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Topographic Wetness Index Urban Flooding Awareness Act Action Support

Will and DuPage Counties, Illinois

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By:
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ILLINOIS STATE WATER SURVEY
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1 INTRODUCTION

The Illinois State Water Survey (ISWS) is a Cooperating Technical Partner (CTP) with the Federal Emergency Management Agency (FEMA) as per the agreement dated September 9, 2013. Under this agreement, ISWS conducts projects work for FEMA. FEMA funded the development of a Topographic Wetness Index (TWI) for DuPage and Will Counties as part of their Community Engagement and Risk Communication (CERC) efforts. The project is described in Mapping Activity Statement ISWS 15-02, which was funded under grant EMW-2015-CA-00063-S01. The development of TWIs for counties across Illinois is an action item in the Urban Flood Awareness Act (UFAA) report, which was published June 30, 2015 (State of Illinois, 2015).

1.1 Project Objective

The TWI is a physically based index or indicator of the effect of local topography on runoff flow direction and accumulation. The index has applications in specialized rainfall runoff modeling and simulation of the spatial distribution of soil moisture and precision agriculture (Beven and Kirkby, 1979; Qin et al., 2011). The computation of TWI is performed using both geographic information systems (GIS) and Python, a programing software used to enhance computing capabilities. The indices help identify rainfall runoff patterns, areas of potential increased soil moisture, and ponding areas.

In promoting flood risk awareness and reducing flood losses, FEMA provided funding to the ISWS to further develop the TWI for Illinois as in the UFAA report (State of Illinois, 2015). The ISWS recommended Will and DuPage Counties for TWI development because both counties have high resolution LIDAR, countywide stormwater management agencies, and capacity to implement county level planning and provide countywide mitigation plans for urban flooding issues. Furthermore, these counties also present the opportunity to demonstrate how a TWI analysis can be utilized for both urbanized (DuPage) and urbanizing (Will) counties.

The TWI data provided by this project can inform activities undertaken by federal, state, and local agencies to help develop awareness of potential local flooding, assist with community's flood risk communication, and support local efforts to reduce flooding risk within a community or watershed area. TWI information can aid in the identification of areas best suited for green infrastructure projects such as pervious pavers, rain gardens, and open space, as well as assist future development projects through the identification of areas susceptible to flooding. The products from this study serve to demonstrate the utility of developing TWI for the rest of Illinois.

1.2 Study Area

Will and DuPage Counties are two of five counties that border Cook County located in the northeastern part of Illinois, as depicted in Figure 1. These five border counties of DuPage, Will, Kane, Lake, and McHenry are the five most populous Illinois counties outside of Cook County.

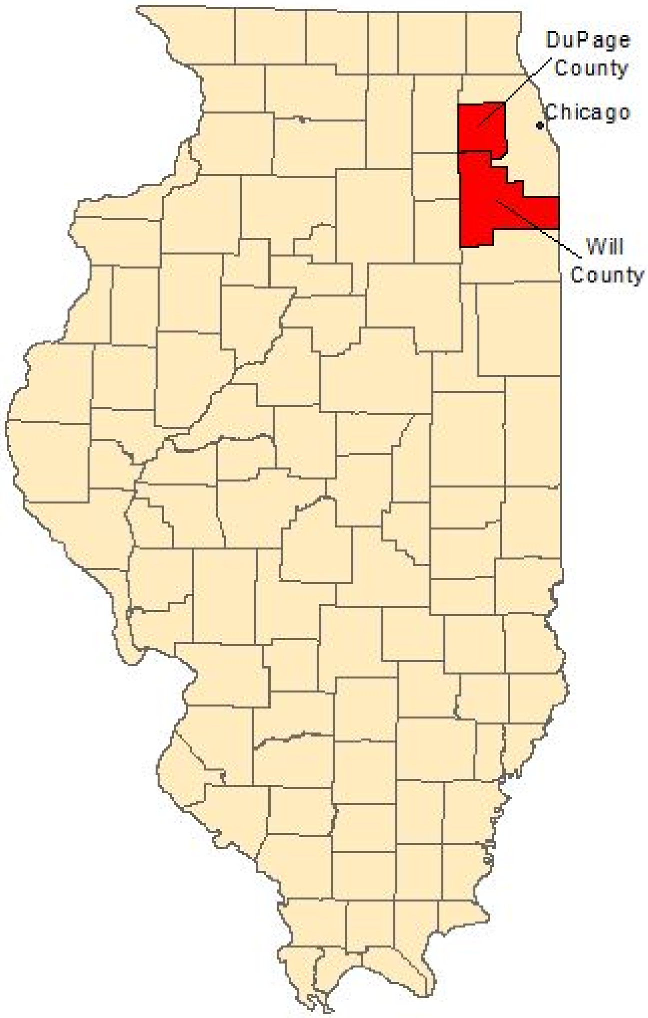

Figure 1: Location of DuPage and Will Counties

According to the 2010 census, DuPage County is the second most populous county in Illinois with a population of 916,924. This represents a 1.4 percent increase from the 2000 census population of 904,161. This 1.4 percent increase in population was accompanied by an increase in development of 6.8 square miles, which is 2 percent of the total county area.

Will County is the fourth most populous county in Illinois with a 2010 population of 677,560. This is a 34.9 percent increase from the 2000 Will County population of 502,255. Accompanying this dramatic increase in population, there was a 66.5 square mile (8 percent of total county area) increase in developed land between 2001 and 2011.

2 LITERATURE REVIEW

A topographic wetness index is based on the idea that a terrain profile controls the distribution of water and areas subject to water accumulation. This index was first developed by Beven and Kirkby (1979) within their physically based runoff model, TOPMODEL, which is based on the assumption that the hydraulic slope can be approximated by the topographic slope. The TOPMODEL simulates groundwater and surface-water interactions with topography to identify which areas are susceptible to saturated land surfaces and thus have a high potential to produce surface ponding. Surface ponding is defined as standing water in depressional areas where the surface soils have become saturated or flooded concrete depressions when rainwater cannot infiltrate the surface.

TWI is calculated by evaluating the flow direction, flow accumulation, slope, and various geometric functions derived using GIS software. The end result is a GIS data layer (raster) that depicts areas with drainage depressions where water is likely to accumulate. The raster values are relative within the specific study area. TWI values cannot be compared between study areas or alternate data sets. The formula used for calculating TWI at a point is: $I=\ln(a/\tan\beta)$, where I is the index value, *a* is the upslope contributing area and β is the topographic gradient. Both *a* and β are calculated utilizing a digital elevation model (DEM) of the study area. Smaller values of the TWI indicate less potential for development of ponding; larger values occur where greater upslope areas are drained and the local slope is gentle (Wolock, 1995)

There are different methods and algorithms available to compute *a* and β, which yield different values and impact the value of TWI. The difference in these algorithms comes in the calculation of the flow direction and whether the algorithm computes a single flow direction (sfd) or multiple flow directions (mfd). Single flow direction algorithms assume water flows in a single direction through a cell in the direction of greatest slope β. The multiple flow direction algorithms allow flow in all downslope directions from any cell, and the local slope is a weighted average for each cell. (Wolock, 1995).

The Arc-Hydro tool set (Maidment, 2002; ESRI, 2012) uses the sfd algorithm also known as D8 which refers to the eight possible directions that flow may take from a single cell. The eight directions are coded as 1, 2, 4, 8, 16, 32, 64, and 128 as illustrated in Figure 2 (ESRI, 2016).

The formula used is: maximum drop = change in z-value / distance * 100; where maximum drop is the direction of steepest descent and the z-value is the change in elevation between two orthogonal cells.

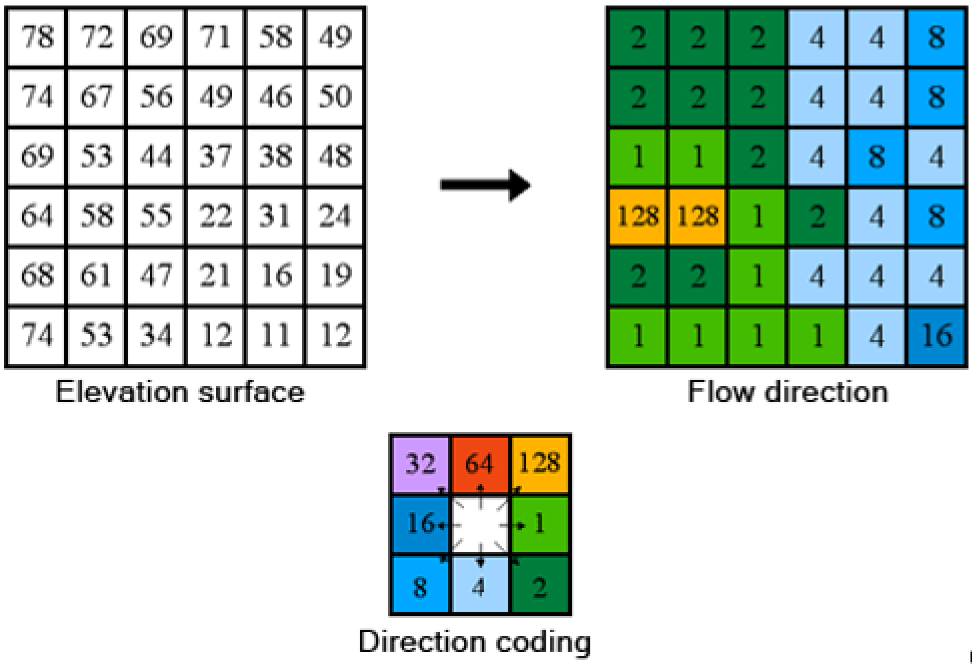

Figure 2: Flow Direction and Accumulation (ESRI, 2016)

Some research (Qin, 2011; Tarboton, 1997; Quinn, 1991) promotes the use of a multiple flow direction algorithm depending on the available data and the scale effect results. However, Quinn (1991) notes that the single flow direction algorithm is more suitable once the flow has entered the more permanent drainage system. Algorithms have been developed for the mfd computation but are not part of the tested ArcGIS and Arc Hydro suite of tools. The sfd method used in the Arc Hydro tool set was used for this study as it provides a tested, repeatable and readily accessible means of determining the cell flow direction. The Arc Hydro tool set was used for flow direction and flow accumulation calculations.

3 PROCESS AND METHODOLOGY

3.1 Calculation Overview

The TWI formula used in this study is $I=\ln(a/\tan\beta)$, where a is the upslope contributing area and β is the topographic gradient, and is calculated utilizing a DEM of the study areas. The methodology for the sfd approach and TWI computation presented by David M. Wolock (Wolock, 1995) was developed into a python algorithm and used for the computation of the TWI for the UFAA report and utilized for the current study area.

3.1.1 Terrain Sources

The topographic data for TWI computation in the study area is a DEM derived from Light Detection and Ranging (LiDAR) data. DEM data is a digital representation of topographic information presented in a raster format. A raster is a matrix of cells organized into a grid where each cell contains a value representing the ground elevation.

The level of detail and accuracy of the TWI results is dependent on the spatial resolution and cell size of the DEM. Low resolution DEMs will have a large cell size creating a less detailed and more approximate TWI analyses. With high resolution DEMs there will be a smaller cell size creating a more detailed TWI.

The DEMs used in this analysis included a 3.5ft by 3.5ft cell size (DuPage County) and 4ft by 4ft cell size (Will County) DEM. Will County's –LiDAR was collected in 2014 and processed into a DEM with a 2ft by 2ft cell size DEM. For this analysis, Will County's DEM had to be resampled from its original cell size to a 4ft by 4ft cell size DEM. This was due to the increased computational capabilities that would have been required to process the 2ft by 2ft grid size of the original DEM produced from the 2014 LiDAR.

Federal Geographic Data Committee (FGDC) has established National Standards for Spatial Data Accuracy (NSSDA). The standards require that digital elevation products fall within a vertical accuracy of Quality Level 0 – Quality Level 3 (QL0-QL3). Vertical accuracy is determined by calculating the root-mean-square error (RMSE) to estimate positional accuracy. RMSE is the square root of the average of the difference between dataset coordinate values and survey grade coordinate values for identical areas. The NSSDA accuracy standards require that coordinate values fall within a 95 percent confidence level for vegetated and non-vegetated areas (FGDC, 1998). The Quality Levels with their associated RMSE and 95 percent confidence levels can be identified within Table 1 below. The DuPage County DEM was derived from QL3 LiDAR captured in 2006. Will County's DEM was derived from QL2 LiDAR collected in 2014. All DEMs have been hydrologically corrected to meet the FEMA Geospatial Accuracy (FEMA, 2016) for QL3.

Table 1: Absolute Vertical Accuracy for Digital Elevation Models, Quality Level 0 – Quality 3 (Heidemann, 2012)

Quality Level(QL)	$RMSE_z$ (non-vegetated) (cm)	NVA at 95-percent confidence level (cm)	VVA at 95th Percentile(cm)
QL0	≤5.0	≤9.8	≤14.7
QL1	≤10.0	≤19.6	≤29.4
QL2	≤10.0	≤19.6	≤29.4
QL3	≤20.0	≤39.2	≤58.8

3.1.2 Upslope Contributing Area

One key factor in developing a TWI is understanding how water interacts with the topography of the study area. This can be captured by calculating the upslope contributing area, *a*, which represents areas that have the potential to contribute runoff to a location of interest. The upslope contributing areas are computed utilizing Python programming software developed by the author to assemble multiple GIS tools found within ArcGIS's hydro toolset (ESRI, 2011).

The ArcGIS hydro tools involved in this automated process include *fill*, *flow direction*, and *flow accumulation*. The fill tool is used to identify and remove both sinks and peaks within a DEM. Sinks and peaks are errors that may be found within a DEM due to the resolution of the data or the rounding of elevations to the nearest integer. These errors can be generated during either the acquisition or processing of LiDAR. Once the surface raster is corrected with the fill tool, the flow direction surface model can then be developed.

The flow direction tool examines the elevational characteristics of the surface to determine the direction of flow from every cell within a DEM. The tool calculates this by analyzing each cell and its eight neighboring cells to determine the direction of steepest descent. The output of this tool results in a raster with cells having one of eight values assigned indicating flow direction as illustrated in Figure 2. When the direction with the

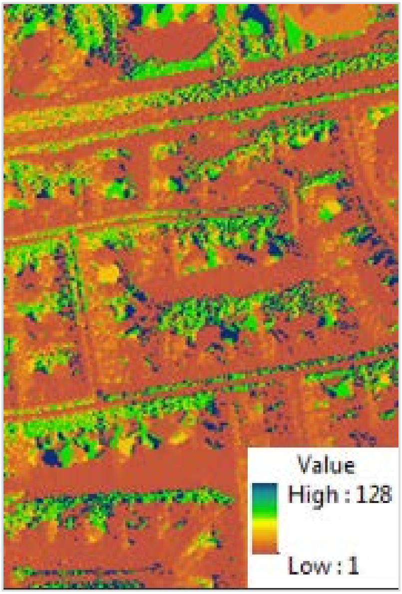

Figure 3: Flow Direction Raster

steepest descent is determined, the cell is populated with a value defining the direction water would flow from cell to cell. A typical output flow direction raster can be seen in Figure 3 where areas of the same color have the same flow direction. With the flow direction created, the upslope contributing area, also known as the flow accumulation area, can be calculated.

The upslope contributing area was calculated within Arc GIS utilizing the flow accumulation tool. The flow accumulation tool uses the flow direction raster to calculate the accumulated weight of all the cells contributing to each downslope cell (ESRI, 2011). The output raster cells with low flow accumulation values tend to be areas with a high local slope, whereas areas with high flow accumulation values are areas with low slope and increased susceptibility to flow accumulation and concentration. The flow accumulation tool is commonly used in the identification of flow routes. The flow accumulation values are the area *a* used in the TWI formula.

3.1.3 Slope

Slope plays an important role in hydrologic processes determining the movement of water on the Earth's surface. For example, flow across areas with a high degree of slope (steeper terrain) tends to concentrate water flow, forming channels moving through the landscape, whereas in areas with low slope (flatter terrain) there is a substantial decrease in the movement of water and an increase in the likelihood of ponding.

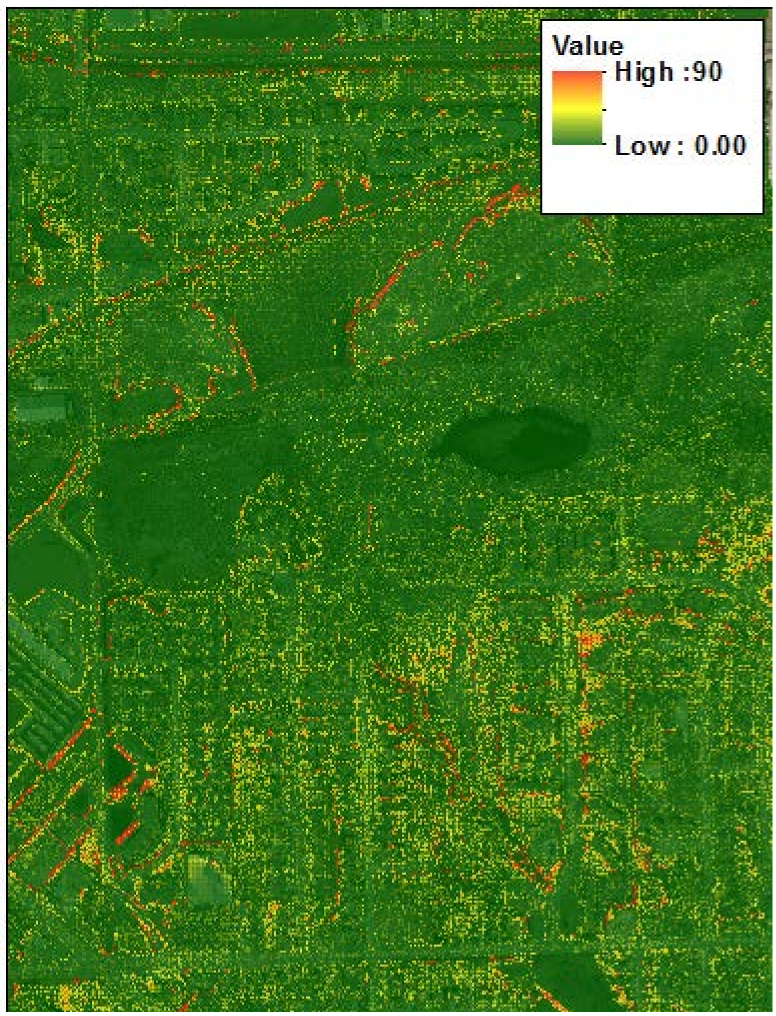

Figure 4: Slope Raster

Slope (tanβ) in the TWI formula is calculated by performing analyses on a DEM to determine the local slope for each cell.

Figure 4 displays an example of local slope created in the development of a TWI. Local slope is calculated for each cell within the DEM by determining the maximum downslope gradient between each cell and its eight neighboring cells. Within this figure the areas shaded in red color indicate areas with steeper slopes with the green cells showing flatter areas.

3.2 Data Analysis

Once the upslope contributing area raster (*a*) and the slope raster (tan β) are generated, these layers are combined on a cell-by-cell basis using the TWI equation. The end result is a TWI raster in which each cell is assigned a wetness indicator value [I=ln (a/tanβ)]. These indicator values are non-dimensional and vary based on the topographic profile of the region and the resolution of the DEM. Typically the raw TWI indicators range from -3 to 30.

Cells with a lower index value represent areas with steepest slope and tend to be ridges or crests present on the landscape. Higher cell values represent areas with increased accumulated runoff potential. These areas are identified by a low slope and large upslope contributing areas.

Based on the TWI raster indicator values, the threshold value for a TWI indicator to be classified as having the high potential of dispersed flow and flow accumulation are determined manually by the user. This is necessary because every independent TWI analysis may contain a different range of indicator values based on the varying topographic profiles of the county or watershed. For example, the TWI values in DuPage County range from -7 through 29.5 with the threshold of values identifying areas of significant wetness between 9 and 29.5.Whereas the Will County TWI range from -5 through 28 with the threshold of values identifying areas of significant wetness between 9 and 27.5.

The best method of classification is performed by reviewing the values and their relationship to the local topography. This is achieved within GIS by reviewing the histogram of TWI value ranges and symbolizing these ranges with an algorithmic color ramp. With the symbolization, the interpreter can calibrate the TWI raster to identify or verify flow accumulation hotspots using surface ponding observations. This is in essence a calibration of the index.

3.2.1 Post-Processing Data Filtering

With the utilization of high resolution LiDAR and DEMs for the calculation of TWI, there tends to be some amount of inherent noise. Noise is the result of irregular fluctuation of wetness indicator values found within the final TWI raster. For example, there may be single raster cells that are identified as "wet" while the area surrounding that cell is "dry. " An example of data noise can be seen in Figure 5 where there are many isolated cells with indicator values different from surrounding cells. These noise values can be removed through a GIS smoothing process called low-pass filtering, which is a tool available in ArcGIS.

Low-pass filtering is a GIS function that assists in smoothing out the anomalous indicator values by reducing local variations and removing noise (Buchanan 2014). This is achieved by calculating the mean value for each cell by its 8 neighboring cells. The end result is raster with averages of the high and low values of each cell neighborhood, thereby reducing the anomalous values (ESRI, 2011). For example, Figure 6 displays the results of the Low Pass Filter run on the TWI results raster. The final TWI raster displays fewer anomalous values making the final product easier to interpret.

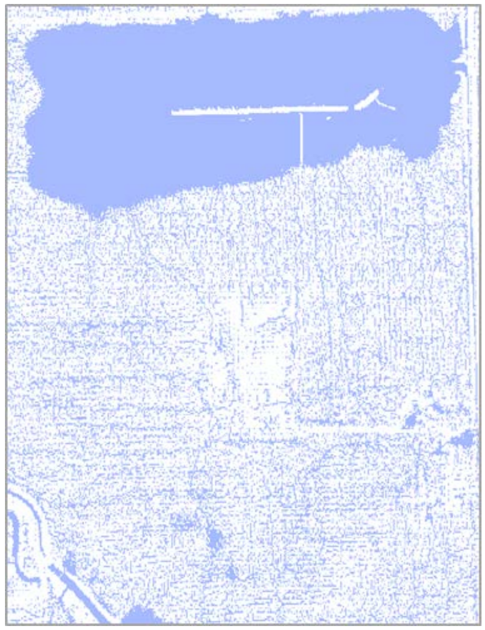

Figure 5: Unfiltered TWI Analysis

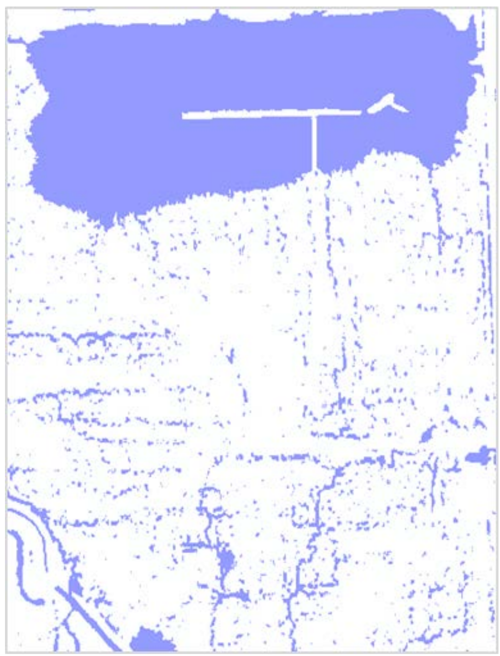

Figure 6: Low-Pass Filter TWI Results

4 APPLICATIONS

4.1 Urban Flooding in Illinois

Within the last decade, non-riverine urban flooding within Illinois has received increased attention due to the frequent inundation of city infrastructure and damage to public and private buildings. Between the periods of 2007 and 2014, there have been at least $2.319 billion in documented damages, of which $1,240 billion were private insurance claims that typically represent basement flooding and sewer backup. In addition, 175,775 out of 184,716 (95.16 percent) of private insurance claims and 12,950 out of 14,693 (88.13 percent) of National Flood Insurance Program (NFIP) claims were located in urban areas. Eighty-five percent of all the payouts were located in the six-county Chicago Metropolitan Areas of Cook, DuPage, Kane, Lake, McHenry, and Will Counties (State of Illinois, 2015).

4.1.1 Green Infrastructure

Green infrastructure is an approach to stormwater management used to reduce rainfall runoff through natural hydrologic functions such as evaporation, transpiration, and soil infiltration. It is beneficial to the environment and often less expensive than structural stormwater management designs.

Green infrastructure is most successful at addressing urban flooding caused by more frequent, lower volume rainfall events and should be part of a comprehensive plan to reduce the volume entering over-taxed drainage systems (Schueler, 2007). The successful use of green infrastructure relies on several site-specific parameters including drainage area, groundwater table levels, soil type, ground slope, expected performance, and the maintenance of the project. Challenges are currently presented in the identification of potential green infrastructure sites that match the specific parameters. TWI data can be applied to the green infrastructure selection process to aid in identifying areas where green infrastructure is likely to be the most beneficial.

The TWI identifies areas which are particularly susceptible to urban flooding or surface ponding caused by rainfall runoff. For example, a city planner can use the tool to pinpoint areas where ponding is likely and target them for green infrastructure projects. Green projects such as bioswales, permeable pavement, and rain gardens are examples of infrastructure that can be installed in low-lying areas identified with the TWI tool.

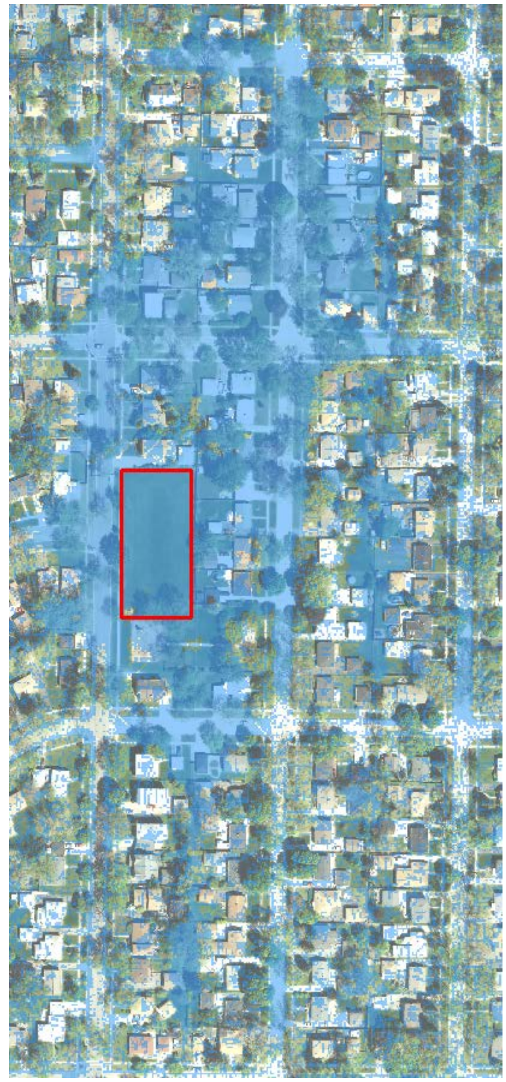
Figure 7: TWI-Defined Area of Wetness within DuPage County

Figure 7 is a map of the TWI for a section of DuPage County. Areas shaded in blue have increased susceptibility to accumulation of runoff and subsequent ponding and flooding. Consulting this map showing areas of increased risk for urban flooding, a city planner or engineer can recognize the need in this area for enhancing rainfall infiltration and/or other stormwater management techniques to help prevent urban flooding. Overlaying the TWI with othrophotography and other GIS data, the vacant land, outlined in red in Figure 7, is readily identifiable and might serve as an optimum location to direct and manage excess runoff to reduce neighborhood flooding and allow for groundwater recharge.

4.1.2 Storm Sewer Infrastructure

Urban flood insurance claims are more common in older communities where storm sewers are frequently under-sized and over-taxed due to increased runoff (State of Illinois, 2015).The oldest parts of communities also tend to have combined sewer networks transport both sanitary and storm flows to water treatment facilities. During large, intense storms events, the combined sewer system can be surcharged, resulting in the discharge of combined stormwater and sanitary water into streams and streets and/or back-up into basements and crawlspaces. Storm sewer capacity exceedance also occurs in dedicated storm sewers when the rainfall event exceeds the storm sewer design.

When rainfall exceeds the design capacity of a storm sewer, the result can be overflow, street flooding, and basement flooding from sewer backups. With access to TWI data, municipalities have a tool to identify neighborhoods susceptible to sewer overflow or basement backups. This can be achieved by recognizing areas identified by the TWI indicator values that have increased likelihood of ponding water when storm sewer capacities are exceeded. Through identification of the ponding areas, planners and engineers could pinpoint zones to consider for sewer upgrade projects or other mitigation actions.

For example, an urban flooding event occurred in the City of Blue Island, Cook County, Illinois on July 12, 2014. Historical weather records from the Midwestern Region Climate Center (MRCC) for this event depict 3.92 inches of rainfall within a four hour time frame (MRCC, 2016). The street flooding from this event can be seen in Figure 8. Due to the high amounts of rainfall over a short period of time and the inability of the storm sewer to accommodate the large amounts of rainfall, many streets, backyards, and basements were inundated. The same neighborhood was evaluated with the TWI tool. The location shown in the photograph is marked with a red dot within Figure 9 on the TWI map (9). The TWI was able to correctly identify the potential for flooding in this urban setting. Communities could identify vulnerable neighborhoods and educate homeowners on programs about disconnecting downspouts from storm sewers to slow flow to the storm sewers; the risk of sewer backups and options for backflow valves and installing a sump-pump system; insurance, and the benefit of elevating property in the basement.

Figure 8: Street Flooding within a TWI-Defined Wet Area. This event occurred on July 12, 2014 in the City of Blue Island in Cook County. The area of flooding is identified with the red dot within Figure 9.

Figure 9: TWI-Defined Flooding Area in the City of Blue Island. The area identified with the red mark is the flooded area identified in Figure 8.

4.1.3 Landscape Development

The increasing population in Illinois over the past two decades has contributed to increasing urban and urbanizing areas. Urban development can also contribute to the loss of wetlands, removal of vegetation and soil, land surface grading, and artificial drainage network construction. It has long been recognized that urban development tends to exacerbate flooding due to the increase in impermeable surfaces and the loss of natural areas to absorb runoff.

The increase in urban development within DuPage and Will Counties can be seen in Figure 10, which depicts the changes in land cover from 2001 to 2011 within counties. The areas in grey have remained developed since 2001, while the areas depicted in red have had an increase in urban development. Utilizing the National Land Cover Dataset (NLCD) and GIS, it was determined that between 2001-2011 DuPage County had an increase in developed area by 6.8 square miles and Will County had 66.5 square miles of development.

The utilization of the TWI in the early planning stages of development can aid in mitigating the risks of urban flooding. Figure 11 shows an area of Will County where there is a subdivision the east side (right side of figure) of the north-south road but as yet is not developed on the west (left side of the figure). Overlaid on the othrophotos is the TWI raster. In this figure, the TWI is indicating where the area has a susceptibility to ponding. Development of the west side may be subject to ponding and flooding. The development of the west area could also intensify the susceptibility of urban flooding within the neighboring residential area to the east. The utilization of the TWI provides planners with the capability of identifying potential risks and the ability to plan for urban flood management practices in the early stages of development.

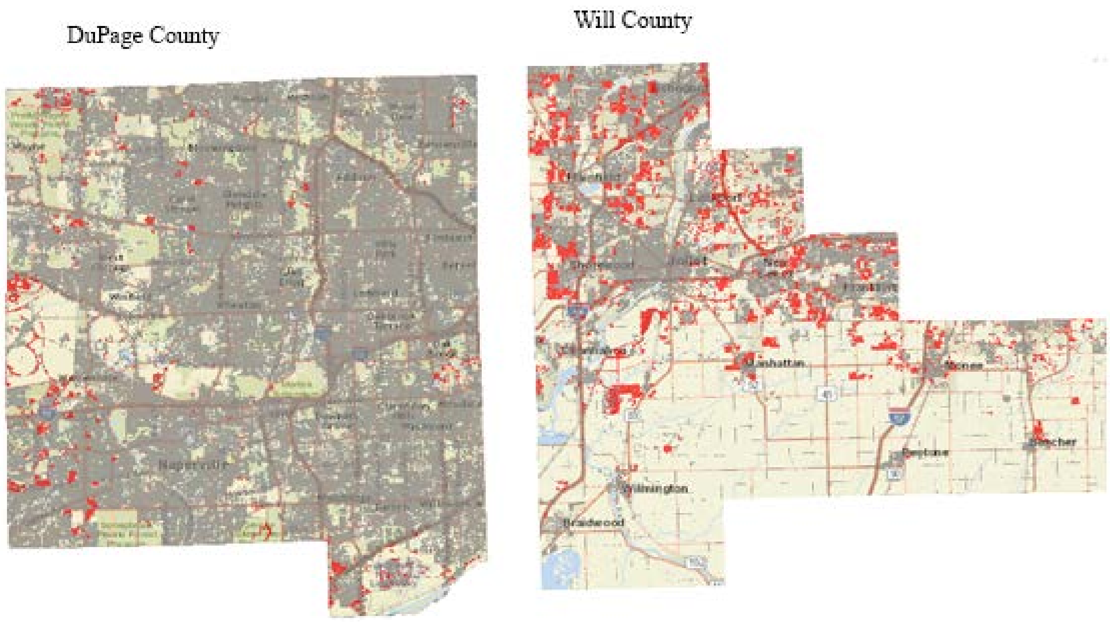

Figure 10: DuPage and Will Counties Urban Development from 2001 to 2011.
The red areas indicate an increase in development. The grey areas have remained developed since 2001.

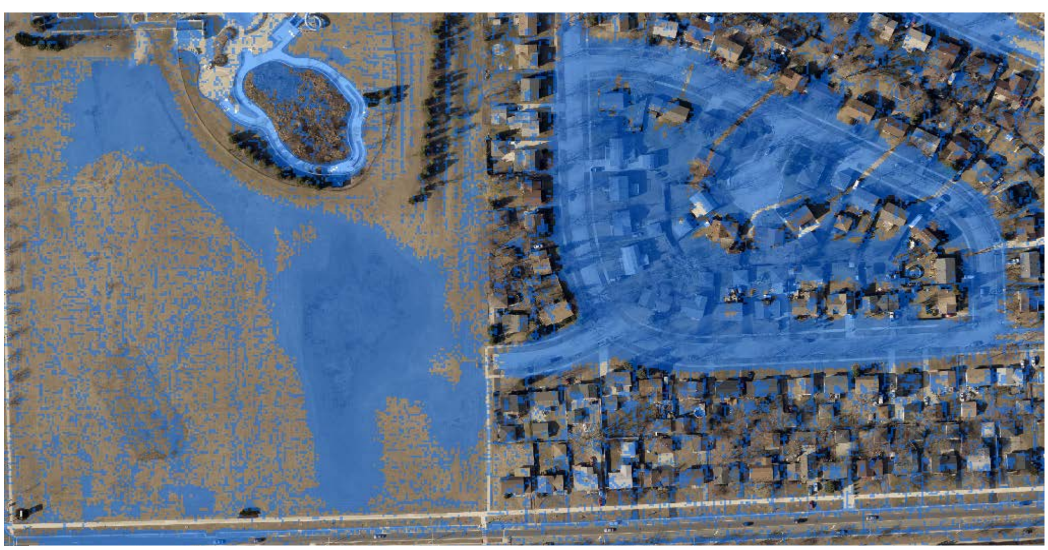

Figure 11: TWI for Land Development

5 RESULTS AND CONCLUSION

Maps of the TWI for DuPage County, the City of West Chicago, Will County, and the City of Joliet are provided in Appendices A-D respectively.

Presently a vast majority of metropolitan and rural municipalities within the U.S. have high resolution LiDAR and DEMs. Given the abundant access to these high resolution topographic data, generation of a TWI is possible over a considerable geographic area. The TWI provides important information at very low cost compared to detailed hydrologic and hydraulic studies and is an excellent planning tool. The TWI is a unique tool which allows the user to identify areas that could be adversely affected by ponding and flooding caused by rainfall events. The TWI added to the compliment of data and GIS tools can provide planners a visual mechanism for site selection of green infrastructure projects, the identification of areas with an increased susceptibility to ponding due to sewer overflow or basement back-ups, and in the planning of new residential and urban areas.

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