GIS ENABLED HYDRAULIC INFRASTRUCTURE DESIGN

Ashton Greer, Zachary Wilbanks, Leah Clifton, Bradford Wilson, Andrew Graettinger, Ph.D.

Department of Civil, Construction, & Environmental Engineering – The University of Alabama

www.gisresarch.ua.edu

Abstract

A GIS enabled hydraulic infrastructure design module is presented. This module employs Python programming to automatically design a culvert by combining a proposed culvert location with widely-available topography, land use, and rainfall data. This approach uses United States Geological Survey digital elevation data to determine watershed boundaries, stream lengths, and slopes. Runoff coefficients are determined from land cover data that is available through the National Land Cover Database. Rainfall data is retrieved from the National Oceanic and Atmospheric Administration and combined with watershed and land use information to calculate peak discharge using the Rational Method. Peak discharge is then combined with culvert parameters such as slope and acceptable headwater and tailwater depths to design a single-barrel culvert. The module was used to re-design ten existing culverts along a highway in Tuscaloosa, Alabama, resulting in designs for updated land cover and rainfall conditions. On average, this automated approach displays a 95% time savings over traditional calculation methods. The module is embedded within ESRI ArcGIS 10.4 software, providing a seamless single-platform that eliminates error propagation associated with cross-platform data transfers among multiple computer programs or hand calculation errors. The automation techniques developed herein may be extended to other sustainable hydrological objectives and runoff mitigation designs such as bioswales and detention and retention ponds.

Introduction

A culvert is a hydraulic structure meant to convey water from one side of an embankment to another. As the most common method of conveying water beneath roadways, the volume of culverts can be burdensome for the agencies that oversee them. They are often managed by municipalities and DOTs who lack the time and financial resources to adequately maintain the infrastructure, thereby leading to increased likelihood of failure.

Culverts are traditionally designed using time-consuming hand calculation methods. The typical design procedure involves calculating the maximum volume of water, or peak flow, that will be entering the culvert. Peak flow determination involves collecting location-specific rainfall intensity data, determining the geographic area, or watershed, that contributes flow to the culvert, and analyzing slope and land cover data to determine how much precipitation will be converted to runoff and how quickly it will take runoff to reach the culvert location. Each of these parameters are highly location specific, making a GIS the ideal environment in which to perform these operations. Once peak flow has been determined, it serves as an input for a set of design equations resulting in a culvert design diameter.

The objective of this work is to demonstrate and test that highway drainage infrastructure can be designed and analyzed using widely available data within a GIS platform. A submerged single-barrel, circular, concrete culvert was chosen as a test scenario for proof of concept. The benefits of this GIS-based approach are:

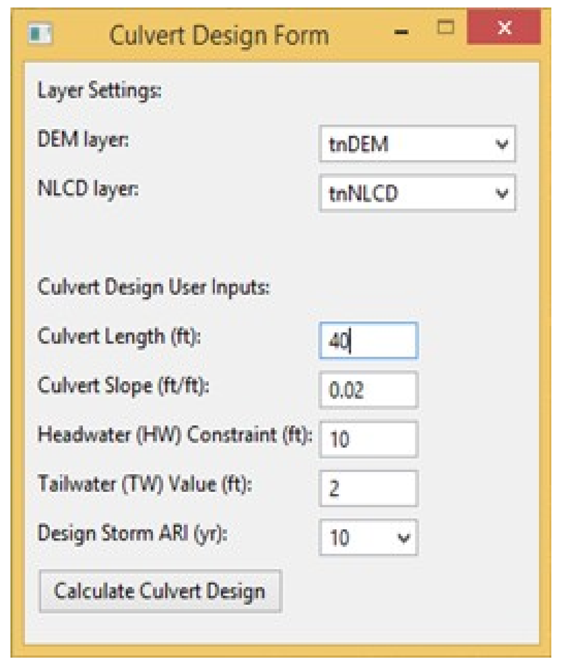
- Decreased amount of time – and consequently, money – spent designing culverts through traditional means
- Elimination of need to use multiple types of software (HEC-RAS, HY-8, etc), therefore reducing error propagation that occurs during data transfer

Methodology

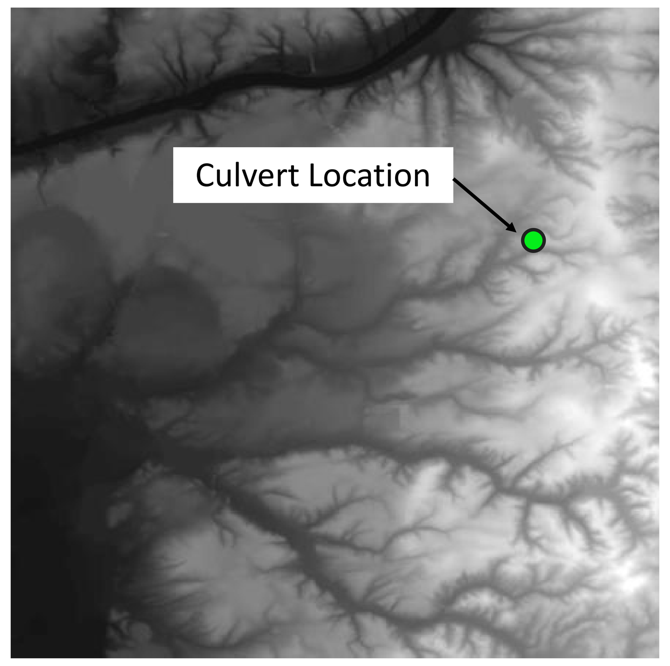
The culvert design tool was programed as a Python Add-In for ESRI ArcMap 10.4. The culvert design procedure can be divided into two primary categories: Peak Flow Determination and Design Calculations. The functions are programmed using Python to automate geoprocessing procedures in response to the event of a user providing input.

User Inputs:

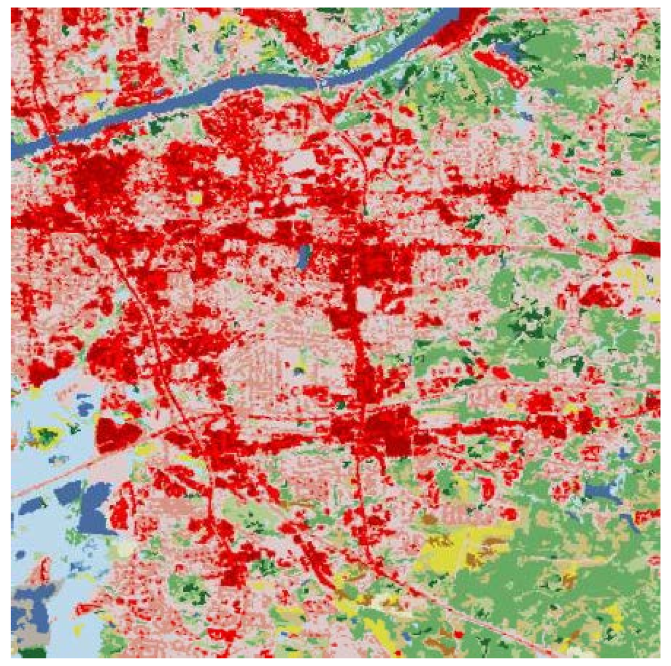
Site-specific Design Criteria



Digital Elevation Model (DEM)

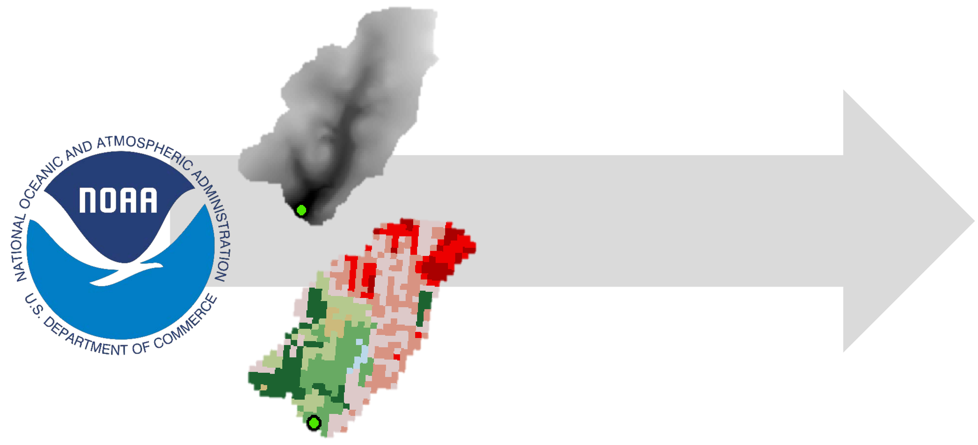


National Land Cover Dataset (NLCD)



Landscape Analysis & Peak Flow Determination:

Peak flow (Q) calculations are based on the Rational Method, one of the most common methods for determining peak runoff volumes. The Rational method calculates peak flow from the following equation. The design tool is programmed to retrieve each of the input parameters from the user-provided data. *A* is calculated by delineating the watershed with elevation data provided in the DEM. *C* is calculated by taking a weighted mean of land cover category data from the NLCD. *i* is automatically retrieved from the NOAA Precipitation Frequency Data Set.



$$Q = CiA$$

Where Q= Peak Flow, cfs
C= Rational Method Land Cover Coefficient, dimensionless
i = rainfall intensity, in/hr
A= drainage area, acres

Design Calculations & Results:

The design portion of the tool Is based on equations developed by the Federal Highway Administration (FHWA). The tool iterates through a list of commercially available culvert diameters until acceptable headwater conditions have been met.

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

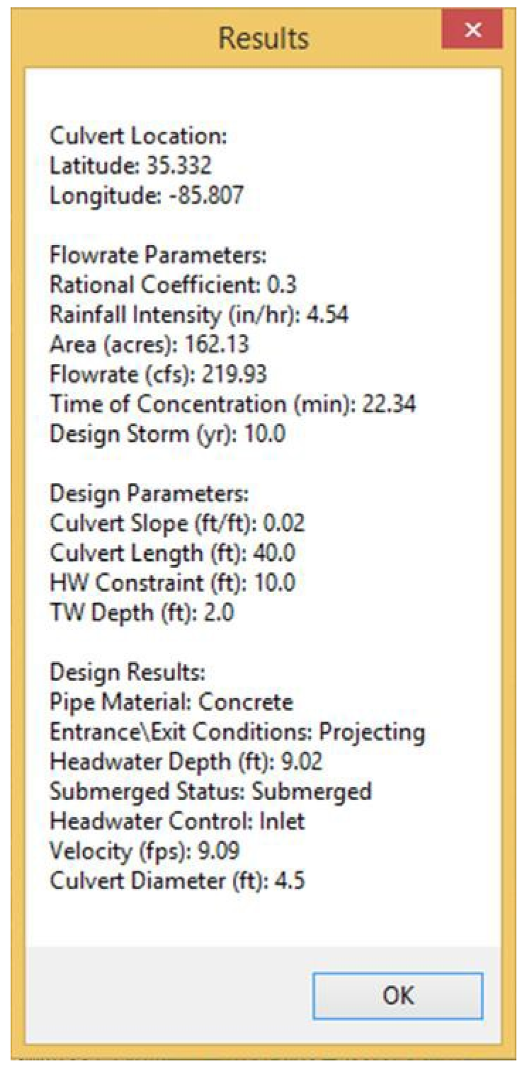
$$\frac{HW}{D} = C\left(\frac{Q}{A\sqrt{gD}}\right)^2 + Y + K_s S_o \quad \text{(Inlet Control)}$$

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

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

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

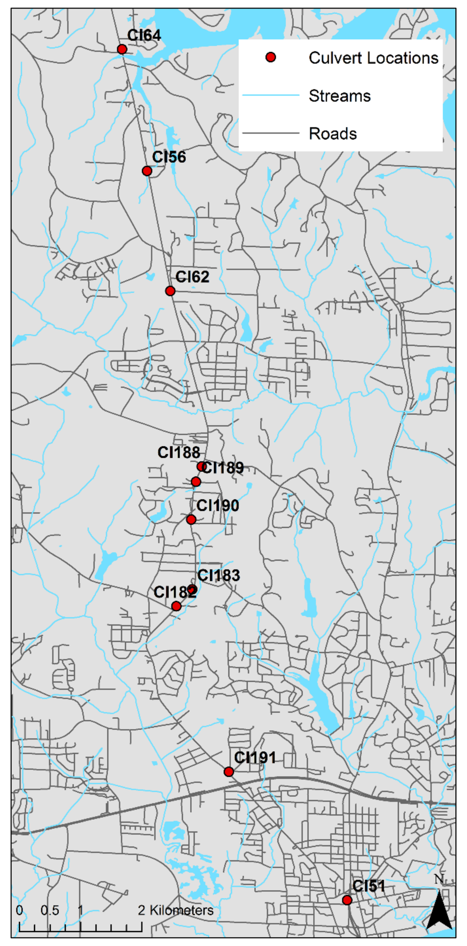
S_o= Culvert slope, ft/ft
L = Culvert Length, ft
n = Manning's coefficient
M = conversion constant (1.00)
C, Y, K-values = Constants for circular, concrete pipes



Once the tool has completed running, the results of the output design parameters are displayed in a dialog box. If any errors occur during the procedure, the user is notified in the dialog box.

Case Study:

- 10 cylindrical, concrete culverts along Highway 43 in Tuscaloosa, AL were chosen to be re-designed with the tool.
- Data was collected in the field for each of the culverts including culvert length, culvert slope, and inlet and outlet dimensions.
- The culverts were designed using the following assumptions:
  - HW Constraint: 10 ft
  - TW Value: 2 ft
  - Design Storm ARI: 25 yr
- The resulting designs were then compared to the in-field observations.



Results

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

- 10 culverts were re-designed in less than ½ an hour.
- 100% of the calculated culvert design diameters were larger than those observed in the field.

Conclusions & Future Work

The tool was used to quickly re-design 10 culverts in Tuscaloosa, demonstrating that drainage infrastructure can be redesigned efficiently through a GIS platform. This highlights the potential to perform large-scale analyses of hydraulic infrastructure as well as produce designs of similar spatially-based structures.

Future work includes:

- Addition of multiple culvert configurations and flow conditions.
- Introduction of finer resolution input data (i.e. LiDAR) for increased accuracy in results.
- Expansion to other types of infrastructure, particularly sustainable alternatives such as:
  - Bioswales.
  - Detention/retention ponds.
  - Permeable pavement.
  - Rain gardens