along AL HY 43 North of Tuscaloosa:
  - Material
  - Inlet/Outlet Configuration
  - Diameter
  - Length
  - Depth of Cover



Case Study

- The GIS-based culvert tool was used to redesign these 10 culverts
- We hypothesized that our tool would result in larger culverts than those currently existing.



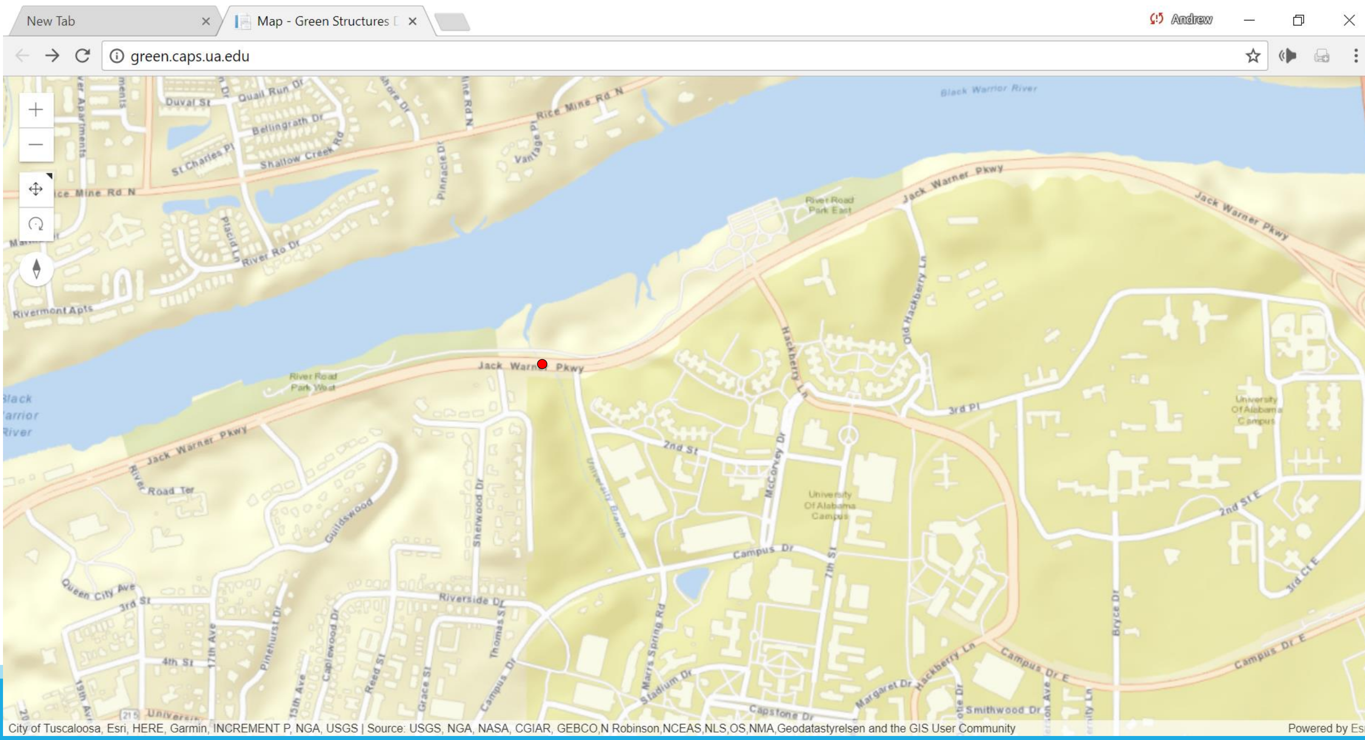
Case Study

- 10 culverts were re-designed in minutes
- 100% resulted in larger cross-section designs than those currently in place
  - Contributing assumptions: 25 year design storm, tailwater
  - Land use/climate change contributions

Culvert ID	C	I (in/hr)	A (acres)	Q (cfs)	D_{tool} (ft)	D_{actual} (ft)
CL51	0.84	7.21	30.9	187.4	4	1.5
Cl64	0.53	8.09	33.8	144.9	3.5	1.5
Cl190	0.56	8.88	14.7	73.5	2.5	2
Cl56	0.33	6.63	41.8	90.9	3	1.5
CL62	0.69	8.39	16.5	95.1	3	2
Cl188	0.73	8.02	22.0	129.2	3.5	2
Cl189	0.54	6.64	33.6	121.4	3.5	2
CL191	0.81	9.12	6.2	46.2	2	1
Cl183	0.78	8.58	16.0	107.7	3	1.5
Cl182	0.69	9.46	6.9	45.1	2.5	1.5

Next Steps

- On-line version of tool: green.caps.ua.edu



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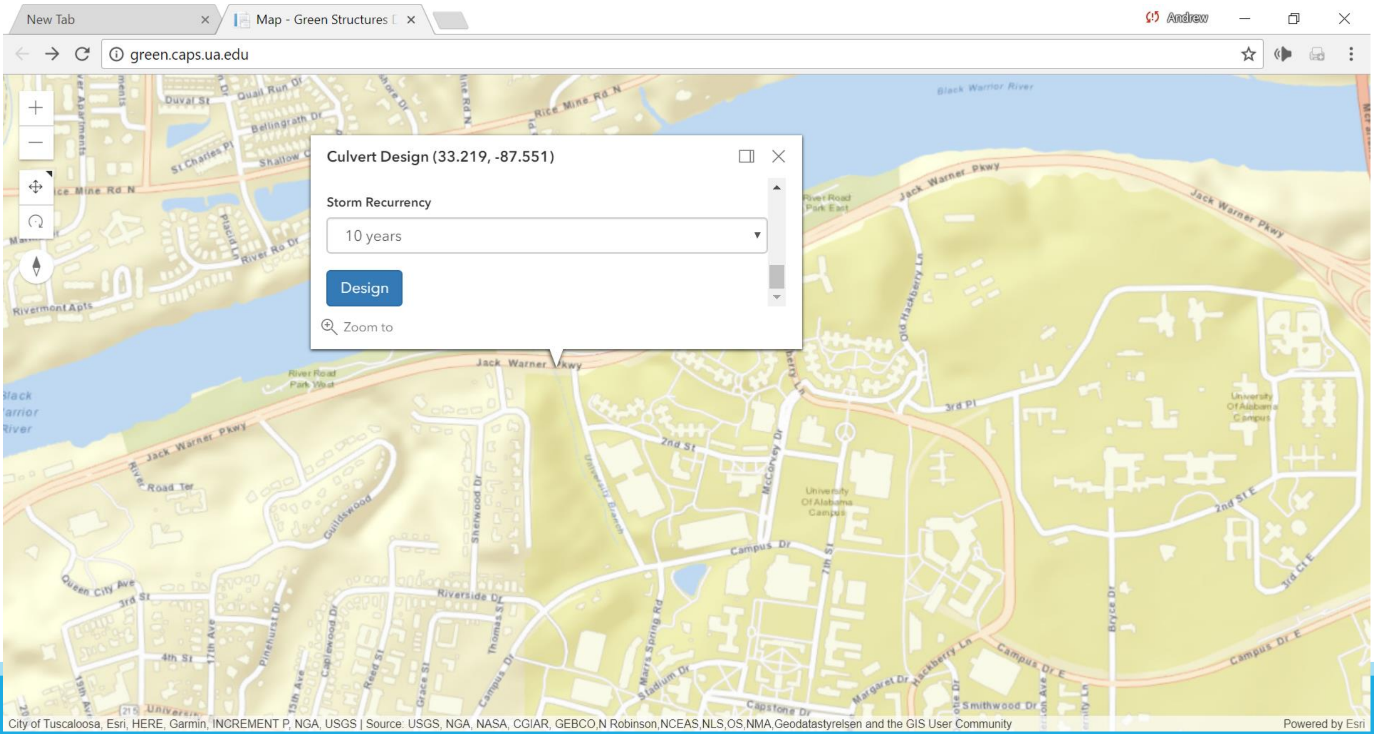

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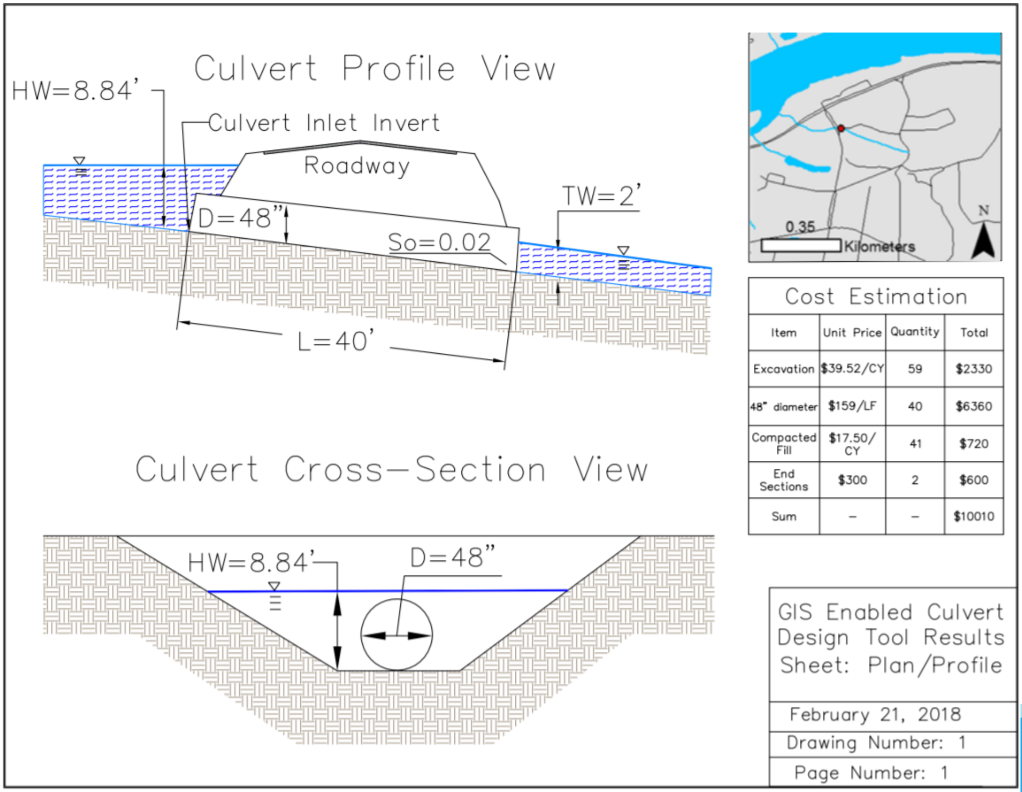
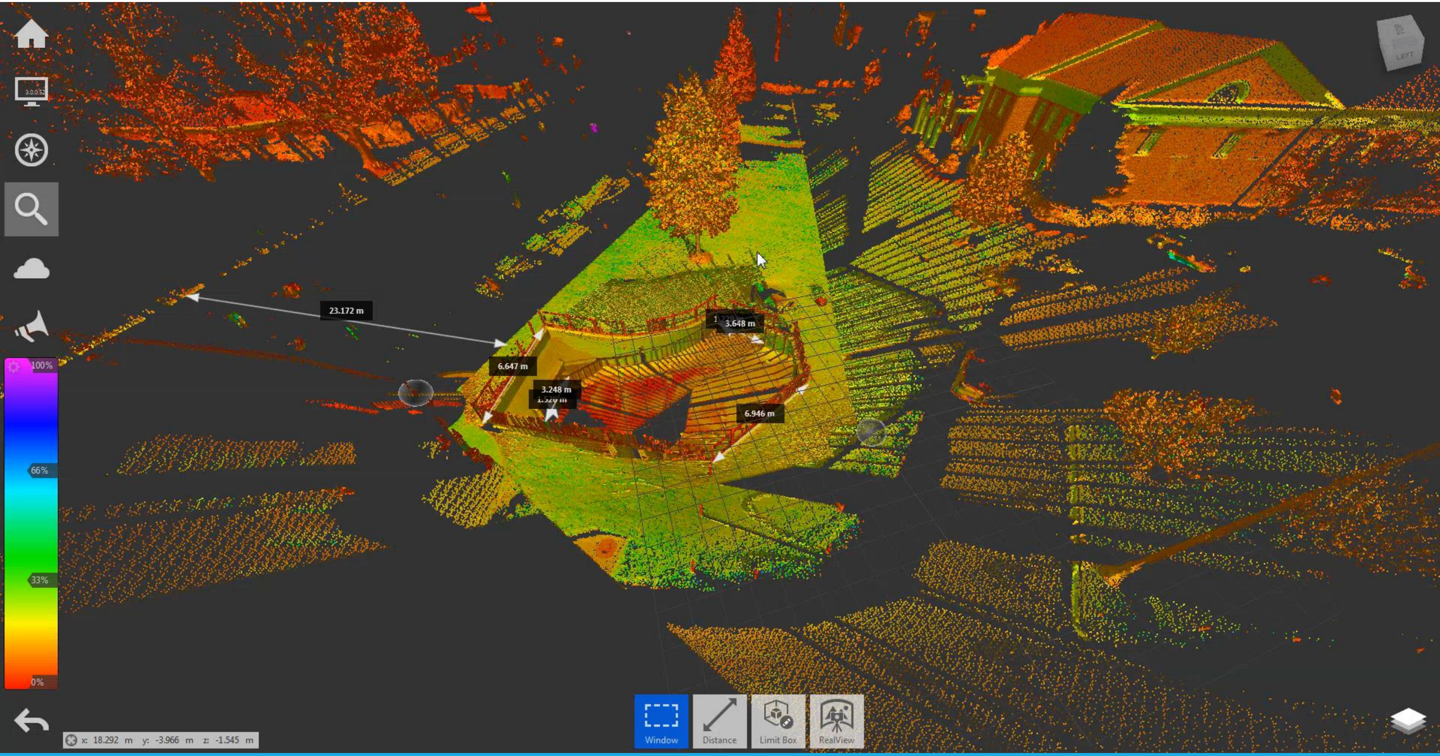


Item	Unit Price	Quantity	Total
Excavation	$39.52/CY	59	$2330
48" diameter	$159/LF	40	$6360
Compacted Fill	$17.50/ CY	41	$720
End Sections	$300	2	$600
Sum	–	–	$10010

Next Steps

- Incorporation of higher resolution data, LiDAR



Next Steps

- Addition of multiple culvert configurations and flow conditions
- Addition of downstream channel cross section, slope, and evaluation for more accurate tailwater depth
- Expansion to other types of infrastructure requiring analysis of elevation and land cover

Conclusions

- Demonstrated that culverts could be automatically designed quickly & easily
- Redesigning multiple culverts along HY43 showed that all are under designed based on current land use and rainfall
- GIS has the potential to assist with many civil engineering designs

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