Evaluation of a Novel Method for Estimating Directly Connected Impervious Area and Unconnected Impervious Area

GIS in Water Resources - Fall 2018

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1. Introduction:

1.1 Objectives

The objective of this project is to evaluate a novel method for determining directly connected impervious area (DCIA). I've termed this new method, the Gregory Method. My aim was to compare the Gregory Method with two, more traditional methods of determining DCIA (e.g. manual scanning and representative sampling). I wanted to compare the speed of each technique as well as where each DCIA estimation differs. In doing this, my goal was to determine the strengths and weaknesses of each technique as well as the situations it would be appropriate to use each technique.

1.2 Significance of Directly Connected Impervious Area

The computation of impervious area is used to determine runoff in nearly every commonly used rainfall-runoff calculation method, including the NRCS method. This impervious area can be divided into DCIA and unconnected impervious area (UCIA). Rain that falls on DCIA can flow directly to the point of concentration without flowing over pervious area. Water that falls on the rest of the impervious area must flow over pervious area before it reaches the point of concentration. This area is called UCIA (Kampa 1).

DCIA is significant because it is a parameter in many hydrologic models (Jones 1). Generally, DCIA and runoff volumes are so closely correlated that DCIA is often assumed to be the contributing area, especially when modeling smaller storms (United 14). Because DCIA and UCIA are critical parameters of the NRCS method, many water modeling softwares (e.g. PondPack, SewerGEMS, CivilStorm), and some floodplain mapping techniques, we are motivated to improve the accuracy and speed at which these two types of impervious area can be differentiated.

DCIA can be used to characterize water quality as well. DCIA causes increases in nutrient and pollutant loads on streams and lakes because nutrients in runoff have no chance to be extracted by vegetation (United 13). These pollutants cause receiving river biodiversity to decrease as well (Lee 421). Because DCIA has such detrimental effects on receiving waters, it is often used to predict stream health (Jones 292). Achieving high accuracy measures of DCIA can improve these predictions of river health (United 14).

As low impact development (LID) gains popularity in stormwater design, the need to quantify their effectiveness has been filled by DCIA (Jones 291). LID designers often seek to reduce DCIA in order to decrease peak flow and attenuate the runoff as well as to improve the biology and cleanliness of the receiving waters.

Site Information

To compare the effectiveness of each DCIA calculation technique, I used all 3 methods to predict the DCIA in Williston, a small city in Levy County, Florida.

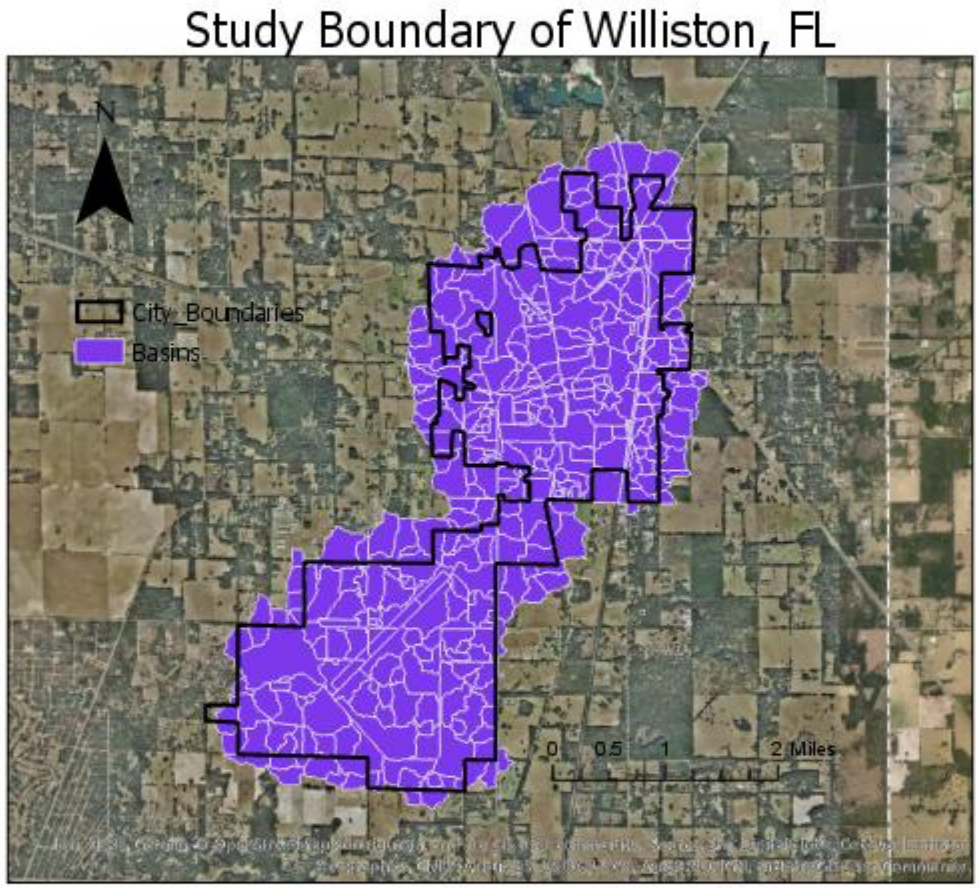


Figure 1: Study site boundary and sub-basins

In figure 1, the black outline delineates the city boundaries and the purple area is the study site. The white lines demarcate the sub-basins that were used in the analysis portion of the study.

2. Data Used

I received nearly all my GIS data from Jones Edmunds and Associates, a civil engineering firm in Gainesville, Florida. They gave me:

- A raster of impervious area for Williston
- An unconditioned digital elevation model of Williston
- A set of impervious features to burn into the digital elevation model
- A set of sub-basins
- An estimation of the impervious area in Williston using the manual method

I also used:

- Land cover polygons from the Southwest Florida Water Management District

3. Data Analysis

3.1 Using the Gregory Method to determine if a grid cell is DCIA

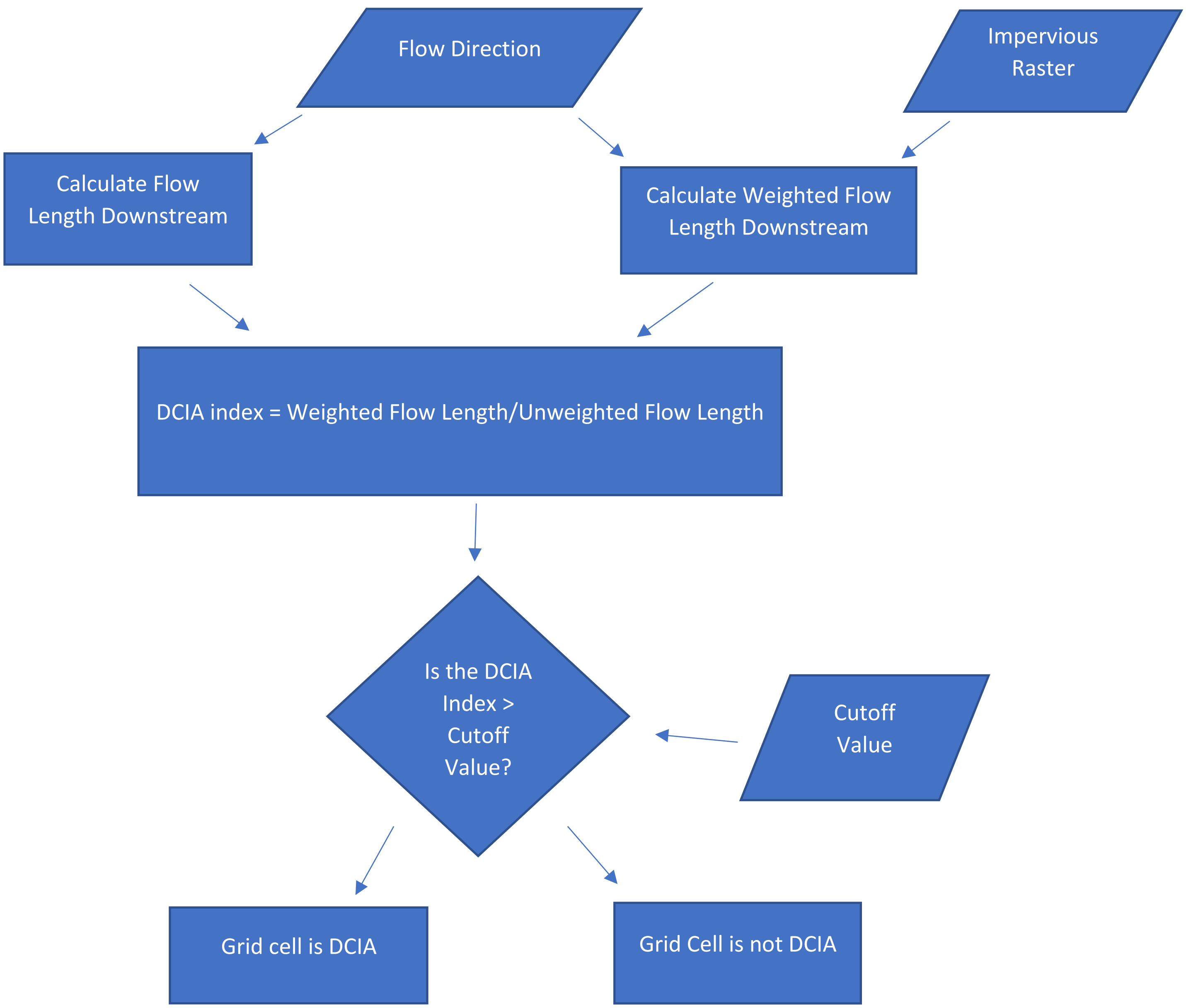


Figure 2: Flow Chart of the Gregory Method

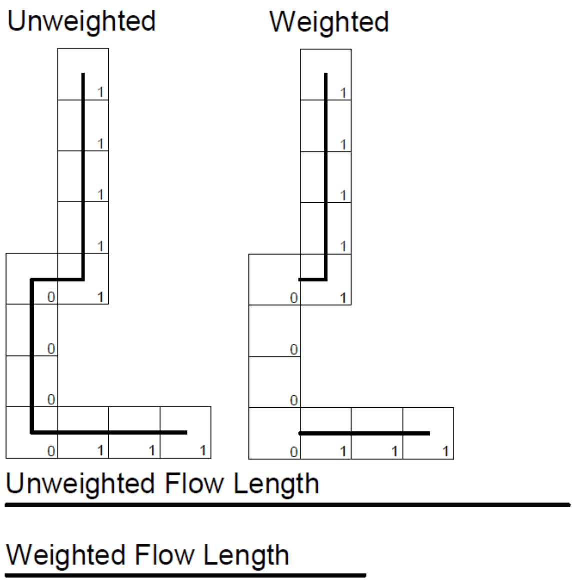


Figure 3: Comparison of unweighted and weighted flow lengths in steps 1. and 2. of the Gregory Method

To perform the Gregory Method, I followed the sequence of steps outlined in figure 2 and explained below. The Gregory needs as inputs: a flow direction raster and a raster of imperviousness. The steps to performing the Gregory Method are as follows:

1. Calculate the unweighted Flow Length downstream

The unweighted flow length is the distance that rain falling on a grid cell would travel until the water reaches a sink or the edge of the raster.

2. Calculate the Flow Length downstream weighted by impervious area.

The weighted flow length is the distance water falling on a grid cell would travel over impervious area. It does not count distance traveled over pervious area. In the ArcGIS flow length tool, the weight is taken to be a raster of impervious area that has a value of 1 where there is impervious area and 0 where there is pervious area.

3. DCIA index = $\frac{Weighted\ Flow\ Length}{Unweighted\ Flow\ Length} = \frac{Flow\ Length\ Over\ Impervious\ Area}{Total\ Flow\ Length}$

Then, the DCIA index is calculated by taking the ratio of the two flow lengths. If the length that the water traveled is equal to the length that the water traveled over impervious area, then the water traveled over mostly impervious area. If this is the case, then the DCIA index is close to 1 and is more likely to be Directly Connected Impervious Area. Figure 4 shows a map of DCIA index. By inspection, we can see that DCIA index tends to be greatest (closest to 1) around the center of the city. This confirms reality, because there tends to be more DCIA in more urbanized environments.

4. All values above a threshold DCIA index are considered Directly Connected Impervious Area.

Theoretically, only grid cells with a DCIA index of 1 should be considered DCIA, because any flow over pervious area, precludes grid cells from being considered DCIA. However, a less stringent classification was taken, to account for flow over insignificant quantities of pervious area and to account for errors in the DEM that might cause the flow path to take slight detours over pervious area. Additionally, a lower DCIA threshold can also be used to counteract the fact that the flow length tool does not stop calculating the flow path, when the flow path reaches a swale. Once the flow path reaches a swale, the flow length over the swale is counted as flow over pervious area.

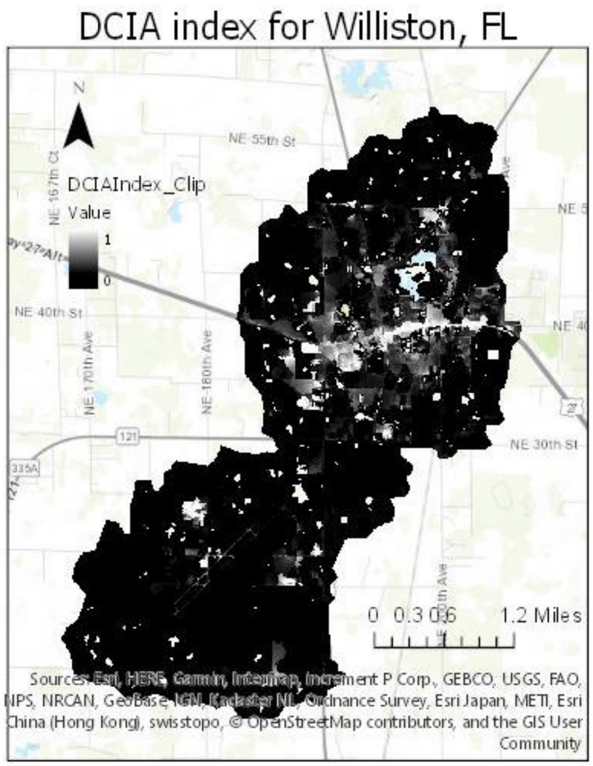


Figure 4: DCIA index for Williston, FL

3.2 Using manual scanning to determine DCIA

There are no specific steps to determining DCIA by manual scanning. It is up to the engineer's intuition and reasoning to determine what is DCIA. The engineer may use elevation contours or a raster of impervious area. Sometimes the engineer may only need to use aerial imagery.

3.3 Using the Land Cover method to determine the amount DCIA inside of polygons

1. Make DCIA estimates for samples of each type of land cover via manual scanning.
2. Create a lookup table that shows the relationship between landcover type and DCIA
3. Use the Reclass by table function to create a new raster, where the value of each grid cell is the DCIA percentage.
4. Use the raster calculator to multiply each grid cell by the grid cell size to create a raster of cell's whose value is the area of DCIA for that grid cell.
5. Use zonal statistics to sum the grid cells inside of each polygon.

The result is a raster of cells clustered into polygons. The value of a cell in a polygon is the DCIA for that entire polygon. In essence, I used representative sampling to estimate DCIA for each land cover type and extrapolated that to classify land cover for the entire study area.

3.3 Determining UCIA in each method:

$$UCIA = Impervious\ Area - DCIA$$

After calculating DCIA, calculating UCIA is more straightforward. UCIA is simply the impervious area that is not DCIA. Because this calculation is so simple after calculating DCIA, the focus of this study is to evaluate methods for determining DCIA.

3.4 Time estimates

The time estimate for performing the Manual Method on the study site was given by Jones Edmunds and Associates and is the time that it took their engineers to determine DCIA for the city of Williston, FL.

The time estimate for performing the Land Cover Method was determined from how long it took me to perform the analysis. I am not an experienced engineer, so in order to take out the role of experience from this analysis, I decided to only count the runtime that my computer was using geoprocessing tools and the time I spent manually sampling.

The time estimate for performing the Gregory Method was determined only by how long the geoprocessing tools were running for.

4. Results

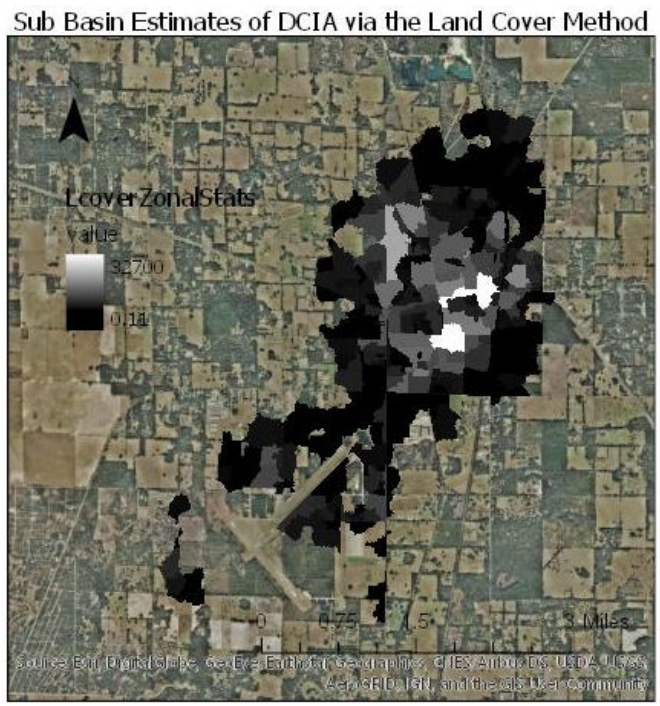


Figure 5: Sub-Basin Estimates of DCIA (number of grid cells) via the Land Cover Method. Some basins appear as if they are missing because their DCIA value was set to null. Those sub-basins were calculated to have zero DCIA.

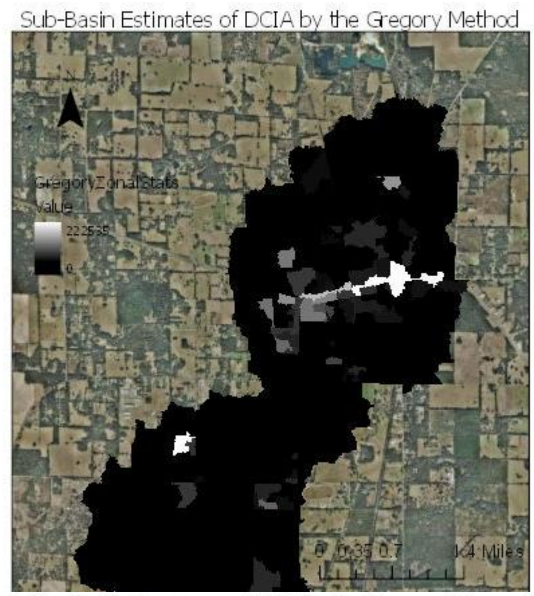


Figure 6: Sub-Basin Estimates of DCIA (number of grid cells) via the Gregory Method

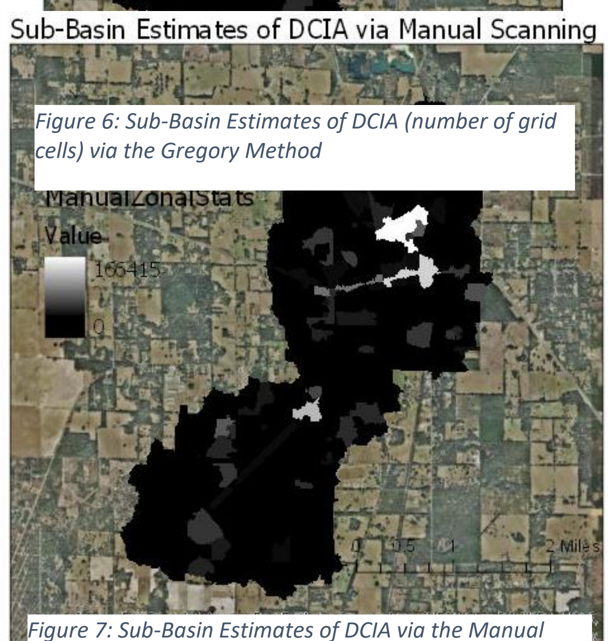


Figure 7: Sub-Basin Estimates of DCIA via the Manual Method

Figures 5, 6 and 7 show DCIA estimates (grid cell count) of the sub-basins within Williston. Brighter sub-basins correspond to sub-basins with more DCIA.

4.1 Accuracy and Variance Analysis

Originally, I intended to treat manual scanning as the gold standard for accuracy to which the rest of the DCIA estimation methods would be compared to. I assumed human intuition and reasoning would outperform any machine attempting to perform this task. However, after performing these analyses, I am not as confident in this assertion. So, I simply compared the three techniques to each other, acknowledging that DCIA is a difficult parameter to obtain exactly. Perhaps, the best that can be achieved is an estimation of DCIA. My goal was to figure out where the three estimations differed and to use that information to draw conclusions about the three estimation techniques.

DCIA estimation for the entire study site

Comparison of DCIA Estimations by Method	
Estimation Method	Impervious Area (ft^2)
Gregory Method (cutoff = 0.95)	2771306
Gregory Method (cutoff = 0.90)	3763988
Gregory Method (cutoff = 0.85)	4644062
Gregory Method (cutoff = 0.80)	5680088
Gregory Method (cutoff = 0.75)	9376512
Manual Method	9008680
Land Cover Estimate Method	7538286

Figure 8: Comparison of DCIA Estimations by Method

The DCIA estimations for the entire study site are shown above. All three DCIA estimation methods fall within the same order of magnitude, which gives credibility to the accuracy of all three methods. At low DCIA index cutoff values, the Gregory method severely under-predicts the DCIA in the watershed. One possible fix for this phenomenon is to stop the flow length calculation at the urban stormwater management system. An easy way to do this may be to make the value of the flow direction raster null where there are burned in features (typically features of the stormwater management system).

I then decided to compare the 3 DCIA techniques using a set of sub-basins. First, I sought to determine how widely the results of the three techniques varied. To quantify this, I calculated the standard deviation of the DCIA estimates for each sub-basin. I performed this using zonal statistics. A map of the standard deviation is shown below:

Variance of DCIA Amongst Analysis Methods

Figure 9: Variance of DCIA amongst Analysis Methods

By inspection, the areas of high variance tend to occur in a few places:

1. Around areas where there is lots of DCIA.

These high amounts of DCIA may cause tiny differences in the computational methods to become magnified.

2. In areas where the engineer performing the manual method used their knowledge of drainage to deviate from what the DEM might suggest the water would go.

Figure 10: Sub-basins of high variance in Williston RV park

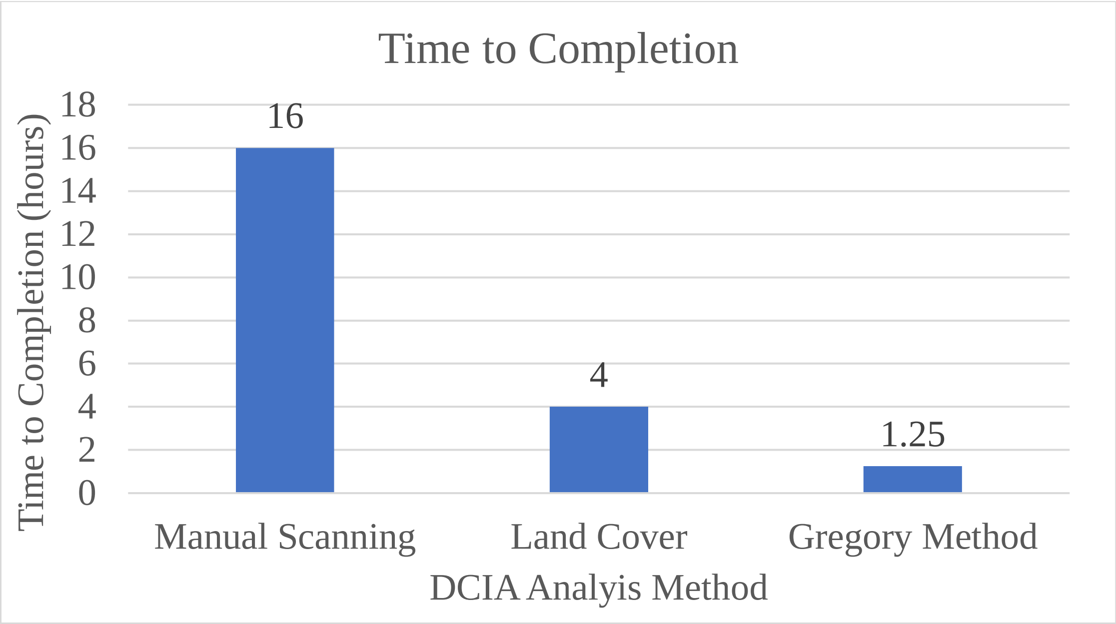
Figure 11: Sub-basin of high variance in a Boat Manufacturing Facility

For example, in southwest Williston, there is a boat manufacturing facility that takes up a substantial amount of area. Although nearly all of the site is impervious area, some of it drains to retention ponds and some of it is routed to the municipal stormwater system. Determining the proportion of impervious area that is DCIA via the manual method becomes somewhat up to the individual engineer. By chance, I manually determined DCIA for this polygon as a sample for the land cover method and my DCIA estimate was different from the one that was computed by the engineers at Jones Edmunds. This points to one weakness of manual scanning, which is that it is not as repeatable as more automated methods.

3. In areas where the engineer performing the manual method made a mistake.

For example, the variance of the DCIA result for the three methods is very high at Williston RV park. The land cover method and the Gregory method both predict close to 0 DCIA in this area. However, an engineer mistakenly classified this area as 100% DCIA, even though the property is mostly filled with water. I found one other instance of a water body being classified as DCIA in the manual method This illustrates the potential of the two automated methods to check the manual method.

4.2 Time to Completion Analysis



The time to completion for the Gregory Method and the Land Cover Method are both extremely low compared to manual scanning. A few factors contribute to this.

4.2.1 Computer Automation

The two methods with some level of automation (Land Cover and the Gregory Method) allow for faster DCIA determination. The idea is that determining DCIA is a repetitive task and computers are better suited for those than human engineers. I hypothesize that these differences become less pronounced as the size of the analysis becomes smaller. For example, if one were analyzing one parking lot, it may take only 15 minutes to print out a contour map and determine DCIA manually. However, it may take more time to gather GIS data, start the ArcGIS software and run the Gregory method. Inversely, if one were analyzing a watershed that was 100+ square miles, it may take more than a week for an entire team of engineers to estimate and check DCIA. Determining DCIA manually for an area this large can be a very unpleasant experience for an office, also. The repetitiveness of determining DCIA manually for an entire week may cause the engineers to fatigue and lose accuracy. Although this might seem like a human problem, it’s very important nonetheless because it affects the ability of real engineers to reasonably perform the manual method.

While completing the Gregory Method for the study site, I discovered that the process was bottlenecked by the flow length calculation. To reduce the time to completion, it may be practical to use a computer with high CPU and Memory. Another strategy is to reduce the number of grid cells by increasing the grid cell size.

4.2.2 Notes on speed and the Land Cover Method

While completing the land cover method for the site, I learned that the component of the method that takes the most time is performing the manual method on land cover samples (step 1). The rest of the process is almost instantaneous. Although this step of the land cover method took the longest, it makes sense to spend time on this step, because small changes in the lookup table can create very large changes in DCIA.

5. Conclusions

For determining DCIA on a small area (< 1 square mile), the Manual Method seems to be the most practical. The manual method allows the engineers to use their intuition to reason through complicated or ambiguous drainage schemes that the land cover method and the Gregory method cannot analyze. It also does not require GIS data and takes little to no time to start performing. However, for larger watersheds (>100 square miles), the manual method may take too long and may cause engineers to fatigue and lose accuracy.

The land cover method is a semi-automated method, and it contains some advantages and limitations of the manual method and the Gregory method. The land cover method works best on watersheds much larger than the size of a land cover polygon. It allows engineers to use their engineering judgement, when creating DCIA estimates of sample land cover polygons (step 1). Despite this, it’s extremely fast compared to the manual method. One drawback of the land cover method is that the method relies on the assumption that the DCIA percentage of a land cover type is somewhat consistent across all polygons of that land cover type. This assertion may not be true in some cases.

The Gregory Method seems to be best at analyzing large watersheds quickly and consistently. The method is nearly completely automated, costing little to no time for an engineer. Although it’s impossible in this study to determine the accuracy of the Gregory Method, given that all the techniques discussed were themselves estimations of DCIA, the Gregory Method gave DCIA estimates that fell near the estimations by the other two methods. The price for the speed and consistency of the Gregory Method is the GIS data required by the Gregory Method. The Gregory method needs a flow direction raster and a raster of imperviousness as inputs. The ability to acquire this data may put a practical limit on the Gregory Methods use in small watersheds.

Works Cited

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