The Effect of Watershed Urbanization on River Hydrology and Ecology: Assessing the Use of Population Density as an Estimate for Percent Impervious Cover

A case study of the Des Plaines River Watershed 1940-2010

by

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Abstract

Population distribution in the United States follows a pattern of development known as urban sprawl. The trend of urban sprawl and its associated development of pervious land cover types such as natural and agricultural land to impervious land cover types such as roads, parking lots, and structures has had significant impacts on watershed hydrology and river ecosystems. As a watershed becomes increasingly developed, the discharge of the watershed increases and in effect the frequency and intensity of flood events increases. Using the Des Plaines River Watershed as a case study, a model was made to demonstrate that the use of population density as a measure of percent impervious cover is a viable proxy to show its correlation with river discharge. Population densities of the watershed were correlated against the watershed’s discharge for the decades between 1940 and 2010. The model indicated with a significance value of < 0.001 and an R² value of 0.92 that population density within the Des Plaines River Watershed was positively correlated with the discharge of the Des Plaines River. The use of population density in this model as a proxy for percent impervious cover when land cover data is unavailable provides a robust approach for revealing how variations in level of development impacts watershed hydrology.

Introduction

Each year, flooding from rivers in the United States causes billions of dollars in damages (NOAA 2011). A majority of these floods can be attributed to the sprawling pattern of population distribution, which requires the construction of roads, parking lots, and structures in place of forests, wetlands, and agricultural land (Dunne & Leopold 1978). These types of surfaces prevent precipitation from soaking into the ground and cause it to runoff into rivers (Dunne & Leopold 1978, Arnold & Gibbons 1996, Booth & Jackson 1997). Such excess amounts of water in rivers increase the likelihood of overflow and floods, sometimes causing significant damage in populated areas (Booth & Jackson 1997). Flood damages are exacerbated when development encroaches upon natural floodplains (Allen & Bejcek 1977). This sprawling
pattern of development also has a negative impact on the ecological health of aquatic ecosystems (Wissmar and Bison 2003). The Des Plaines is a characteristic example of a river that experiences chronic flood events and damages as a result of sprawling development (Carns 1973, Wilson & Weng 2011). It is essential for management agencies to understand how changes in level of development impacts rivers in order to facilitate efforts to reduce the occurrence of flood events and damages and to improve the ecological health of its aquatic ecosystems (NRC 1992 & 1999, Baer & Pringle 2000). However when specific information about level of development is not available or feasibly obtainable, as is often the case, other techniques are required to obtain this measure.

**Purpose and Scope**

It is known that there is a positive correlation between population density and percent impervious cover and that there is a positive correlation between percent imperviousness cover and watershed discharge (Allen & Bejcek 1977, Chabaeva et al. 2004). In an effort to better understand how changes in land use impact a watershed’s hydrology the objective of this study is to evaluate the use of population density as a proxy for percent impervious cover when land cover data is unavailable to analyze the effect of development on river discharge. This model will be applied to the Des Plaines River Watershed between the years 1940 to 2010 as a case study. It is first hypothesized that the population density and the discharge rate of this watershed have both increased to a significant degree. In addition, it is expected that annual precipitation has neither increased nor decreased to a significant degree showing that variations in climate would not have a significant impact on the increased discharge rate of the watershed. It is then hypothesized that there will be a positive correlation between population density and river discharge thus indicating that population density is a viable proxy for percent impervious cover when analyzing the effect of development on river discharge.

**Literature Review**

*Patterns of Population Distribution:*

The current pattern of population distribution in the United States had its beginnings during the gilded age but did not begin to develop until the end of World War II. Facilitated by
the wide scale diffusion of the automobile and the completion of the interstate highway system, populations rapidly moved out of the city and settled beyond the urban fringe in a pattern of development known as urban sprawl. Urban sprawl refers to the literal ‘sprawling’ of edge-city and suburban development around urban centers, and has accounted for the majority of urbanization in the United States since the end of World War II. Urbanization is the general movement of populations from rural to urban areas and the associated growth of urban populations.

The initial trend toward urban sprawl in the United States began with the start of the industrial revolution (Baldassare 1992, Archer & Blau 1993, Nechyba & Walsh 2004). At the height of the industrial revolution urbanization was at its most rapid pace (Nechyba & Walsh 2004). With urban centers becoming increasingly densely populated and polluted, the growing upper-middle class at the time was looking for a place to retreat from the bustle of the big city (Binford 1985, Archer & Blau 1993). Getting inspiration from the mansions of wealthy, they built their own stately homes where there was space on the outer limits of the cities (Binford 1985, Archer & Blau 1993). As this trend became more popular, streetcars began stretching lines out from the urban center to these communities of homes (Burgess 1967, Fishman 1987). Transit technology like the streetcar was popular in major urban areas throughout the United States between 1880 and 1920 however this technology was limited by its slow speed (Binford 1985). Because these communities were very dependent on having ready access to the central business district of the city for employment, groceries, and commodities, the distance that these communities could be built from the city-center was limited (Fishman 1987). Therefore much of the population remained centralized around the city and did not extend far beyond the outer limits of the cities (Burgess 1967). The technology of the streetcar would remain dominant until being surpassed by the age of the automobile, a faster mode of transportation (Hawley 1971).

By 1920 half of people living in the United States lived in urban areas, and automobiles were becoming increasingly popular with eight million registered (Fishman 1987). The seeds for expansion beyond the outer limits of the city were beginning to be sown, however the onset of economic depression and war brought new housing development to a halt (Nechyba & Walsh 2004). It was not until shortly after the end of the Second World War that economic prosperity and a rapidly growing population pushed for a boom in housing development (Nechyba & Walsh 2004). Soldiers that came back from the battlefronts married, had children, and had begun
looking for a place to live (Archer & Blau 1993). This generation of young families was driven by the same yearning to own a stately home on their own plot of land that was initially brought upon by the upper middle class during the gilded age (Archer & Blau 1993). To satisfy this desire, housing development companies looked to the large tracts of open land that surrounded the urban centers (Guest 1979). It was during this time that the first organized suburbs were developed (Binford 1985). As the popularity of the automobile continued to grow and with the beginnings of the development of the interstate highway system, the feasibility of living on the outside the limits of those urban centers and commuting to one’s place of employment in the urban center increased (Hawley 1971). Populations began to spread farther beyond of the outer limits of the city (Hawley 1971). At first, populations mostly resided in small suburbs known as bedroom communities, in which the inhabitants would only sleep and then commute to their place of employment in the city during the day (Guest 1979, Binford 1985). These small bedroom communities were the beginning of the widespread trend of urban sprawl that would, within the next half of the century, change the landscape of major urban areas across the United States from densely populated clusters to wide-spread suburban development around the original urban center (Baldassare 1992).

By 1952 most households owned at least one automobile, and with the completion of the interstate highway system about a decade later, decentralization of urban areas across the United States was in full swing (Hawley 1971). Whole towns of suburbs began springing up along the newly constructed highways (Guest 1979). No more were these small bedroom communities; these new suburbs had their own downtown areas with their own grocery stores, pharmacies, department stores, and schools (Fishman 1987). Although many people still commuted into the city for work, there was an increasing trend of these suburbs becoming self-sufficient, where the people living within them can work, get their groceries, commodities, and amenities without ever having to leave (Hawley 1971, Fishman 1987). These towns may become so large and densely populated that they may develop into edge-cities, which is an entirely self-sufficient city laying on the outer fringes of an urban area (Fishman 1987, Baldassare 1992). Today’s urban landscape is nothing like the early, tightly clustered metropolises of the past (Fishman 1987). The modern city covers significantly more land than its predecessors and its populations are sprawled for miles around the urban center (Nechyba, Walsh 2004).
Effects of Urbanization on Watershed Hydrology:

Such wide-scale urbanization can cover large tracts of a watershed, which can result in a multitude of significant changes to the watershed’s hydrology and aquatic ecosystems (Allen & Bejcek 1977, Dunne & Leopold 1978, Booth 1991, Arnold & Gibbons 1996). A watershed, also known as a catchment basin or drainage area, is an area of land where all of the precipitation that falls on it flows towards a single drainage system such as a river (Allen & Bejcek 1977, Bedient, Huber 2002). Every point on the earth’s terrestrial surface can be associated with a particular watershed (Bedient, Huber 2002). Urbanization refers to the growth of urban and suburban areas both in population and the physical amount of space that it occupies on the surface (Nechyba, Walsh 2004). Suburban areas are classified as having a population density of 600 persons per square mile (Paul & Meyer 2001). Urban areas are defined as having a population density of over 1000 persons per square mile (U.S. Census Bureau 2011). As an area becomes more urbanized, the increasing population in that area requires the construction of a certain level of infrastructure and shelter to support the increasing population (Allen & Bejcek 1977). This process involves the conversion of pervious land such as forests, wetlands, and agricultural land into developed land with impervious surfaces such as roads, parking lots, and structures (Allen & Bejcek 1977). Impervious surfaces are those, which prevent the infiltration or absorption of precipitation water into the ground, while pervious surfaces allow for the infiltration of precipitation water (Allen & Bejcek 1977, Bedient & Huber 2002). Usually as population density within an area increases so does the percent of the area that is developed with impervious surfaces (Allen & Bejcek 1977, McMahon & Cuffney 2000). A study for the United States Geographical Survey showed that there is a strong positive correlation between population density in persons per square mile and percent impervious cover (Allen & Bejcek 1977). When precipitation water is prevented from infiltrating the surface, it flows or drains with the force of gravity towards a lower elevation – this is known as runoff (Bedient, Huber 2002).

Compared to forested land cover, an area that is 10-20% developed with impervious covers has twice as much runoff; 35-50% three times as much runoff; 75-100% five times as much runoff (Arnold & Gibbons 1996). Percent impervious cover is an accurate indicator of the impacts of urbanization on rivers with 10-20% development being the threshold for measurable impact on hydrology and aquatic ecosystems (Booth & Jackson 1997, Klein 1979). Runoff often drains into a river causing more water to enter that river, which results in increased river
River discharge is a measurement of the amount of water flowing through a river and is measured in cubic feet per second (Bedient & Huber 2002). It is calculated by multiplying the flow rate of the water moving through a segment of the river channel with the transected area of that channel segment (Bedient & Huber 2002). River discharge rates are sensitive to variations in runoff rates (Booth 1991). Excess runoff entering a river increases the flow rate and amount of water in the river, and in effect the discharge rate of that river is increased (Booth 1991, Bedient & Huber 2002).

**Effects of Urbanization on the Drainage System Geomorphology and Associated Ecology:**

River channel geomorphology is responsive to changes in runoff rates and sediment inputs (Wolman 1967, Dunne & Leopold 1978, Roberts 1989). As river discharge increases, the river channel’s geomorphology is altered through a process known as river channelization (Wolman 1967, Dunne & Leopold 1978, Roberts 1989, Bedient & Huber 2002). The process of river channelization involves phase changes in the geomorphology of the river channel (Wolman 1967, Dunne & Leopold 1978). The first occurs during the time period that the watershed surface is undergoing development, which involves the construction of impervious surfaces and structures after removing the previous land cover, whether it is natural forest, prairie, or agricultural land (Wolman 1967, Dunne & Leopold 1978). During this phase, the previous surface cover, which had been holding the underlying substrate in place, is removed and the substrate, now at the surface, is exposed and is highly susceptible to erosion (Wolman 1967, Dunne & Leopold 1978). Erosion of this substrate usually occurs during heavy rain events, where it is transported via runoff into rivers causing sediments to aggregate at the bottom of the river channel (Wolman 1967). This process can make a river channel shallower, reducing its ability to support the higher discharge rates associated with excess runoff from large precipitation events and from impervious surfaces (Wolman 1967, Roberts 1989). As a result, overbank flooding occurs commonly during this phase (Wolman 1967, Dunne & Leopold 1978, Roberts 1989). As these floods deposit sediments along the banks a mound is gradually built up (Wolman 1967). This mound raises the height of the bank and therefore increases the channel depth, creating a channel cross-section that is similar to the original river channel (Wolman 1967).
The second phase of channelization occurs after development of the watershed surface is complete and the substrate is covered with impervious surfaces (Wolman 1967). With the substrate being covered once again, it cannot readily be transported via runoff, and therefore sediments are no longer being deposited into the river channel (Wolman 1967, Dunne & Leopold 1978, Roberts 1989). Without the addition of new sediment, the channel experiences a general deepening as the sediments within the channel are eroded away (Roberts 1989, Booth 1990). During this phase, the channel may tend to narrow as eroded sediments from the bed are deposited along the sides of the channel (Dunne & Leopold 1978). The additional runoff from impervious surfaces increases average river discharge as well as the frequency and intensity of overbank flood events, which further erodes the channel and increases the area of the channel cross-section (Roberts 1989, Booth 1990). There is then a general widening of the channel cross-section as increasing discharge begins to erode away at the banks (Dunne & Leopold 1978, Booth 1990, Booth & Jackson 1997). The resulting increased area of the channel cross-section accommodates the increased average discharge of the river (Booth 1990). This process also facilitates increased discharge rates as the velocity of flow increases as a result of the reduced proportional amount of water that is in contact with the air surface and channel bed relative to the total amount of water flowing through the channel, effectively reducing friction (Bedient, Huber 2002).

This bank erosion occurs gradually if the increasing discharge rate increases at a proportionately gradual rate (Booth 1990). However, changes in discharge rates caused by the urbanization of a watershed are rarely gradual and therefore bank erosion occurs at an unstable pace especially in response to heavy rain events (Neller 1988, Booth 1990). These rapid fluxes in river discharge rates as a result of the increased runoff from impervious surfaces leave the banks susceptible to sudden erosion events and catastrophic bank failure (Neller 1988, Booth 1990). Destabilized banks pose a severe threat to any structures or surfaces that are near to that river (Neller 1988, Booth 1990).

A channelized river has a geomorphology that is less effective at containing excess runoff, causing it to spill over its banks and flood more frequently and intensely (Dunne & Leopold 1978). This can be a major problem to human populations living near to these rivers (Roberts 1989, Booth 1990). Structures and surfaces lying within the flood zone of these rivers are at a constant risk of being damaged by a flood especially when this development encroaches

Another major effect of urbanization of a watershed on its geomorphology is reduced drainage density, which is a measure of combined drainage system length relative to the area of the watershed (miles/miles$^2$) (Dunne & Leopold 1978, Bedient & Huber 2002). As a watershed becomes increasingly urbanized smaller, natural drainage channels are filled in or replaced with roadside ditches and storm water sewers, and naturally meandering rivers are straightened to make way for roads, parking lots, and homes (Dunne & Leopold 1978). This straightening of the river channel increases the velocity of flow by reducing the friction that natural meanders in the river channel would create (Gregory et al. 1994, Bedient & Huber 2002). Reducing drainage density also acts to reduce the volume of water that can be contained within the remaining channels of the watershed, increasing the frequency and intensity of flooding especially after heavy rain events (Dunne & Leopold 1978). Roadside ditches and storm water sewers further exacerbate the intensity of floods by efficiently funneling runoff water into the river channel (Graf 1977). Another effect of the river channel straightening is the decrease in the frequency of pool-riffle segments along the river (Gregory et al. 1994). Pool-riffle segments are those, which form with the natural meandering of rivers, where the relative increased velocity between pools created by meanders causes a riffle effect in that section of the river (Gregory et al. 1994, Bedient & Huber 2002). The morphological effect of straightening a river that channelization has reduces habitat heterogeneity by eliminating these riffles and pools that would occur along a naturally meandering river (Gregory et al. 1994). A heterogeneous habitat supports greater diversities of species and contributes to the overall ecological health of ecosystems (Gregory et al. 1994, Dodson 2004, Lau et al. 2006).

Effects of Urbanization on the Abiotic Factors of the Drainage System and Associated Ecology:

Urbanization of a watershed has the effect of altering the sediment composition within the river channel and bed (Roberts 1989, Pizzuto et al. 2000). There is a general decrease in finer silt and clay sediments and an increase in sandy sediments (Roberts 1989, Pizzuto et al. 2000). Coarser gravel sediments are also decreased by watershed urbanization (Roberts 1989, Pizzuto et al. 2000). This change in sediment composition affects the types of organisms that
can survive in the river channel, particularly those aquatic macrophytes, invertebrates, and fish that depend on a natural mix of sediment types (Hogg, Norris 1991). While there are less finer sediments being deposited on the channel bed, there are more sediments suspended and flowing through a river in an urbanized watershed compared to a forested one (Roberts 1989, Pizzuto et al. 2000). This is a result of higher flow velocities having the ability to pick up and move sediments more readily (Roberts 1989, Pizzuto et al. 2000). As sediments suspended within a river increase, so too does its turbidity (Roberts 1989). Turbidity is a measure of water clarity, where the more turbid a body of water is, the less clear it is (Dodson 2004). Because rivers in urbanized watersheds are more turbid, less light is able to penetrate through them to reach the channel bed, reducing or eliminating the ability of the original submerged aquatic macrophytes to photosynthesize (Dodson 2004). As a result, there is a lower diversity and abundance of submerged aquatic macrophytes in the rivers of urbanized watersheds (Dodson 2004).

Water temperature is an important factor that affects river life (Galli 1991, Dodson 2004). As the turbidity of a river increases, sunlight being absorbed by the suspended sediments in that river is given off as heat, causing the water temperature to increase (Dodson 2004). A second factor that increases the temperature of water in the rivers of urbanized watersheds is heated precipitation runoff from impervious surfaces that had been absorbing sunlight during the day (Pluhowski 1970, Galli 1991). Impervious surfaces also act to prevent the infiltration of precipitation, which reduces the recharge of groundwater that provides the base flow for rivers (Klein 1979, Barringer et al. 1994). A reduction the supplemental flow of groundwater recharge, with its relatively stable temperature, increases the daily and seasonal variability of temperatures in the rivers of urbanized watersheds (Klein 1979, Galli 1991, Barringer et al. 1994). Temperatures are also more variable in rivers of urbanized watersheds compared to rivers in forested watersheds because the removal of forest cover within a watershed and riparian vegetation along the banks of a river reduces the natural insulation of that river from changes in air temperature and the amount of sunlight reaching it (Pluhowski 1970). A study of urbanized Long Island rivers indicated that mean temperatures ranged from 5-8°C warmer during the summer months and 1.5-3°C cooler in the winter months compared to forested rivers. Sudden changes in temperature associated with summertime storm runoff from urbanized rivers altered river temperatures by 10-15°C warmer compared to forested rivers as a result of the runoff from heated impervious surfaces (Pluhowski 1970). Changes in water temperature and water
temperature patterns alter ecological processes such as leaf decomposition (Webster & Benfield 1986), and a variety of aquatic organisms’ life histories (Sweeney 1984).

The chemical affects of urbanization on a river are significantly more variable than geomorphic effects and are dependent on the type of land cover (residential, industrial, commercial) and the density of urbanization. General increases in nutrient abundance are associated with rivers of urbanized watersheds (Porcella & Sorensen 1980, Duda et al. 1982). Wastewater and fertilizers from residential lawns and commercial properties are a significant source of nitrogen, phosphorus, and potassium in these rivers, and often cause algal blooms in these rivers (Lavalle 1975). Algal blooms occur when excess nutrients enter a water body, causing a rapid growth in algae on the water surface (Lavalle 1975, Dodson 2004). Algal blooms prevent sunlight from penetrating through the water, which kills the submerged vegetation beneath it (Dodson 2004). After the algae uses up all of the available nutrients, it dies and begins to decompose, quickly starving the water of oxygen in the process (Dodson 2004). Fish die in the resulting extreme low oxygen conditions (Dodson 2004). Other chemicals found elevated in these rivers include sodium and chloride from road salts, pesticides, and other contaminants such as polychlorinated biphenyls (PCB’s) (Whipple & Hunter 1979). Metals such as lead, chromium, zinc, copper, manganese, nickel, and cadmium are the more common metals found in elevated levels within urbanized rivers and can bio-accumulate in the bodies of fish (Wilber & Hunter 1979).

Watershed urbanization alters the abiotic properties of rivers to such an extent that it effectively changes the habitat of the entire aquatic ecosystem (Lavalle 1975, Porcella & Sorensen 1980, Duda et al. 1982, Malmqvist & Rundle 2002, NRC 1992). Species that are not able to adapt to these changes die off and may be replaced by species that are more suited for the new habitat, but the overall species richness is likely to decrease (Duda et al. 1982). Species richness refers to the number of different species within an ecosystem (Duda et al. 1982, Dodson 2004). Significant changes in the species composition of an ecosystem threaten the ecological integrity of that ecosystem (Duda et al. 1982, Malmqvist & Rundle 2002, NRC 1992).

Changes in the aquatic ecosystem and increased flooding risk caused by river channelization as a result of increased discharge rates from excess runoff from impervious surfaces is the effect of large-scale development of a watershed. It is essential for management agencies to understand how changes in level of development impacts rivers in order to facilitate
efforts to reduce the occurrence of flood events and damages and to improve the ecological health of its aquatic ecosystems (Baer & Pringle 2000, NRC 1992 & 1999).

Study Area

The Des Plaines River Watershed covers an area of approximately 1,455 square miles and lies within parts of Racine and Kenosha counties in Southeast Wisconsin and Lake, Cook, DuPage, Will, Kane, Kendall, and Grundy counties in Northeast Illinois (figure 1) (USGS 2011). In 2010, the population of the area was approximately 3,832,000 (U.S. Census Bureau 2011). Between 1950 and 2010 the population of the area increased by 75 percent (NHGIS 2011, U.S. Census Bureau 2011). During the past century this watershed has undergone a radical transformation from mostly wilderness and agricultural land cover in 1940 to its current state - a sprawling developed urban and suburban landscape (Allen & Bejcek 1977, Wilson & Weng 2011). This transformation was facilitated by the completion of Chicago’s highway system in 1963, which made this region accessible for urban and suburban development (Hawley 1971). The city of Buffalo Grove is a typical example of how urban sprawl managed to transform a small rural township into a densely populated suburban area (BGHS 2011). When Buffalo Grove became incorporated in 1958, it had a population of 164, and in a period of 40 years, grew to a population of over 43,000 (BGHS 2011). This pattern of rapid growth is common throughout the Des Plaines River watershed (Wilson & Weng 2011). The watershed is now mainly covered with urban and suburban developed areas, as well as remnants of agricultural land, forest, and wetland (figure 2) (USGS 2011).

Its climate is temperate humid continental with hot summers and cold winters (NOAA 2011). There is a slight stabilizing effect from Lake Michigan (Allen & Bejcek 1977). The average annual temperature is 50° F, ranging from a mean monthly temperature of 23° F in January to 74° F in July (NOAA 2011). The average annual precipitation is 35 inches, of which 10 percent is in the form of snow (NOAA 2011). This region frequently experiences short and intense storm events (NOAA 2011, Allen & Bejcek 1977).

The natural landscape is primarily flat with any features formed primarily as a result of glacial activity during the Pleistocene Age (USGS, 2011). The bedrock in the region is mostly Dolomite and the overlying surface substrate, with an average depth of 100 feet, is composed mainly of unconsolidated glacial till deposits (USGS 2011).
The Des Plaines River begins near Union Grove, Wisconsin and flows southward for approximately 150 miles before joining with the Kankakee River to form the Illinois River west of Channahon. (figure 1) (USGS 2011). Much of the Des Plaines River is flanked by developed urban and suburban areas, county parks and natural areas, and remnant wetlands (figure 2) (USGS 2011).

This watershed was selected as a case study because of the characteristic pattern of post World War II sprawl development that it had experienced (appxs 1-8) (NHGIS 2011, U.S. Census Bureau 2011, Allen & Bejcek 1977). Its flat landscape, temperate climate, and central location on the continent reduced the possibility of extraneous variables affecting the results of the study.

**Figure 1:** Map of Des Plaines River Watershed (outlined in black) showing gauging stations/water monitoring sites in red.
Figure 2: Map showing the land cover types and level of development of Des Plaines River Watershed (outlined in black) in 2006.
Methods

The National Historical Geographic Information System (NHGIS) was used to obtain historic population data and census tract shape files for the states of Illinois and Wisconsin for each decade from 1940 to 2010. A watershed shape file for the United States was obtained from the United States Geological Survey (USGS). The data and shape files were uploaded into Arc Geographic Information System (ArcGIS) program for analysis. The desired Des Plaines River Watershed feature was selected by the ‘feature name’ attribute and a layer was created from the selection. Census tract shape features were selected by their location ‘partly or completely within’ the Des Plaines River Watershed feature and a layer was created from the selection. This process was repeated for each decade. The total population count of the census tracts was summed for each decade and then divided by total area in square miles of the watershed feature layer to calculate a population density value in persons per square mile for each decade. These values were recorded for later use when testing its correlation with river discharge. For the decades of 1940 and 1950 the limited population data at the census tract level was accounted for by assuming that human impact would be negligible for these two decades in that the population of the areas from which no data is present had little to no measurable impact on river discharge. Air photo analysis of these areas confirmed that negligible development (less than the threshold value of 10 to 20% impervious cover) existed in these areas prior to recorded population data. A linear regression of the population density of the Des Plaines River Watershed by decade was run in the Statistical Package for the Social Sciences (SPSS).

The data was further analyzed in ArcGIS by creating a density map of total population count of each census tract by its respective area in square miles by decade from 1940 to 2010 in a geometric interval classification normalized by the 1970 classification for each decade. This was done to allow for visual comparison of population change among the maps throughout the varying decades. The geometric interval classification from 1970 was used as the standard normalization because it represented the median decade of the years being studied and the least biased classification (in terms of insensitivity to patterns of data within a particular decade). For those areas and where population data was not available at the census tract level, county data and shape files were used. The same method of calculating density was used- that is total population count in the county by its respective area in square miles. Again, for the decades of 1940 and
1950 the limited population data at the census tract level was accounted for by assuming that human impact would be negligible for these two decades.

USGS supplied historic mean daily annual river discharge data from five water monitoring/gauging stations along the length of the Des Plaines River from the earliest year of data available to 2010. The gauge stations from which the discharge data were gathered are as follows (moving downstream): 0552780 at Russell, IL for the years 1967-2010; 05528000 at Gurnee, IL for the years 1946-2010; 05529000 at Des Plaines, IL for the years 1941-2010; 05532500 at Riverside, IL for the years 1944-2010; 0553800 at Joliet, IL for the years 1931-2010 (figure1). Discharge data from all five sites were graphed and observed, but only data from the location at Joliet was used when testing its correlation with population density because of its location nearest to the mouth of the river being most representative of the total discharge of the watershed. Mean daily annual discharge data from the Joliet site was averaged by decade from 1940 to 2010 to feasibly correlate it with the population density values obtained earlier. A linear regression of the mean daily decadal discharge of the Des Plaines River at Joliet was run in SPSS.

Annual precipitation data in inches per year from 1931-2010 was obtained from the National Oceanic and Atmospheric Association (NOAA) weather station 114530 at Joliet. The annual precipitation was averaged by decade from 1940 to 2010. A linear regression of the mean annual precipitation by decade was run in SPSS to determine whether or not variations in climate over the time period of this study had a significant effect on potential variations in river discharge.

A linear regression was run in SPSS for the population densities of the Des Plaines River Watershed by decade against the mean daily decadal discharge of the Des Plaines River at Joliet. All regressions in this study were graphed using Microsoft Excel.

Results

GIS analysis of the census data showed a visual increase in the average population density of the Watershed between 1940 and 2010 (appxs 1-8). A linear regression of the population density figures extracted from the GIS analysis confirmed that the population density of the Des Plaines River Watershed had increased between 1940 and 2010 with an R² value of 0.977 and a significance value of p<0.001. The population density of the watershed increased
from about 100 persons per square mile in 1940 to about 1750 persons per square mile in 2010, with an average annual increase of 24 persons per square mile per year (figure 3).

![Des Plaines River Watershed Population Density](image)

**Figure 3:** Linear regression of population density of the Des Plaines River Watershed from 1940 to 2010.

Excel graphs revealed visual increases in discharge at all the sites along the Des Plaines River from the earliest year of data available to 2010 (figure 4). A linear regression of mean daily decadal river discharge at Joliet, IL showed a significant increase between 1940 and 2010 with an R² value of 0.985 and a significance value of p<0.001. Mean daily decadal discharge of the Des Plaines at Joliet, IL increased from about 2536 cfs in 1940 to about 3936 cfs in 2010, with an average annual increase of about 20 cfs per year (figure 5).
Figure 4: Map of Des Plaines River Watershed (outlined in black) showing gauging stations/water monitoring sites with associated graphs showing linear regressions of the mean daily annual discharge of Des Plaines River in cubic feet per second at the various sites during study period.
A linear regression of mean annual precipitation by decade showed no significant change between 1940 and 2010 with an $R^2$ value of 0.012 and a significance value of $p>0.377$. Average annual precipitation gauged at this station is 35 inches per year (figure 6).
A linear regression of population density against river discharge between 1940 and 2010 revealed a positive correlation between the two with an $R^2$ value of 0.92 and a significance value of $p<0.001$ (figure 7). Population density increases river discharge by a factor of 1.3 (figure 7).

![Population Density Correlated with River Discharge](image)

**Figure 7:** Linear regression of population density of the Des Plaines River Watershed against mean daily decadal discharge of Des Plaines River in cubic feet per second at Joliet, Illinois from 1940 to 2010.

**Discussion**

This study indicates that growing population densities can increase the discharge of a watershed by a factor of 1.3 (figure 7). This study demonstrates the use of a technique for estimating changes in discharge from watersheds experiencing varying levels of development when specific land cover data is unavailable. Watershed area and population are required to use this procedure. Population density and the discharge rate of this watershed have both increased to a significant degree (figures 3, 5). In addition, annual precipitation has neither increased nor decreased to a significant degree showing that variations in climate did not have a significant impact on the increased discharge rate of the watershed (figure 6). The analysis indicated a strong positive correlation between population density and mean daily discharge (figure 7).
Through these results, it is demonstrated that population density is a viable proxy for percent impervious cover when analyzing the effect of development on river discharge.

When applied to a given watershed, it would be possible for management agencies to view and analyze how changes in population distribution and their associated pattern of development impacts its hydrology and in turn the ecology of its aquatic ecosystems to facilitate efforts to restore and preserve the watershed’s natural, pre-urbanized condition. The particular watershed in this study for example has no detailed land cover data prior to 1992 (appxs 9-11), therefore analyzing the impacts of varying levels of development on the watersheds hydrology would be limited to that time period (appxs 12-14). With the model demonstrated in this study it is possible to analyze the impacts of varying levels of development on the watershed’s hydrology as far back as the earliest record of population for the watershed; in this case, 1940 (appxs 1-8). This makes it possible to estimate historical (pre-urbanized) conditions and to predict future conditions of the watershed. In addition, this model makes it possible to see patterns between the ways changing population distributions make use of the land they inhabit and watershed hydrology.

With this information in hand, there are several actions that management agencies can taken to reduce the flow rate and discharge of a river system, mainly focusing on reducing runoff (NRC 1992 & 1999, Baer & Pringle 2000, Wissmar & Bisson 2003). In order to reduce runoff there are a variety of environmentally conscious construction methods that can be applied. The use of rooftop gardens and other rain catchments, permeable asphalt, and minimal impact building plans, all of which are focused on preventing precipitation from running off and allowing it to percolate into the soil (NRC 1992 & 1999). One of the most effective ways to reduce damage from flood events is to conserve existing wetlands and floodplains and to restore ones that have been damaged by the encroachment of development (NRC 1992 & 1999, Baer & Pringle 2000, Wissmar & Bisson 2003). This may involve the relocation of populations living in the floodplain and in areas that were historically wetlands. The wetlands and floodplains will not only reduce river discharge and flow, but will also act to provide a buffer for floodwaters and will create habitat for a variety of aquatic and bird species (NRC 1992 & 1999, Wissmar & Bisson 2003). Wetlands also help to capture and filter out pollutants before reaching a river, improving the overall health of the drainage system (NRC 1992 & 1999, Wissmar & Bisson 2003). Studies show that the application of these techniques throughout a watershed may help to
restore its drainage system to its natural, pre-urbanized condition (NRC 1992 & 1999, Wissmar & Bisson 2003). The implications of doing this include a reduction in the intensity and frequency of flood event and the damages that result from their occurrence and an improvement in the ecological health of the watershed’s aquatic ecosystems (NRC 1992 & 1999, Baer & Pringle 2000, Wissmar & Bisson 2003).

**Summary and Conclusion**

It is essential for management agencies to understand how patterns of population distribution and its associated pattern of development impacts a watershed’s hydrology in order to facilitate efforts to restore and preserve the watershed’s pre-urbanized condition (NRC 1992 & 1999). An ultimate goal is to reduce the occurrence of flood events and the damage caused by them and to restore the health of the watershed’s aquatic ecosystems. The use of population density in this model as a proxy for percent impervious cover when land cover data is unavailable provides a robust approach for revealing how variations in level of development impacts watershed hydrology. This model may be applied to watersheds similar to the Des Plaines for the use of management agencies. Future studies can be done to analyze the viability of applying this model to watersheds with varying climates, landscapes, and patterns of population distribution.
Citations


Appendix

Appendix 1: Map of Des Plaines River Watershed (outlined in black) showing population density in persons per square mile by census tract in 1940.
Appendix 2: Map of Des Plaines River Watershed (outlined in black) showing population density in persons per square mile by census tract in 1950.
Appendix 3: Map of Des Plaines River Watershed (outlined in black) showing population density in persons per square mile by census tract in 1960.
Appendix 4: Map of Des Plaines River Watershed (outlined in black) showing population density in persons per square mile by census tract in 1970.
Appendix 5: Map of Des Plaines River Watershed (outlined in black) showing population density in persons per square mile by census tract in 1980.
Appendix 6: Map of Des Plaines River Watershed (outlined in black) showing population density in persons per square mile by census tract in 1990.
Appendix 7: Map of Des Plaines River Watershed (outlined in black) showing population density in persons per square mile by census tract in 2000.
Appendix 8: Map of Des Plaines River Watershed (outlined in black) showing population density in persons per square mile by census tract in 2010.
Appendix 9: Map showing the land cover types and level of development of Des Plaines River Watershed (outlined in black) in 1992.
Appendix 10: Map showing the land cover types and level of development of Des Plaines River Watershed (outlined in black) in 2001.
Appendix 11: Map showing the land cover types and level of development of Des Plaines River Watershed (outlined in black) in 2006.
Appendix 13: Map showing permeability rating of land cover of the Des Plaines River Watershed (outlined in black) in 2061.
Appendix 14: Map showing the change in permeability rating of land cover of the Des Plaines River Watershed (outlined in black) from 2001 to 2006.