Areas in Wayzata, Minnesota USA at Risk for Environmental Impact from Runoff and Flood Events

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Abstract

Floods are among the most common natural disasters in the world with increasing occurrences due to increases in precipitation and urbanization. Several factors cause floods making floods, especially flash floods difficult to predict. Digital Elevation Models (DEMs) were used to determine areas of depression throughout Wayzata, Minnesota USA. Areas with the largest depressions were found in locations where lakes and wetlands were mapped in the U.S. National Wetland Inventory (NWI) lakes and rivers layer. Color and infrared aerial photography, LiDAR, soil data, NWI, lakes and rivers data were used to identify areas at risk. Comparisons between 2008 and 2015 color and infrared aerial photographs were used to determine changes in vegetation. ArcGIS Hydrology tools were used in conjunction with elevation and soil data to determine areas at risk of erosion. Areas at risk of soil erosion were found near areas with little or no vegetation, impermeable surfaces, and on the boundaries of wetlands. Urban flood management programs need to include areas of depressions, vegetation, and impermeable surfaces when developing a plan.

Introduction

Floods and droughts are the most common and deadly forms of natural disasters in the world (World Health Organization, 2009; Lamond, Proverbs, and Hammond, 2010). In July 2012, Beijing had a flood that caused 79 deaths and collapsed 10,660 homes (Zhang and Pan, 2014).

Greater precipitation variability today is causing an increase in occurrence and intensity of floods and droughts (World Health Organization, 2009). Small changes in the average precipitation can have large effects on areas (The Economist, 2012). Economic costs for flooding disasters are rising, causing nations to develop preventative planning for large events (The Economist). 20,000 communities in the United States are at risk for major flooding and flood management is a top priority in planning development (Johnson, 2009). In areas with dense populations investing in reducing flood effects is more important than ever (Deckers, Kellens, Reyns, Vanneuville, and Maeyer, 2010). Furthermore, disease and freshwater contamination can spread during flood events causing health problems communities (World Health Organization, 2009).

Short-lived events that have extreme amounts of rainfall within a few hours in localized areas are called flash floods due to their rapid runoff (Hirschboeck, Ely, and Maddox, 2000). Major damage and loss of human life

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occur during flash floods and their small spatial scales and short durations make them hard to predict (Hirschboeck *et al.*, 2000).

Runoff refers to the precipitation that flows across the surface of the land and into streams, rivers, and lakes (Bethea, 2011). Runoff is determined by rainfall and surface characteristics (Vojinović and Abbott, 2012). Rainfall characteristics are intensity, type, pattern and duration, while surface characteristics are permeability; slope and amount of moisture already present (Vojinović and Abbott).

Erosion, sedimentation, and landslides are the natural result of floods (Vojinović and Abbott, 2012). Water erosions and compaction are major-processes worldwide leading to soil degradation (De Paz, Sanchez, and Visconti, 2006).

Soil is a complex plant-supporting system made up of organic matter, microorganisms, water, gases, nutrients and disintegrated rock (Withgott and Brennan, 2008). Soil is a renewable resource because it has the ability to renew itself over long periods of time (De Paz *et al.*, 2006; Withgott and Brennan, 2008). Soil health is vital for agriculture and forestry industries. The Global Soil Degradation Database defines soil degradation as a "human induced phenomena which lowers the current and/or future capacity of soil to support human life" (Gerrard, 2002). Soil degradation can harm ecosystems and pollute water sources (De Paz *et al.*, 2006). Degraded soils require huge investments of effort to maintain profitable yields of crops (De Paz *et al.*). Three main factors cause soil degradation: chemical, physical, and biological (De Paz *et al.*). These factors are caused by inappropriate use and bad management practices of soils (De Paz *et al.*).

The finer the soil particles, the smaller the pore spaces between them and the less preamble with the soil (Withgott and Brennan, 2008). Clay particles are less than 0.002 mm in diameter while sand particles are particles 0.05-2 mm (Withgott and Brennan, 2008). Silt particles lies between clay and sand (Withgott and Brennan, 2008).

The angle of repose is the maximum angle at which a slope of loose material will stay without falling (Press and Siever, 2001). Areas with slopes that are greater than the angle of repose are classified as unstable (Press and Siever, 2001). A general classification for the angle of repose derived from New York State Department of Transportation excavation safety bulletin and Burch Estimating Excavation book is listed in Table 1 (New York State Department of Transportation, 1996; Burch, 1997).

Table 1. Average Angle of Repose for Sand, Loam and Clay soil types (New York State Department of Transportation, 1996; Burch, 1997).

Angle of Repose	
Type	**Angle**
Musk	20 degrees
Sand or sand plus other	35 degrees
Loam or Loam plus other	45 degrees
Clay	53 degrees

The most common method to measure land cover is the Normalized Difference Vegetation Index (NDVI) (Weier and Herring, 2000). NDVI can be used to identify long-term changes in vegetation over an area (Fu and Burgher, 2015). An ecological response to flooding is an increase in primary vegetation in wetlands (Sims and Colloff, 2012). Sims and Colloff found a flood that occurred in 2008 increased the NDVI vegetation by 19% above non-flood levels (Sims and Colloff).

Urbanization transforms the landscape from natural to urban causing instability which leads a higher frequencies and severity of flood events (Vojinović and Abbott, 2012). Development in urban areas increases impermeable surfaces which in turn increases the chance of flash floods as water drains from urban surfaces at a faster rate than from natural surfaces (Bethea, 2011). Urban area surfaces create flow paths to natural catchment basins and thereby reducing filtration (Vojinović and Abbott, 2012; Zhang and Pan, 2014).

Methods

Project Area

The City of Wayzata, Minnesota USA is located 11 miles west of Minneapolis, Minnesota USA in Hennepin County (City of Wayzata, 2016; Hennepin County, 2016). Wayzata is 8.125 km^2or 3.137 $mile^2$ in size (Hennepin County Resident and Real Estate Services Survey Division, 2015). The 2010 population was 3,688 and the 2015 population estimates was 4,610 (United States Census Bureau, 2010).

Data

The City of Wayzata boundary was obtained from the Hennepin County Resident and Real Estate Services Survey Division (Hennepin County Resident and Real Estate Services Survey Division, 2015).

Aerial images from 2008 were obtained from United States Geological Society (USGS) with and a 1-foot resolution. The 2008 aerial photographs were taken on July 30 and August 17. Imagery from 2008 contains as much as 10% cloud cover. 2015 was obtained from the National Agriculture Agency Program (NAIP) again with a 1m resolution and included RGB and near infrared imagery collected on September 27.

Light Detection and Ranging (LiDAR) data were obtained from the Minnesota Department of Natural Resources and was used for elevation analysis (Minnesota Department of Natural Resources, 2015). The LiDAR dataset contained 2ft, 10ft and 50ft contours for the area (Minnesota Department of Natural Resources, 2015). The 2ft contours were used in create the DEM for Wayzata. The LiDAR fight date for the area was November 16, 2011 (Minnesota Department of Natural Resources, 2015).

Soils data were obtained from the United States Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS) Soil Survey Geographic (SSURGO) database for Hennepin County was used to find areas at risk of erosion (United States Department of Agriculture, Natural Resources Conservation Service, 2014). Soils data were field verified and developed by the National Cooperative Soil Survey.

The National Wetlands Inventory (NWI) data came from the U.S. Fish and Wildlife Service website developed by Ducks Unlimited, Inc. and Minnesota Department of Natural Resources (Ducks Unlimited, Inc., n.d., Minnesota Department of Natural Resources, 2013). The NWI data was based on aerial imagery from 2010 and 2011.

Lakes and rivers were obtained from the Twin Cities Metropolitan Council (Metropolitan Council, 2013). The Lakes and Rivers dataset was derived from 2005 Generalized Land Use data (Metropolitan Council, 2013). Lakes larger than 3 acres, rivers wider than 200ft and small open water features in the Metropolitan Council monitoring programs are included in the dataset (Metropolitan Council, 2013).

Process and Analysis

A size of 1 x 1m to 5 x 5m resolution is recommended for urban analysis (Mark, Weesakul, Apirumanekul, Aroonnet, and Djordjevic, 2004). The 1m resolution can produce a more detailed analysis but does not always provide a significantly more accurate result (Mark *et al.,* 2004). The 5m DEM can be used to generate a faster analysis of an area in a model by reducing the amount of data processed (Mark *et al.*, 2004). A DEM was created from 2ft LiDAR contours with an IDW interpolation. Sinks were filled with the Spatial Analyst fill tool (Zhang and Pan, 2014).

Depression areas for Wayzata were determined by subtracting the original DEM from the filled DEM (Zhang and Pan, 2014). Calculated depression areas were converted to square meters by multiply by 0.3048. Each raster cell was rounded to the nearest meter. The finished depression raster was converted to polygon layer where fields for depression depth and total area of depression were added. The total storage capacity of depressions was calculated by multiplying the area (m^2) by the depth of depression (m).

The flow direction tool in the Hydrology toolbox was used to determine flow direction (Zhang and Pan, 2014). Using the filled DEM raster as the surface raster created the flow direction raster. Flow directions numbers were than labeled as cardinal direction using ArcGIS Resource Center information (Figure 1) ESRI, 2012). Flow direction that overlaid areas with depressions of 1m to 7m were extracted for further analysis.

With the flow direction raster as the input parameter for the basin tool under the hydrology toolbox, watersheds were identified throughout the city. Areas with high slopes for Wayzata were determined by identifying areas with 20% or greater slopes. Areas with high slopes were combined with USDA soil data to determine areas at risk of erosion.

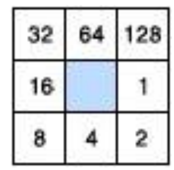

Figure 1. Image taken from ArcGIS Resources Center shows the different flow directions values (ESRI, 2012). Each cardinal direction has an exact value (North is 64, Northeast is 128, East is 1, Southeast is 2, South is 4, Southwest is 8, West is 16 and Northwest is 32).

Soil classification used the main soil textures of muck, clay, sand and loam to classify the soil. These categories were chosen for their soil porosity characteristic. Udorthents and urban land soil types were classified based on their parent material obtained from Soil Survey of Hennepin County, Minnesota (Kim Steffen and Natural Resources Conservation Service, 2003). Udorthents, wet substratum 20% and urban land 80% were labeled under muck due to their fill material, urban land 70% labeled Sandy and udorthents, loamy 100% and urban land 75% were labeled loamy parent material. During the processes, any areas classified as water were omitted from the areas at risk of erosion.

Vegetation and non-vegetation was calculated as follows:

NDVI = Normalized Difference Vegetation Index
NIR = near-infrared radiation
VIS= visible wavelength

$$NDVI = \frac{(NIR - VIS)}{(NIR + VIS)}$$

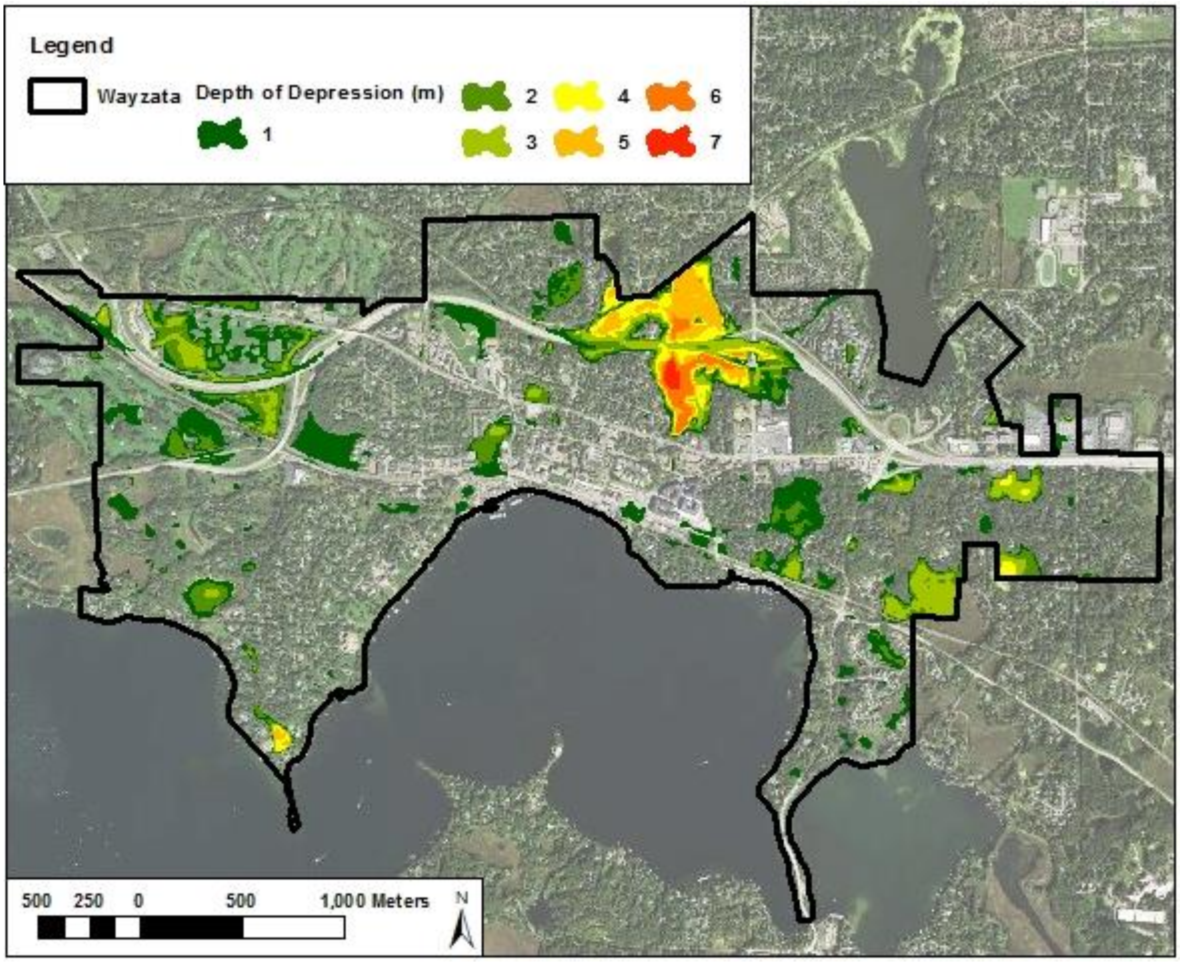

Figure 2. Depth of depressions for Wayzata, Minnesota USA are shown in green, yellow, orange and red. The dark green is the smallest volume with 1m, light green 2m, yellow green 3m, yellow 4m, yellow orange 5m, orange 6m and red 7m. A 2015 aerial photograph was set as the background.

NDVI uses a Vegetation Index algorithm from wavelengths of visible and near-infrared radiation minus visible radiation plus visible radiation (Weier and Herring, 2000). Vegetation close to zero means no vegetation and close to +1 or 0.8-0.9 indicates high densities of green vegetation (Weier and Herring).

Barren rock, sand, snow, and water are values 0.1 and below (Weier and Herring, 2000; Fu and Burgher, 2015). Values 0.1 and below were classified as non-vegetated while values above 0.1 were labeled as vegetation.

Results

The depth of each depression was measured in meters. Figure 2 shows the location of each depression throughout the city. Depression ranged 1m to 7m deep (Figure 2). Depressions 1m to 7m deep made up 16.9% or 1378679m^2 of the area. Depressions with depths of 1m could hold 19.9% or 611,383m^3, 2m - 19.7% or 601,550m^3, 3m - 22.5% or 687,786m^3, 4 m - 11.3% or 347,003m^3, 5m - 16.3% or 500,025m^3, 6m - 8.2% or 249,404m^3, and 7m - 2.1% or 62,551m^3. The total calculated volumes depressions could hold resulted in 3,059,705m^3 (Table 2).

Figure 3 displays flow direction for

each cardinal direction with north in blue, northeast in red, east in pink, southeast in brown, south in yellow, southwest in orange, west in purple, and northwest in green.

Table 2. The total sum for the holding capacity of depressions 1 m to 7 m deep.

Total Sum of Areas of Depressions		
Depth (m)	Volume m^3	Percentage %
1	611,383	19.9
2	601,550	19.7
3	687,786	22.5
4	347,003	11.3
5	500,025	16.3
6	249,404	8.2
7	62,551	2.1
Total	**3,059,705**	**100**

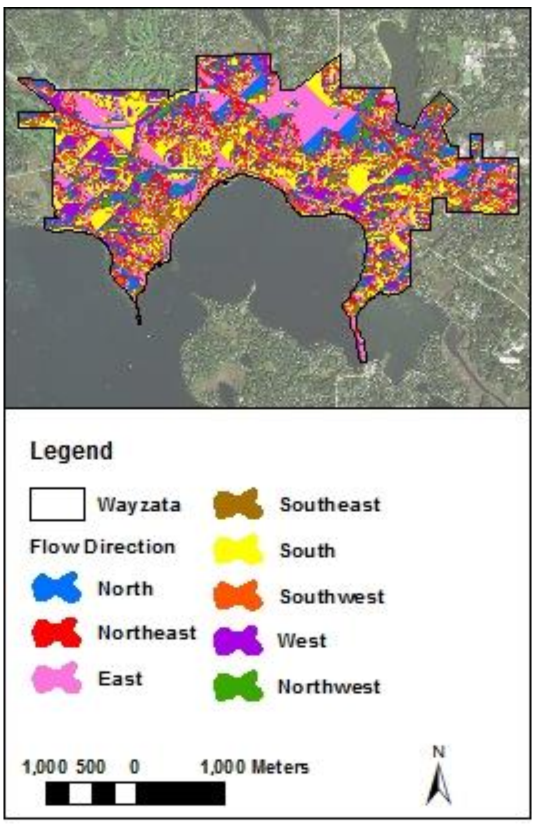

Figure 3. Flow direction for the City of Wayzata; north in blue, northeast in red, east in pink, southeast in brown, south in yellow, southwest in orange, west in purple, and northwest in green. A 2015 aerial photograph was set as the background.

The East direction represented the highest percentage of flow for Wayzata at 19.2% and the lowest being north at 8.1%. East flow direction covered an area of 1,559,886m^2. The South flow direction was second with an area of 1,500,126m^2 or 18%. The area and percentage for all cardinal directions are listed in Table 3.

Depressions 1 to 7m deep made up 38.8% or 33518m^2 of the east flow direction, 24.6 or 30,385m^2 for south, 18.7% or 22744m^2 for west 15.8% or 17,875m^2 for north. Small portions of the southeast, southwest, northwest, northeast flow directions depressions are 2.1% or 18,873m^2, 1.8% or 13,011m^2, 1.4% or 7391m^2, and 1.1% or 11758m^2.

Table 3. Amount and percentage of flow direction within Wayzata, Minnesota.

Flow Direction for Wayzata, Minnesota		
Flow Direction	**Area m^2**	**Percentage %**
North	1,016,469	12.5
Northeast	758,125	9.3
East	1,559,886	19.2
Southeast	797,992	9.8
South	1,500,126	18.0
Southwest	791,670	9.7
West	1,043,640	12.8
Northwest	657,249	8.0

There were 29 watersheds identified by using the basin tool. The four largest watersheds had areas of 2,531,137 m^2, 2,035,021m^2, 1,679,932m^2 and 850,989m^2 totaling to 87.3% of the area of Wayzata. The 5th to 9th largest watersheds had areas of 359,856m^2, 176,659m^2, 161,43m^2, 111,166m^2 and 81,986m^2. The 9 largest watersheds made up 98.3% of the total area of the city. The remaining 20 watersheds made up 1.7% or 136,975m^2 area. Figure 4 outlines each watershed in blue.

Figure 5 illustrates areas derived

from LiDAR 2 foot contours with angles 20 to 35 degrees in green, 35 to 45 degrees in yellow, 45 to 53 degrees in orange and areas 53 degrees or greater shown in red. The maximum angle of repose for Wayzata was 67.57 degrees. Areas with slopes 20 to 35 degrees covered 1,579,630m^2 or 45.9% of the total areas with high slopes. Slopes ranging 35 to 45 degrees made up 1,297,579m^2 or 37.7% of the total areas. Areas with 45 to 53 degrees showed an area of 416,075m^2 or 12.1% while 53 degrees and greater slopes had an area of 148,412m^2 or 4.3%. The total area with 20 degrees or more was 2,294,716m^2.

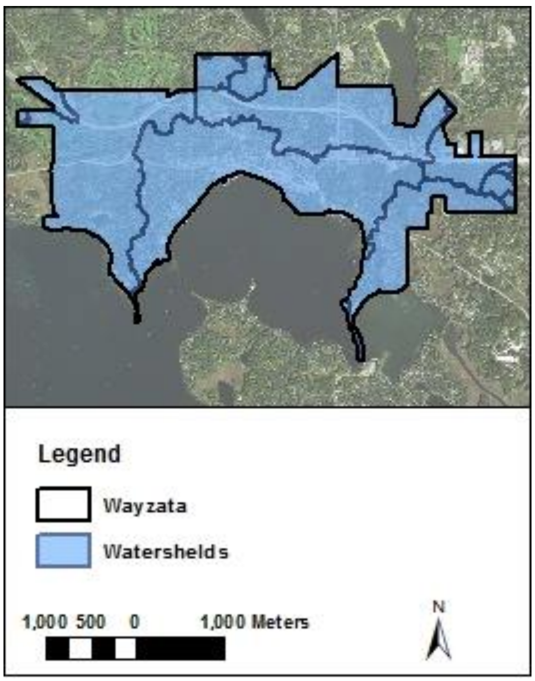

Figure 4. Watersheds numbers in blue created using Hydrology toolset. A 2015 aerial photograph was set as the background.

Areas at risk of erosion were determined by finding areas were slope was greater than angle of repose for each soil type (Figure 6). Slopes 20 to 35 degrees, 35 to 45 degrees, 45 to 53 degrees, and 53 degrees or greater have areas and percentages at risk of erosion of 222,096m^2 or 33.9%, 202,167m^2 or 30.9%, 165,757m^2 or 25.3%, and 64,192m^2 or 9.8%. The total calculated area at risk of erosion amounted to 654,212m^2 (Table 4).

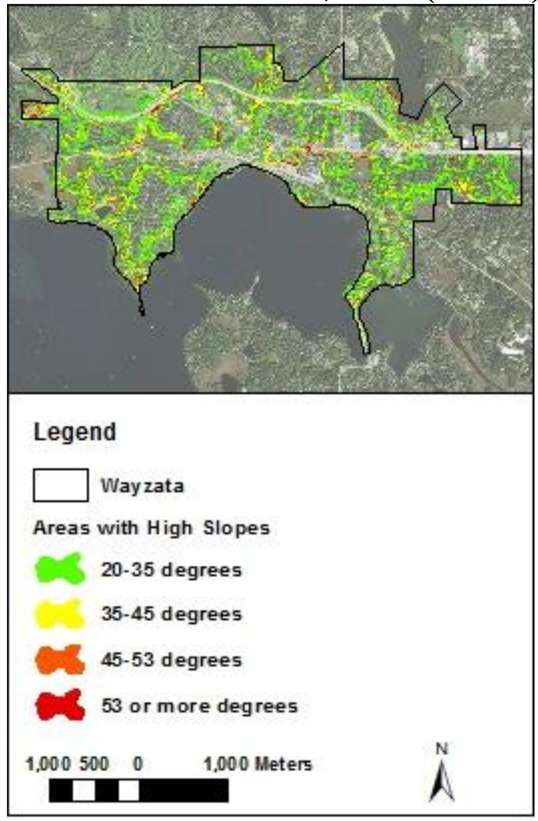

Figure 5. Shows areas with high slopes green shows 20 to 35 degrees, yellow is 35-45 degrees, orange in 45-53 degrees and red is 53 degrees or higher. A 2015 aerial photograph was set as the background for the map and the City of Wayzata outlined in black.

Muck, sandy loam, and loam at risk of erosion measured 201,620m^2 or 30.8%, 188,576m^2 or 28.8%, and 122,001m^2 or 18.6%. Urban land 80%, udorthents, wet substratum 20%, Loamy fine sand, and urban land 70%, had areas 10% to 1% of the area at risk of erosion, measuring 59,726m^2 or 9.1% for Urban land 80%, 49,455m^2 or 7.6% for udorthents, wet substratum 20%, 13,240m^2 or 2.0% for Loamy fine sand, and 6,979m^2 or 1.1% for urban land 70%. Urban Land 75%, Udorthents, loamy 100%, Clay loam, Silty clay loam, and very fine sandy loam measured less than 1% of the area at risk of erosion with areas and percentages of

4,687m^2 or 0.7%, 4,325m^2 or 0.7%, 1,937m^2 or 0.3%, 1,424m^2 or 0.2%, and 243m^2 or 0.04%. Muck soils had the greatest percentage of at risk of erosion (Table 5).

Non-vegetation and vegetation for 2008 and 2015 are mapped in Figure 7 with green indicating vegetated and red indicating non-vegetated areas. Non-vegetated and vegetated areas for 2008 measured 4,089,737m^2 or 50.3% and 4,035,760.333m^2 or 49.7%, respectively. 2015 non-vegetated and vegetated areas covered 2,972,010.25m^2 or 36.6% and 5,153,486.74m^2 or 63.4%.

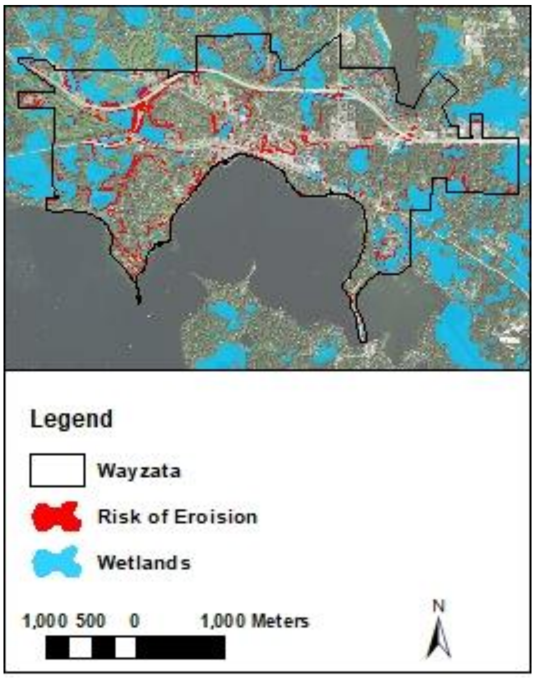

Figure 6. Map shows the areas at risk of erosion in red and wetlands overlay in blue. A 2015 aerial photograph was set as the background.

Discussion

Depth depressions are important to understanding runoff and reducing the impacts of flood events (Figure 2). Reducing flood risk includes short-term storage for large volumes of water (Deckers *et al.*, 2010). Areas identified in Figure 2 are locations where water will pool during events and provide the storage needed to minimize flooding. The depressions show the maximum storage capacity for the area (Zhang and Pan, 2014). Areas indicated in red have the most storage capacity.

Table 4. Areas with high slopes at risk of erosion. (New York State Department of Transportation, 1996; Burch, 1997).

Areas with High Slopes at Risk of Erosion		
Slopes	**Area m^2**	**Percentage %**
20-35 Muck	222,096	33.9
35-45 Sand/Sand plus	202,167	30.9
45-53 Loam/Loam plus	165,757	25.3
53 > Clay	64,192	9.8
Total	**654,212**	

Table 5. Table shows the amount and percentage of each soil type at risk of erosion in Wayzata, Minnesota USA.

Types of Soils at Risk of Erosion		
Type of Soil	**Area m^2**	**Percentage %**
Clay loam	1,937	0.3
Loam	122,001	18.6
Loamy fine sand	13,240	2.0
Muck	201,620	30.8
Sandy loam	188,576	28.8
Silty clay loam	1,424	0.2
Udorthents, loamy 100%	4,325	0.7
Udorthents, wet substratum 20%	49,455	7.6
Urban Land 70%	6,979	1.1
Urban Land 75%	4,687	0.7
Urban Land 80%	59,726	9.1
Very fine sandy loam	243	0.0

Depression areas can be found across the city. The 1m to 7m depth provide an estimate of storage capacity throughout the city. This estimate is within one half meter accuracy connected to rounding to the nearest meter.

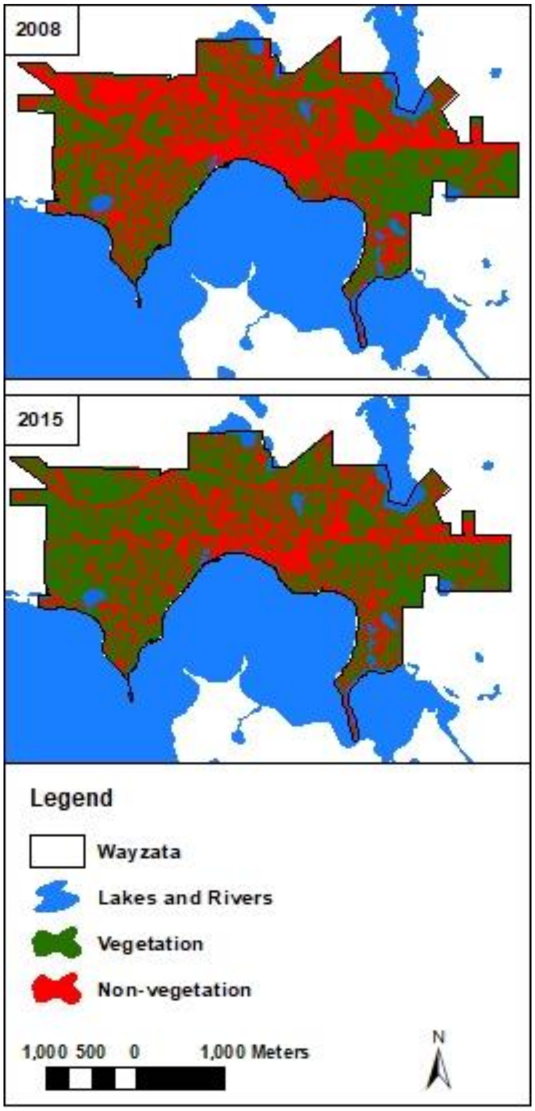

Figure 7. Maps show vegetated areas (green) and non-vegetated areas (red). 2008 featured more barren land and potential construction areas. There is a lake and river overlay obtained from the Metropolitan Council showed in blue (Metropolitan Council, 2013). The City of Wayzata, Minnesota USA is outlined in black.

The areas in the north of Wayzata had 1,524,844m^2 or 49.0% of the total storage capacity of the depression area in the city. This area has the deepest depressions contained within it. The north section has 21.1% or 328,210m^2 of the total east flow direction. The north area contains 5.2% or 52,712m^2 north flow directions and 3.4% or 51,093m^2 of the south flow direction. These areas should be taken into consideration when deciding what areas are best for zoning restriction in a Flood Management program for the City of Wayzata.

Having zoning restriction in areas with high risk for floods can be used in flood management (Bethea, 2011). These restrictions can limit construction in high-risk area to reduce the impacts floods have by decreasing the amount of damage (Bethea, 2011). Other restrictions for the area might include elevated structures codes or parkland zoning (Bethea).

Knowing hydro-meteorological conditions and streams flow of flood situations is useful in forecasting flood risk areas (Johnson, 2009). The flow direction map shows the water flow direction for the city once the depressions are filled (Figure 3) (Zhang and Pan, 2014). There is large section of the city with the flow direction of east and south. There are 47.5% of the flow direction of the city is flow and east southeast or south (Table 4). These results show water flows to Lake Minnetonka south of the city and to Gleason Lake northeast of the city.

The watershed map has 29 watersheds. Nine large watersheds account for 7,988,185m^2 or 98.3% of the city. Nineteen of the smaller watersheds are located on the perimeter and likely extend past the city limits. The 10th largest watershed was on the southern tip of Wayzata boarding the large lake of Lake Minnetonka.

Areas at risk of erosion make up 8.05% of the city. The areas at risk of erosion along roads could indicate an increase in of runoff from the impermeable surface. Slopes 20 to 35 degrees had the area and percentage with

222,096m^2 and 33.9% of the areas at risk of erosion. Slopes 53 and greater had the smallest area and percentage of area at risk of erosion with 64,192m^2 and 9.8%.

Soils at high risk of erosions were used to identify areas that were at risk for environmental pollution. The soil type primary at risk were muck, sandy loam, and loam. Muck, sandy loam, and loam made up 78.3% or 512,196m^2 of the soil at risk of erosion.

The NDVI 2008 Figure 7 has 1,117,726.65m^2 or 13.8% more non-vegetated area than the 2015 NDVI. This can be seen in the northwest corner of the city. This area changed from barren soil to vegetation. In areas with 1 to 7m depressions 2008 non-vegetated and vegetated area measured 579,102m^2 or 42.0% and 799,578m^2 or 58.0%. Areas with depression in 2015 non-vegetated and vegetated area covered 380,067m^2 or 27.6% and 998,613m^2 or 72.4%. Areas at risk of erosion had non-vegetated and vegetated areas in 2008 measuring 275,615m^2 or 42.1% and 378,596m^2 or 57.9%. In 2015, non-vegetated areas were 133,942m^2 or 20.5% and vegetated areas were 520,269m^2 or 79.5%.

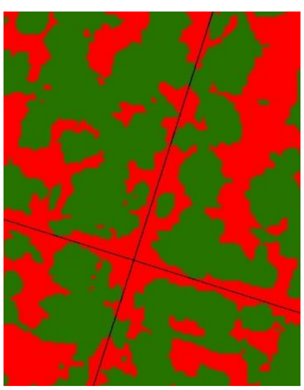

Figure 8. A sample view of the NDVI showing roads center lines (in black) of a city/block-like area where vegetation (green) and non-vegetation (red) are shown.

Tree canopies along the streets block the impermeable surface causing the pixels to be mixed with vegetation (Yang and Li, 2015). This can be seen in Figure 8 where trees cover roadways to the point of which there was separation in the middle of the street.

Conclusions

Determining locations impacted by floods and areas for storage is beneficial for Flood Management programs. Wayzata, Minnesota has areas of depressions that could hold excess water during heavy rainfall events. Areas with high slopes are vulnerable to erosion and increases the probability floods. Wayzata has high slopes at risk of erosion along roadways and areas around wetlands. Focusing on areas that have high slopes and limited storage capacity will identify problem areas in the future.

Acknowledgements

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