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Subbasin Characteristics and Hydrological Response to Anticipated Urbanisation

Woonsup Choi*

Abstract : This study investigated the relationship between the hydrological response of a river basin to anticipated urbanisation and its subbasin characteristics by applying a hydrological model (HSPF) with land use scenarios generated by an urban growth model (LEAM). The hydrological model was set up and run for the Kishwaukee River basin in northeastern Illinois, USA. The results show that the subbasin size and imperviousness were found to be more correlated to runoff changes than slope. However, no basin characteristics have significant relationships with percent changes in any hydrological variables due largely to the effects of upstream subbasins. When the effects of upstream subbasins are excluded, it becomes clear that the subbasin size is negatively correlated with percent changes in total runoff, storm flow and peak flow. The percent change in impervious land is positively related to the percent changes in storm flow and peak flow, but the relationship itself is dependent on the initial imperviousness level. The geographical pattern of the basin response implies that it requires more targeted measures to mitigate negative hydrological impacts.

Key Words : hydrological model; urbanisation; HSPF; LEAM; runoff

I. Introduction

Urbanisation is defined in hydrologic terms as the increase in impervious areas and the loss of vegetation (Dow and DeWalle, 2000). Urbanisation of a watershed has impacts on the local and regional hydrology and ecology, as the presence of impervious surfaces and the reduction of vegetation in a basin may impact the generation of runoff and subsurface flow in various ways (Ferguson, 1996; Valeo and Moin, 2000). Therefore, it is imperative that new development plans take into account the cumulative impacts of development processes on hydrology and ecology.

There have been numerous studies linking urbanisation and hydrology. It is well known that urbanisation within a basin tends to increase peak streamflow, to decrease the time of concentration, and to increase runoff volume (Campana and Tucci, 2001; De Roo *et al*., 2003). Similar results were obtained in many other regions around the world (Ismail, 1997; Brenner *et al*., 1999; Braune and Wood, 1999; Lange *et al*., 2001; Rose and Peters, 2001; Cheng and Wang, 2002; Jennings and Jarnagin, 2002). With respect to base flow, there are different arguments. White and Greer (2006) found significant increase in annual minimum and median discharges and dry-season total runoff. On the other hand, Brun and Band (2000) found an exponential decrease in base flow, and Rose and Peters (2001) also found a negative relationship between urbanisation and low flow and groundwater level.

This article investigates the hydrological response of a river basin to anticipated urbanisation focusing on the spatial variation by subbasin. Considering the findings in the literature, it is concluded that there

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are needs for subbasin scale modeling and quantitative analysis on the relationships between hydrological changes and subbasin characteristics. This study utilised the output from a conceptual hydrological model previously applied to a meso-scale river basin in the Midwestern U.S. to find out how the impacts will occur in subbasins and how they are related to subbasin characteristics.

II. Methods

1. The Kishwaukee River Basin

The Kishwaukee River Basin (KRB) in northern Illinois and southern Wisconsin (Figure 1) was selected for case study. It is located between Rockford and Chicago Metropolitan Areas, which are 'creeping' eastward and westward respectively (Warner, 2003). The KRB is mainly an agricultural watershed, with raw crops (mostly corns and soybeans) covering more than 70 percent of the KRB (U.S. Geological Survey, 2004). Local people utilise the Kishwaukee River system for recreation activities such as fishing and canoeing.

The 1971-2000 climate normal for Rockford, Illinois (National Weather Service Cooperative Station ID 117382) indicates that the mean annual precipitation is 930mm, and the mean annual temperature is 8.9°C. The mean temperature falls below 0°C in December, January and February and rises above 20°C in June, July and August. The mean annual runoff during the same period measured at the hydromeric station USGS 05440000 Kishwaukee River near Perryville, Illinois is 303mm, which is about 1/3 of the annual precipitation. Mean monthly runoff is the highest in March with 38mm and the lowest in September 12mm.

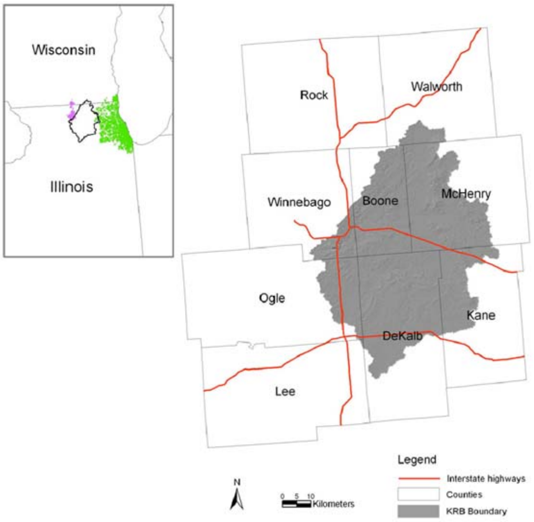

Figure 1. Location of the Kishwaukee River basin along with Metropolitan Chicago (right) and Rockford (left) Areas in the inset map

2. Hydrological modeling

This study used the output from hydrological modeling conducted for another study (Choi and Deal, 2008) where detailed descriptions are available about the hydrological modeling procedure. Only a summary is provided in this section.

Better Assessment Science Integrating Point and Nonpoint Sources or BASINS (U.S. Environmental Protection Agency, 2001) was utilised to delineate subbasins of the KRB and calculate related parameters. BASINS delineated twenty subbasins using the digital elevation model from the National Elevation Dataset (U.S. Geological Survey, 2005) and the hydrography data from the National Hydrography Dataset (U.S. Geological Survey, 2006) (Figure 2).

The streamflow of the KRB was simulated by the Hydrologic Simulation Program - Fortran or HSPF (Bicknell *et al*., 2001). HSPF requires eight meteorological time series data sets at an hourly time step including precipitation, air temperature and evaporation. The data measured at Rockford were used for

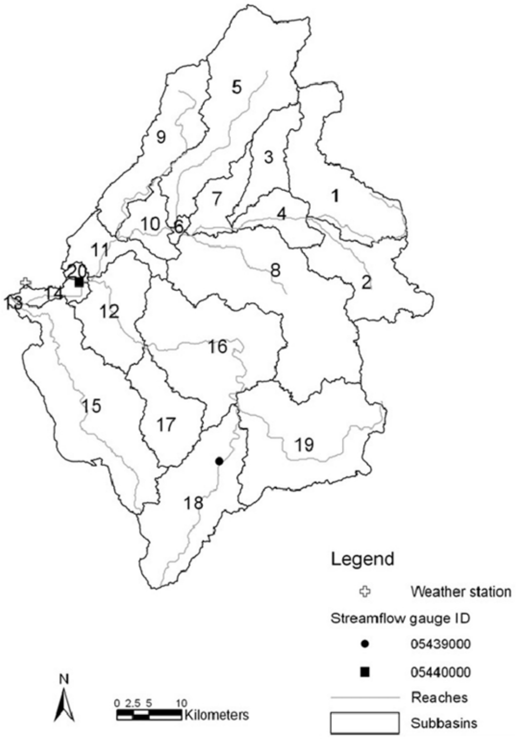

Figure 2. Delineated subbasins of the KRB, weather station, and hydrometric stations

this study. Three major outputs from HSPF are surface runoff (SURO), interflow (IFWO), and active groundwater flow (AGWO). IFWO is equivalent to subsurface flow in some other models which occurs with storms.

The HSPF model was set up and calibrated against the measured streamflow data from two locations (Table 1). The period 1988-1989 was selected for calibration and 1993-1994 for validation. Relative error was under 10% except for the station 05439000 for the calibration period (12.4%). Nash-Sutcliffe Efficiency values for daily streamflow series were over 0.8 for both periods for the station 05440000. Overall model performance was satisfactory (Choi and Deal, 2008).

3. Urbanisation scenario

The same urbanisation scenarios as in Choi and Deal (2008) were used in this study. They were generated from the Land use Evolution and impact Assessment Model (LEAM), which was developed to simulate land use conversions to low-density residential, commercial/industrial, and open space in large areas (e.g. several counties) at a high resolution (30m × 30m). Complete description about LEAM is available elsewhere (Deal, 2001 and Deal and Schunk, 2004).

LEAM was applied to the eight counties touched by the KRB. Depending on population growth projections, LEAM projected different magnitudes of urbanisation in the region. The different LEAM results are denoted as ‘Uber,’ ‘High,’ and ‘Base’ scenarios respectively. The Base scenario assumes a reasonable growth in population as projected by the U.S. Census Bureau, while the Uber scenario is a very extreme and unlikely growth scenario.

Figure 3 shows where new developments are likely to occur under the Uber scenario by 2051. Most developments are projected to occur in the western and southern part of the KRB. However, majority of the developments in the eight county region are pro-

Table 1. Selected hydrometric and weather stations in the studied region

Station name	Type (ID)	Location	Elevation (meter a.s.l.*)
Rockford Greater Rockford Airport	Weather (117382)	42°12’N / 89°06’W	222.5
Kishwaukee River near Perryville, IL	Hydrometric (05440000)	42°11’40”N/ 88°59’55”W	211.0
South Branch Kishwaukee River at DeKalb, IL	Hydrometric (05439000)	41°55’52”N/ 88°45’34”W	253.6

* a.s.l.: above sea level

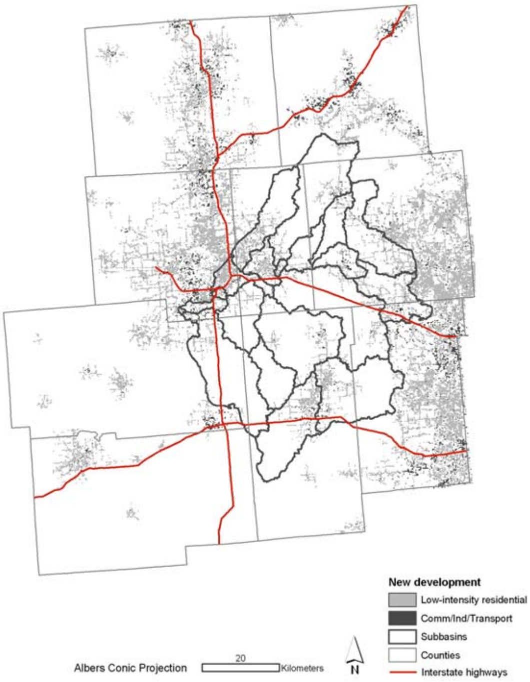

Figure 3. New urban developments in and around the KRB under the Uber scenario

jected to occur just outside the KRB, and much less development is projected under the Base and High scenarios (not shown). The urban areas (low-density residential, high-density residential, commercial/industrial, and road) currently occupy 2.9% of the KRB and they are projected to grow to 6% by 2051 under the Uber scenario. Therefore, the overall magnitude of urbanisation in the region is not large, but there is some spatial variation.

III. Results

The HSPF model was run for the current condition and with different urbanisation scenarios (Base, High and Uber), respectively. The impacts on several hydrological variables are visualised as maps, and a correlation analysis is conducted between hydrological variables and subbasin characteristics. The results only from the Uber scenario are presented in this paper because the changes due to the Base and High scenarios are too minute (Choi and Deal, 2008).

1. Hydrological response in each subbasin

The subbasin-scale hydrological responses to urbanisation are presented in Figure 4 through Figure 8. Selected cities and interstate highways are also displayed for geographical reference. Figure 4, Figure 5, and Figure 7 show that the largest increases in annual mean streamflow, annual storm flow (SURO + IFWO), and annual peak flow would occur in northeastern and northwestern subbasins. The subbasin where DeKalb is located is also projected to have large increases in those variables. It can be inferred from Figure 3 that the subbasins with large increases in those hydrological variables are related to the location of new developments. However, it should be noted that the magnitudes of changes are very different among the variables. The annual mean streamflow is projected to change by up to 3.11%, while the storm flow is projected to change by up to 18%.

Figure 6 shows the geographical pattern of the percent changes in base flow. It looks opposite to Figure 5, but actually is similar since smaller absolute changes are shown darker. Base flow is projected to decrease more where storm flow is projected to increase more, but the percent changes are very small, primarily because of its large proportion in total streamflow. The pattern in the percent changes in annual minimum flow shown in Figure 8 is somewhat different from others. The change is generally larger in subbasins in the central part and smaller or negative in some outer subbasins. The magnitude of changes is also very minute.

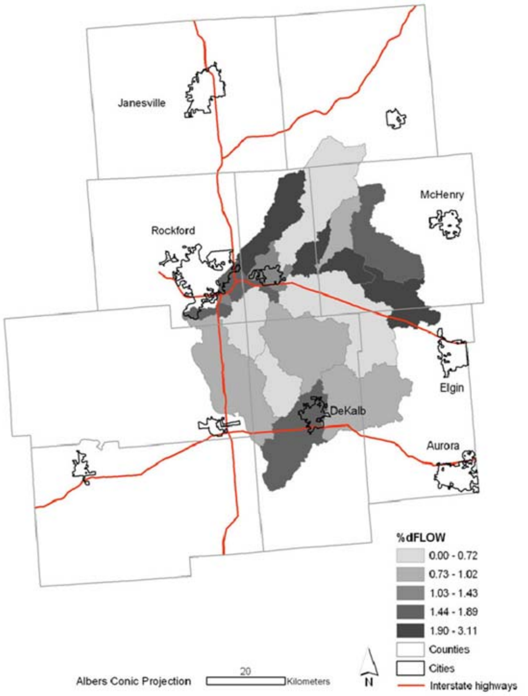

Figure 4. HSPF projected changes in annual mean flow in each subbasin by 2051 under Uber scenario

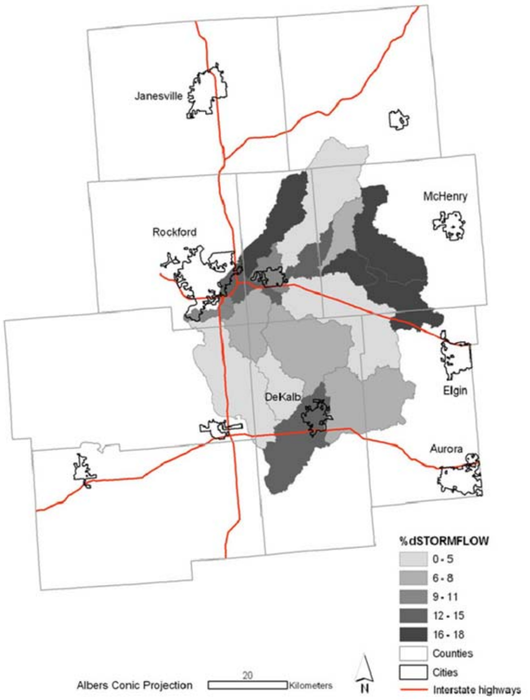

Figure 5. Same as Figure 4 but for annual storm flow

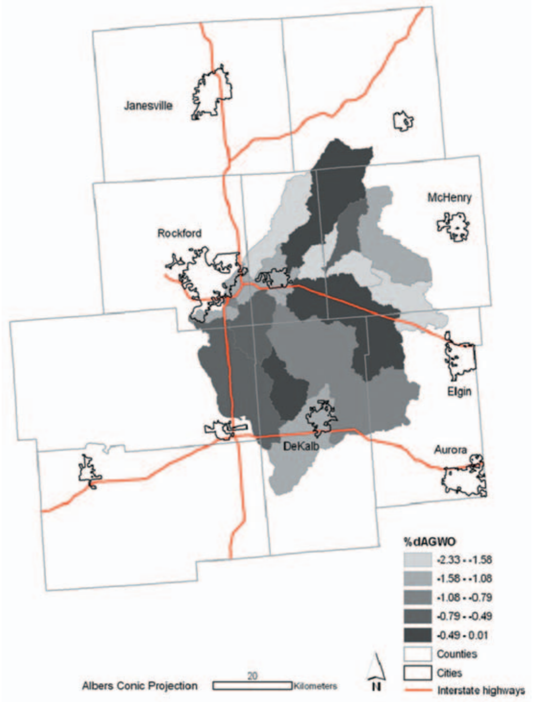

Figure 6. Same as Figure 4 but for annual base flow (AGWO)

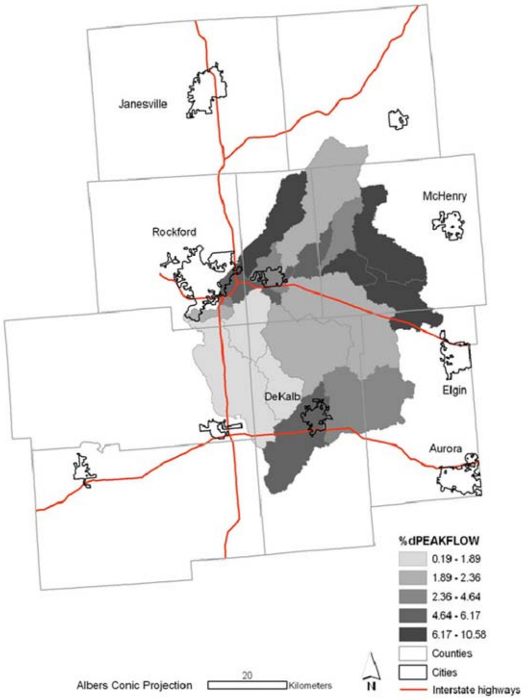

Figure 7. Same as Figure 4 but for annual peak flow

Table 2. Correlation coefficients between basin characteristics and projected percent changes in hydrological variables under Uber scenario. Here %dIMPLND denotes percent change in impervious land

		% dIMPLND	Slope	Length	Area
% change in storm flow	Pearson Correlation Sig. (2-tailed)	.068 .775	.151 .524	-.293 .210	-.386 .093
% change in total runoff	Pearson Correlation Sig. (2-tailed)	.051 .832	.132 .579	-.268 .252	-.351 .129
% change in AGWO	Pearson Correlation Sig. (2-tailed)	-.015 .950	-.082 .730	.233 .323	.327 .160
% change in peak flow	Pearson Correlation Sig. (2-tailed)	-.125 .601	-.105 .661	-.064 .788	-.175 .460
% change in minflow	Pearson Correlation Sig. (2-tailed)	.071 .766	.122 .608	-.288 .219	-.249 .289

2. Correlation between hydrological variables and subbasin characteristics

A correlation analysis was performed for all the subbasins (n = 20) between variables indicating basin characteristics and percent changes in selected hydrological variables. The basin characteristics include percent change in impervious land (%dIMPLND), mean slope (slope), overland path length (length) and basin area (area), and the hydrological variables include storm flow, total runoff, AGWO, annual peak flow, and annual minimum flow (minflow).

The results presented in Table 2 demonstrate that no basin characteristics have significant relationships with percent changes in any hydrological variables. Area is the only variable correlated with percent change in storm flow with significance level less than 0.1 (0.093). One of the reasons for such low correlation coefficients is that hydrological variables in each subbasin include the results of hydrological processes in upstream subbasins. As can be seen in Figure 4 through Figure 7, large percent changes tend to occur in the fringe of the KRB rather in the middle. Nevertheless, one can see that area and length are more correlated with hydrological changes than slope and %dIMPLND, which means that larger or longer subbasins tend to show smaller percent increases in storm and total runoff under future urbanisation.

To remove the effects of upstream subbasins, several subbasins without upstream subbasins were chosen. They are Subbasins 1, 2, 5, 8, 9, 15, 18 and 19 (see Figure 2). Scatterplots between the variables in Table 2 except length and percent changes in hydrological variables were examined for those subbasins. Correlation analysis was not performed since the number of cases is too small. The scatterplots are shown in Figure 9 through Figure 11, where ordinates are for percent changes in hydrological variables and abscissas for subbasin characteristics.

It is clear that subbasin area is negatively correlated with percent changes in total runoff, storm flow and peak flow (Figure 9). Percent change in base flow seems to be positively correlated with area, which means base flow decreases (not increases) more in terms of percentage in smaller subbasins with urbanisation. It is hard to find any relationship between percent changes in the hydrological variables and slope (Figure 10). It might be due to the fact that the variation in slope is too small in the KRB. Percent changes in total runoff, storm flow and peak flow tend to increase with %dIMPLND

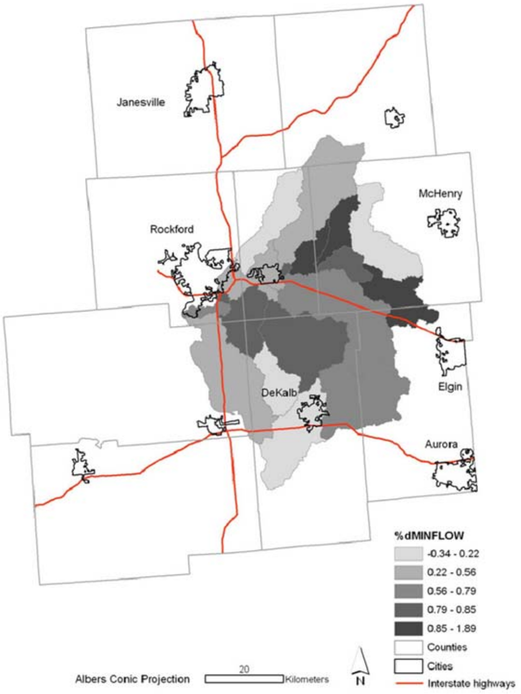

Figure 8. Same as Figure 4 but for annual minimum flow (minflow)

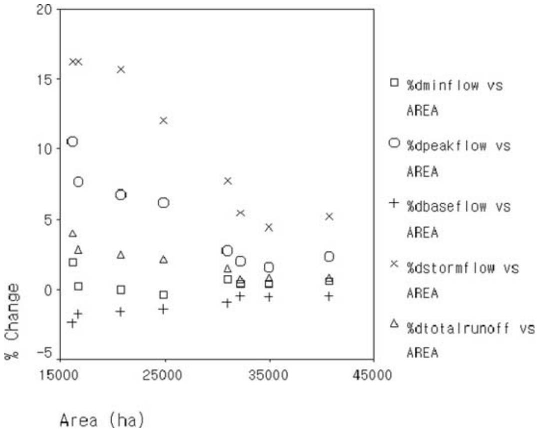

Figure 9. Relationship of subbasin area and percent changes in selected hydrological variables under Uber scenario

(Figure 11). Overall, the results with regard to area and %d IMPLND look reasonable.

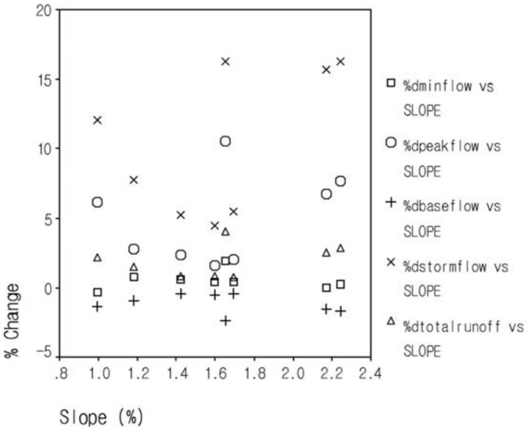

Figure 10. Relationship of subbasin slope and percent changes in selected hydrological variables under Uber scenario

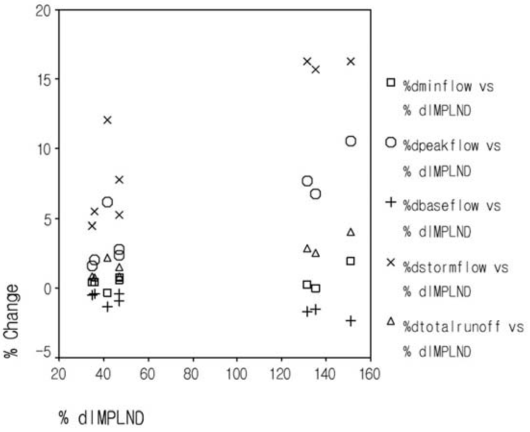

Figure 11. Relationship of percent changes in subbasin imperviousness (%dIMPLND) and percent changes in selected hydrological variables under Uber scenario

IV. Discussion

The results from the subbasin-scale analysis are generally in agreement with other studies. Chang (2003) finds smaller effects of urbanisation on larger subbasins of the Conestoga River Basin in Pennsylvania. Kletti and Stefan (1997) mention that the basin area has been the most important basin topographic parameter in predicting runoff in the literature, and Drogue *et al*. (2004) identify drainage area as one of the variables that explain the changes in hydrological variables. With respect to slope, there are different arguments among researchers. Rose and Peters (2001) find a positive relationship between runoff ratio and relief in several basins in Georgia. Slope is one of six landscape attributes chosen by Post and Jakeman (1996) to predict daily streamflow of ungauged basins in Australia, and it significantly improved the regression model's ability to predict the representative runoff response (Arthur-Hartranft *et al*., 2003). On the other hand, McKillop *et al*. (1999) argue that traditional hydrologic parameterisations involving slope are probably not significant at wetland sites. In this study, the scatterplot shows no correlation with slope, probably due to its little variation. Subbasin 14 has the highest mean slope (3.93%), and there are only two subbasins with mean slope higher than 3% (Subbasins 14 and 20).

The subbasin-scale analysis also provides insight to which area would be most subject to the impacts. According to the LEAM simulation, the City of Rockford is projected to expand southeastward in Subbasins 9 and 11, and the City of DeKalb northeastward in Subbasin 19. Urban development will also encroach on eastern subbasins (1 and 2) from the east of the KRB. Such geographical patterns of development bring the need to redefining flood zones and reconsidering flood mitigation strategies in such areas using more detailed hydrological modeling.

The results in the scatterplots generally make sense, but Figure 11 brings some attention, which shows two distinctive groups along the abscissa. It is projected that subbasins in the right group (Subbasins 1, 2 and 9) would undergo more increase in total runoff, storm runoff and peak flow and more decrease in base flow than those in the left group (Subbasins 5, 8, 15 and 19). Subbasin 18 is somewhat exceptional since it is in the left group in terms of %IMPLND (42%) but the storm flow and peak flow are projected to increase as much as in the right group (the highest X mark and circle in the left group). LEAM projected that Subbasins 1, 2, and 9 would undergo much more development than Subbasins 5, 8, 15, 18 and 19. Impervious lands in Subbasins 1, 2 and 9 are projected to increase by 135%, 151%, and 131% respectively by 2051 under Uber scenario, while that in other subbasins no more than 50%. In Subbasin 18, the storm flow and peak flow are projected to increase as much as in Subbasins 1, 2 and 9, while its impervious land is projected to increase only 42%. The reason should be found from the uniqueness of Subbasin 18 that its 1992 imperviousness is 3.34% while that of other subbasins is no more than 1.6%, and its imperviousness would be still higher than any others in 2051. The result lets one infer that initial land conditions matter as well as their percent changes.

V. Conclusions

This study attempted to quantify the impacts of future urbanisation to the streamflow of the Kishwaukee River flowing in Illinois and Wisconsin by linking a dynamic urban growth model (LEAM) and a semi-distributed hydrology model (HSPF). The results indicate that the impacts are significant in some subbasins where substantial new developments are anticipated even though the impacts measured at the outlet of the KRB can be negligible.

When it comes to the relationship between subbasin characteristics and hydrological changes, only storm flow has a negative relationship with subbasin size significant at the 90% confidence level. No other hydrological changes are significantly correlated with any subbasin characteristic, partly due to the effect of upstream subbasins. A detailed examination on upstream subbasins indicates that the changes in storm flow and peak flow are strongly related to the initial imperviousness level. When the initial impervious level was very high compared to other subbasins, relatively small increases in impervious lands resulted in increases in storm flow and peak flow as large as in other subbasins with large increases in impervious lands.

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