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Investigating Urban Land Use Effects on Runoff by Using the Distributed Large Basin Runoff Model

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Abstract

Urbanization is a growing trend world wide and presents many significant challenges in watershed planning. Distributed operational hydrology models can assist decision-makers in understanding the effects of land use and urban development policies on large watersheds, including runoff quantity and quality. The National Oceanic and Atmospheric Administration's Great Lakes Environmental Research Laboratory (GLERL) has developed the Distributed Large Basin Runoff Model (DLBRM) as a large-scale model for the Great Lakes basin. This paper illustrates how the daily DLBRM may be used to model runoff impacts of urbanization. Urbanization trends within the Clinton watershed of Southeastern Michigan are discussed, including analysis of stationary stream flow trends of the watershed. Calibration issues regarding temporal parameter variability are also addressed followed by urbanization scenario simulations within the Clinton watershed.

Urbanization and Hydrologic Impact

Global urban population growth continues to outpace total population growth and, along with its corresponding development or urbanization, represents one of the greatest environmental and social challenges of this new century. Five billion people are currently predicted to live in urban areas by 2030, with smaller urban settlements of less than 500,000 absorbing most of the new growth (UNESA, 2004). This transformation of rural to urban land use will have significant impacts on surface water quantity and quality as evident in the hydrological literature (McClintock et al., 1995; Beighley and Moglen, 2002; Choi, et al., 2003). The Great Lakes Basin is a prime example of such impact, where several urban areas have developed along waterways now significantly altered from their pre-colonization conditions (Figure 1).

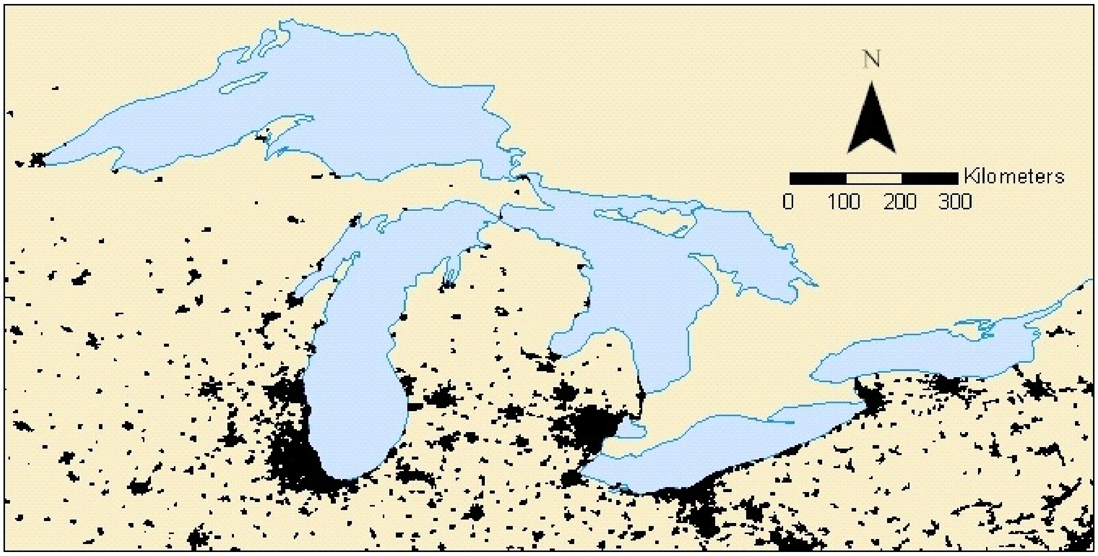

Figure 1. U.S. Urban Areas About the Great Lakes Basin (Data obtained from U.S. Census, 2000).

Urbanization impacts on water quantity/quality are well documented and include, among others, peak flow increases, non-stationary discharge signals, decreases in travel time, total runoff increases, base flow changes, non-point source runoff contamination, and sewage overflows. Extreme hydrological impact can be seen in many cities as they straighten, line, and/or cover urban streams in an effort to route flooding downstream, though these drastic alterations are becoming less favored by people willing to balance flood control with ecological benefits (Novotny et al., 2003). The prime physical cause of these impacts is an increase in impervious area within the watershed.

Impervious areas can be defined as areas in which all rainfall is converted to surface runoff, and are categorized into buildings (e.g. roof surfaces) and transportation infrastructure (e.g. roads, driveways, parking lots, etc.) (Schueler, 1994). Impervious areas related to transportation often have greater impact than rooftops, especially in highly automobile-dependent areas. Several studies have shown imperviousness to be directly related to urban runoff and pollutant loading, with effects being evident at levels as low as 10% impervious coverage (Schueler, 1994).

Gauging the impact of urbanization on watershed hydrology is now a primary concern of most communities facing these challenges. Many models and data sets have been developed to assist decision makers in mitigating these impacts, ranging from event-based, microscale models to macroscale models with large areas and timescales. Several studies have advocated the use of relatively simple, long-term models to initially assess hydrologic impacts of urban development, as the data is readily available, and the models are easy to use (Choi et al., 2003; Bhaduri et al., 2001). The use of long-term models is also seen as advantageous in assessing long term land use impacts, as the cumulative effects of smaller precipitation events may be more significant than large, single, storm events (McClintock et al., 1995).

The objective of this paper is to illustrate the ability of the Great Lakes Environmental Research Laboratory's Distributed Large Basin Runoff Model (DLBRM) to represent hydrologic impacts of urbanization. Following a trend analysis of watershed response, the first step is to calibrate the model parameters several times over a 50-year period and examine any trends in the spatially averaged parameter values. These trends should be consistent with urbanization impacts, such as decreases in infiltration and faster response times. The calibrations will be conducted on the Clinton watershed in Lower Michigan. Located near the Detroit metropolitan area, the Clinton watershed has experienced significant urbanization over the past few decades. The second step is to illustrate the effects of further urbanization scenarios.

Clinton Watershed Urbanization Trends

The Clinton watershed lies in Southeastern Michigan and drains into Lake St. Clair just north of Detroit. The counties within the watershed have seen substantial population growth over the last century, with some areas of the watershed experiencing over a 20-fold increase in population density (Figure 2). Associated with this increase in population density have come significant landscape alterations in the form of forest-to-agriculture conversion, property development, and urban infrastructure expansion. Figure 3 illustrates the extent of urbanization in the watershed represented by the DLBRM.

As watersheds become more urban, non-stationary trends emerge in the stream flow signal (Beighley and Moglen, 2002). Figure 4(a) shows the variation in the annual average daily stream flow and precipitation of the Clinton watershed over the past 7 decades, with the stream flow increasing over time under consistent rainfall condi-

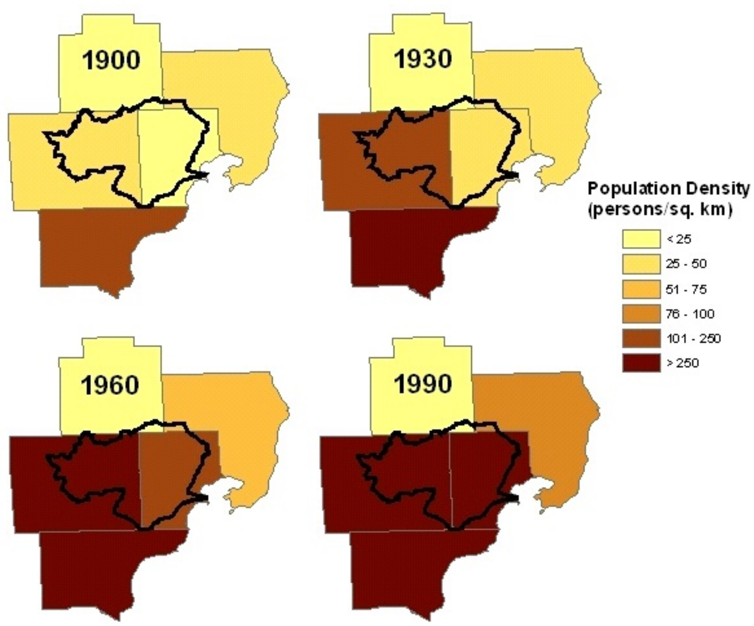

Figure 2. Population Density in the Clinton Watershed (Data obtained from U.S. Census, 2000).

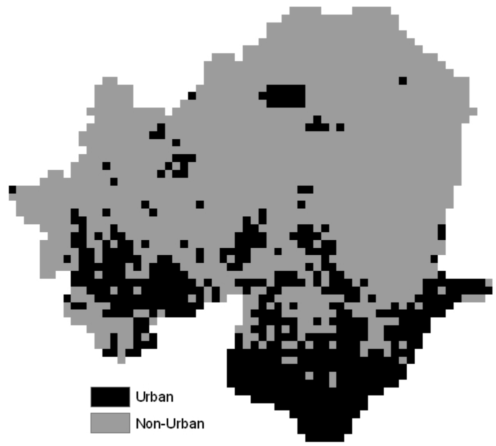

Figure 3. Urban Extent of Clinton Watershed in 1990 as Used in the DLBRM.

tions. This non-stationary trend could be a result of an urbanizing watershed as more rainfall is diverted to surface runoff due to increased imperviousness and storm water conveyance networks. Figure 4(b) illustrates another non-stationary trend in the annual maximum discharge data, which may at first be surprising. The maximum two-day precipitation occurring in the three-day window around the maximum discharge was used due to watershed response timing (Beighley and Moglen, 2002). This figure shows an opposite trend than Figure 4(a), with peak discharges decreasing over time relative to precipitation. Initial assumptions about this trend could be made regarding the building of flood control and retention infrastructure in urbanizing watersheds, which would diminish peak flows. More investigation into the urban history of the Clinton watershed needs to be completed to fully understand the mechanisms behind these non-stationary trends. Statistical tests also need to be completed to determine the significance of the stream flow trends.

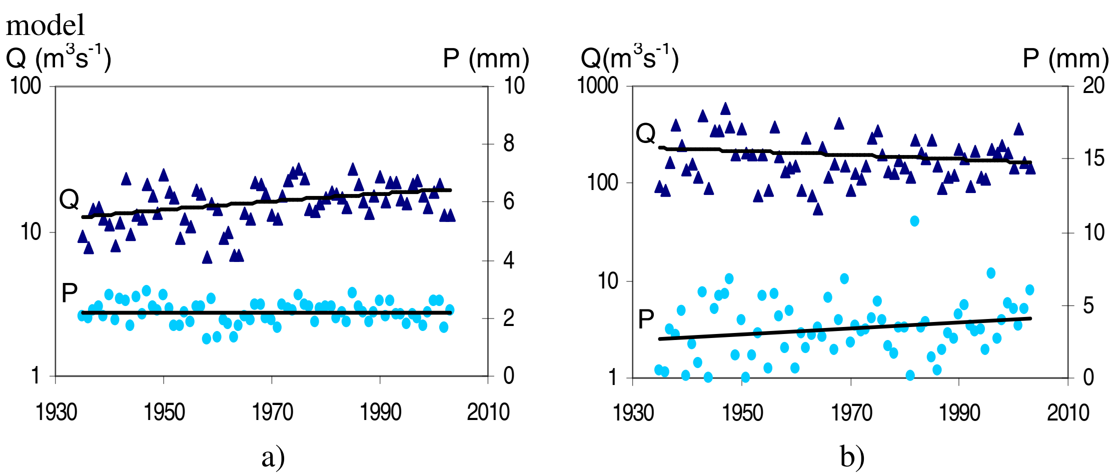

Figure 4. Trends in the Clinton Watershed: a) Annual Average Daily Stream Flow Q and Precipitation P, and b) Annual Maximum Discharge Q and Corresponding 2-Day Precipitation P.

Large Basin Runoff Model

The original Large Basin Runoff Model (LBRM), developed by NOAA's Great Lakes Environmental Research Laboratory, is a macroscale model created for operational use over large areas and time scales (Croley, 2002). The LBRM was intended to create a link between the research and operational communities and to help the Great Lakes Basin hydrology using readily available data. Recently, a distributed version of the LBRM has been developed, downscaling the macroscale model to 1-km^2 grid cells (Croley and He, 2005). The Distributed LBRM (DLBRM) continues to be a physically based tank cascade model (Figure 5), incorporating the major hydrologic components necessary to understand and explain land use impacts (Croley and He, 2005; Choi et al., 2003).

The calibration of the DLBRM involves changing the spatially averaged parameter values systematically to minimize the root-mean-square error between modeled and observed daily outflows (Croley et al., 2005). It was hypothesized that if a watershed experienced any significant alteration to its landscape (e.g. urbanization), then changes should occur in that watershed's spatially averaged parameter values in the DLBRM. To determine any trends in the parameter values, the DLBRM was calibrated several times, using 5- and 10-year intervals between 1950 to 2000. If urbani-

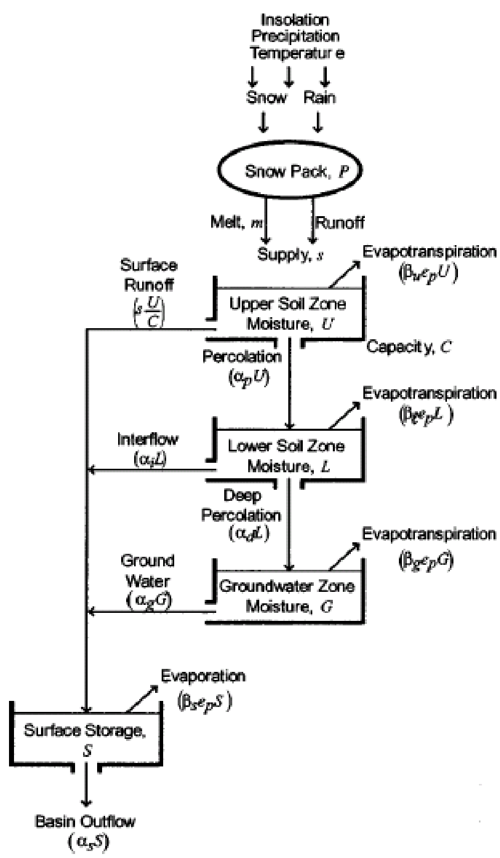

Figure 5. The Large Basin Runoff Model Tank Cascade (Croley and He, 2005).

zation were to affect the watershed parameter values, it was assumed these effects would be most apparent in the upper soil zone (USZ) parameters; therefore all other parameter values were held constant in most of the calibration runs.

Figure 6 shows spatial parameter trends in 10 year calibrations which examined these coefficients. The calibrated values in Figure 6 were determined in a calibration using the years of the preceding decade. Upward trends are evident in USZM/USZC, which is the ratio of the USZ moisture content to its capacity and determines runoff volume (Figure 5), and Surface Runoff/Net Supply, which is the ratio of surface runoff volume to net supply volume to the watershed surface. The trends, along with the downward trend in the spatial average percolation coefficient, indicate a faster and greater response in the USZ surface runoff, which may be due to urbanization impacts. Care must be used when interpreting these trends, however, as the calibration of the DLBRM produced non-unique parameter values. Any evident trends may be caused by parameters compensating for others within the calibration. There is also concern that most watersheds modeled by the DLBRM, including the Clinton, are relatively large and may not exhibit any watershed response to small changes in urbanization.

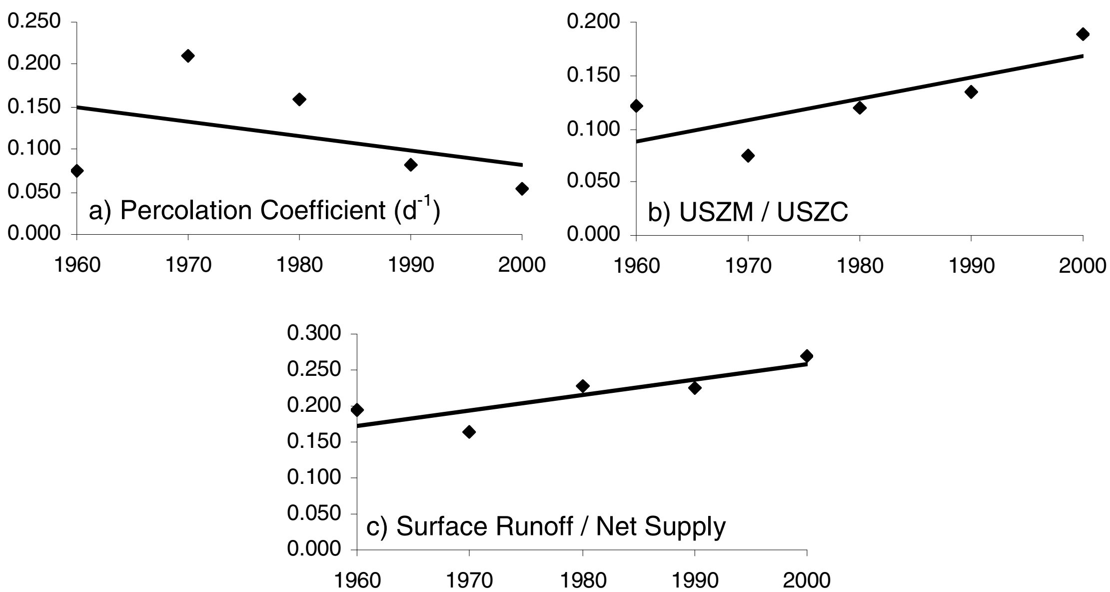

Figure 6. DLBRM Spatial Average Trends: a) Percolation Coefficient, b) USZ Content / Capacity Ratio, and c) Surface Runoff / Net Supply Ratio.

The DLBRM has the capability to model hydrologic impacts of land use by discretizing the watershed into a grid (1x1 km), with each grid having distinctive characteristics of soil, vegetation, topography, and land use, as determined by geographic databases (Croley et al., 2005). These databases are used to determine the slope, flow roughness, and depth and permeability of the upper and lower soil zones for each grid cell, which in turn are used to determine linear reservoir coefficients for each cell (Croley et al., 2005). To investigate the DLBRM's ability to model the hydrologic effects of urbanization, scenario maps of the Clinton watershed were constructed to simulate possible future levels of urbanization. It was assumed that future urbanization would occur around existing urbanized cells in an agricultural-to-urban transformation, and that these newly urbanized cells would take on the soil and roughness characteristics of the average residential cell. These particular urbanization scenarios resulted in little change in the model's outflow. One explanation for this lack of impact is that the watershed characteristics used in the model (i.e. Manning's roughness coefficient, slope, soil depths) may not represent urbanization impact as accurately as would using large percentages of imperviousness. The model would therefore not be very sensitive to urbanization changes in the watershed map. It is also a possibility that the directly urbanized cell parameters were not significantly altered to incur considerable outflow response changes. The watershed size and time step of the model could also moderate outflow and mask any flashy runoff responses resulting from large, but short-duration storm events, as typically seen in urban hydrology.

Discussion

It is clear that urbanization can strongly impact the hydrology of a watershed. The changes in soil characteristics, impervious cover, and channel alteration all have a part in these impacts. The Clinton River watershed in Southeastern Michigan has seen significant urbanization over the last century and may continue to see substantial landscape alterations in the future. Initial investigations into the historical stream flow response of the watershed indicate non-stationary trends in the watershed. Additional statistical analysis as well as investigations into the urbanization history and spatial extent of the watershed will yield more definitive conclusions into these non-stationary trends.

The distributed Large Basin Runoff Model is used to model the large watersheds associated with the Great Lakes Basin. It is a physically based, tank cascade model that uses land use, slope, and soil characteristics in determining model parameters. To reflect urbanization effects in the DLBRM, the model was recalibrated over different periods of the historical record to represent changing urbanization levels. Investigations into trends within the spatially averaged parameters as determined by the calibration procedure indicate that the changing watershed may exhibit increasing runoff parameter values over time. This highlights some inherent problems with using a calibrated model in a watershed that is experiencing significant alterations over time.

Land cover modifications (and consequently Manning's n) were also made directly to the discretized grid cells, representing increasing levels of urbanization. These scenario simulations, however, resulted in insignificant changes in the model output. Several reasons could exist for this lack of sensitivity, including the model's use of soil characteristics and slope in parameter determination, the values chosen to urbanize cells within the simulations, and the size of both the watershed and time step.

Suggestions for future investigations are to use the modified land use maps to recalibrate the model, and examine changes in the spatially averaged parameters as the land cover and soil characteristics of the watershed change. These calibrated parameter sets would then be used with the DBLRM to examine outflow responses. Additionally, performing these scenario simulations on smaller sub-basins of the watershed and/or using a smaller time step could result in significant output changes. Improvements in the DLBRM's capability of accurately modeling and predicting urbanization impacts on a watershed's hydrology, such as changing the upper soil zone capacity to reflect increases in imperviousness, will also be investigated.

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