REMOTE SENSING OF IMPERVIOUS SURFACE AREA FOR IMPROVED HYDROLOGIC MODELING

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ABSTRACT:

Impervious surface area (ISA), one of the consequences of urban development, has been used as an important indicator for environmental impacts of urbanization. In this study, we extracted ISA information for the state of Rhode Island, USA from 1-m spatial resolution true-color digital orthophotography data by an object-based classification. As the importance of ISA in the watersheds hydrology, we developed a distributed object-oriented rainfall-runoff simulation model (DORS) with incorporation of high spatial resolution ISA. The DORS model simulates hydrologic processes of precipitation interception, infiltration, evaporation and evapotranspiration, fluctuation of soil moisture and water table, runoff routing, ground water routing and channel flow routing. The model takes objects based on land cover data as the spatial units in order to reduce data volume, increase computational efficiency, strengthen representation of watersheds and utilize the data in variable scales. We validated the temporal variation of simulated discharge using measurements from USGS gage in a study watershed. The validation results indicate that the DORS model is capable of capturing the relationship between rainfall and runoff in the study area. The precise ISA information enhances the performance of the model simulation. Finally, we analyzed the relationship between watershed characteristics and hydrology pattern in selected watersheds with various levels of urbanization using spatial regression models. The result indicates that ISA plays important role in the change of watershed hydrology and the spatial autocorrelation in observations can not be neglected in the analysis.

1. INTRODUCTION

Increasing impervious surface area (ISA) resulted from urban and suburban development is a particularly important component of human-induced land-use and land-cover change (LULCC). ISA is a critical factor in cycling of terrestrial runoff and associated materials to and within ocean margin waters. Increasing ISA impacts watershed hydrology in terms of influencing the runoff and associated erosion and nonpoint pollutions (Arnold and Gibbons, 1996).

The answer of how increasing ISA influences environment, especially rainfall-runoff relationship, will provide valuable information in land management activities. Previous studies provided useful information about the impact of land cover change and increasing impervious surface on infiltration and runoff and validated the importance of ISA in hydrology (Arnold and Gibbons, 1996). In these studies, ground measurements of hydrology including peak and total discharge and laboratory rainfall simulation or different levels of urbanization using historical data were employed to explore the relationship between basin land-use and land-cover characteristics or difference of imperviousness and hydrologic response to precipitation (Warnemuende et al., 2003; Dougherty et al., 2007).

Although the methods were useful and effective in these studies, it was difficult to collect enough field measurements for these analyses. Other studies employed hydrologic modeling to quantify the impacts of LULCC on hydrological regimes at various scales (Brun and Band, 2000; Fohrer et al., 2001; Lee et al., 2003; Ott and Uhlenbrook, 2004; Wegehenkel et al., 2006). These studies designed land use change scenarios to study its impact on the various water balance components, utilized different levels of accuracy in estimation of DCIA to study its impact, or employed artificial watershed to study the impact of land use changes on water balance.

Hydrologic modeling is an effective method to evaluate the impact of ISA on watershed hydrology. The lumped, semi-distributed and distributed models were extensively used for their advantages. In terms of temporal and spatial change of parameters in hydrologic models, distributed models have advantages over lumped models because lumped models use aggregated and empirical parameters that lack clear physical meanings. Moreover, it is difficult to evaluate change of spatial parameters on hydrologic process based on lumped models (Kuchmenta et al., 1996). The distributed hydrologic models are promising because these models are based on physical, chemical and biological theories and the simulation results are more reliable. The performance of distributed model depends on their representation of watersheds.

Wegehenkel et al. (2006) found that a precise estimation of settlement areas in a catchment together with an improved estimation of the degree of actual imperviousness of these areas is a must for precise calculations of surface runoff and the flood peaks even in a rural catchment with a relative low amount of settlement areas. Lacking high spatial resolution ISA data, most of current hydrologic models used estimated ISA from land cover data or assigned values for specific land cover types (Ott and Uhlenbrook, 2004). However, as ISA is a key parameter in the runoff production and routing, using estimated percentage

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of ISA instead of precise ISA data may cause considerable errors in the hydrologic modeling.

After obtaining hydrology pattern from the simulation using hydrologic models, statistical regression is useful tool to quantify the relationship between ISA and hydrology pattern. However, the spatial dependence received less attention in the conventional regression methods because they assumed that observations were independent. Without the consideration of spatial dependence, these regression methods had errors in estimating regression coefficients, coefficient of determination and significance level. Spatial regression techniques with consideration of spatial autocorrelation have been extensively used in analyses of spatially explicit data (Ji and Peters, 2004; Anselin et al., 2006; Aguiar et al., 2007; Luck, 2007). In studies of spatial related phenomena, the consideration of spatial autocorrelation can improve the fitness of prediction models.

In this study, we developed a distributed object-oriented rainfall-runoff simulation (DORS) model with the incorporation of high spatial resolution ISA. We performed the analysis of hydrologic simulation in selected watersheds with various level of urbanization in the state of Rhode Island. We evaluated the relationship between watershed hydrology using ratio of runoff to base flow and variables of percentage of ISA, distance from ISA to stream and stream density based on regression analysis in watershed scale.

2. STUDY AREAS AND DATA

2.1 Study Areas

We delineated a watershed in Rhode Island with USGS discharge measurement at the outlet for model validation. The study watershed centers at 41.5^{0} N and 71.5^{0} W and lies on the border of three towns of Exeter, South Kingstown and North Kingstown (Figure 1). The elevation varies from 20-m to 90-m. There are about 10 soil types in the study area, and the main soil type is loam that has relatively medial value of porosity and hydraulic conductivity. The watershed includes typical land cover types in Rhode Island. This watershed is appropriate for our algorithm validation because of these characteristics.

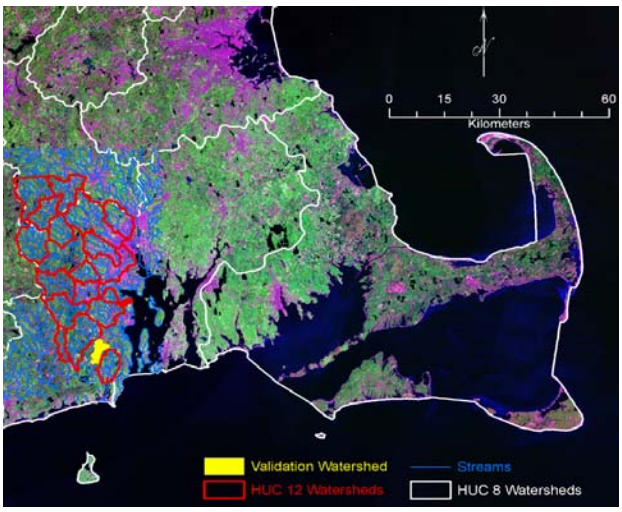

Figure 1. Validation watershed and 20 HUC-12 level study watersheds in Rhode Island

We select 20 HUC-12 level watersheds in Rhode Island (Figure 1). The study watersheds lie within HUC-8 level Blackstone River Watershed and Pawcatuck-Wood watershed between $41^{0}25^{'}$ to $42^{0}1^{'}$ northern latitude and $71^{0}20^{'}$ to $71^{0}47^{'}$ western longitude. The area of study watersheds range from 1500 ha to 13000 ha. The land cover types distribute heterogeneously in the study watersheds.

2.2 Data

The main data used in the DORS model include high spatial resolution ISA, DEM, land cover, vegetation index, soil type, and meteorological data. ISA is one of the most important factors impacting watershed hydrology, and it is the focus of this study. We extracted ISA information from the 1-m high spatial resolution Orthophoto using an object-based classification method (Zhou and Wang, 2008).

In the study watersheds percentages of ISA range from 0.03 to 0.29. The dynamic range of ISA percentage is enough to evaluate the impact of ISA on hydrology pattern. We extracted DEM from 1:100,000 USGS Hypsography Dataset 10 Meter Elevation Contour Lines and converted the vector data to 10-m spatial resolution grid. We obtained land cover data from the Landsat TM imagery at 30-m spatial resolution. We delineated flow network based on the DEM and NHD data. We derived soil type data from 1996 USDA/NRCS SSURGO data and employed the lookup table between soil types and soil prosperities to extract the soil parameters. We obtained Leaf Area Index (LAI) from vegetation index of simple ratio (SR) with the help of land cover data. We adapted the relationship between SR and LAI from Zhou et al. (2007) and modified it for Landsat TM with the adjustment coefficient. As the main purpose of this study is to evaluate the impact of ISA on watershed hydrology, this study excludes the impacts from other factors at most. Therefore, we used meteorological data including hourly precipitation, daily maximum, minimum and mean temperature, humidity, and radiation from one weather station.

3. METHODS

3.1 DORS Model

We adapted and modified algorithms from the distributed hydrologic models by Chen et al.(2005) and Wigmosta et al. (1994). These models processed the regular grids as spatial units and simulated the groundwater and overland water movement. For our application of rainfall-runoff study, we modified the algorithms for hydrologic processes in these grid-based models and developed a new model based on spatial units of objects and added important processes such as infiltration.

The hydrologic processes within an object in horizontal and vertical view are described in Figure 2. The horizontal boundary of the simulated area is a watershed delineated from the DEM. Vertically, the simulation extends from the saturated zone to the top of vegetation canopy. The model divides the study watershed into basic spatial units, objects, based on land cover and DEM data. Furthermore, the model splits the objects with large area into small ones to make the runoff and groundwater route more reasonably. The model treats each spatial unit as a unique vegetation-soil system.

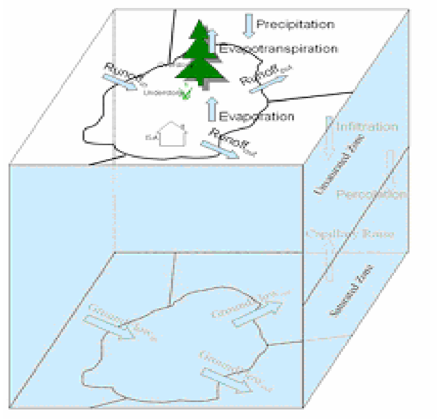

Figure 2. Hydrologic processes within an object

The model includes major components of segmentation, parameterization, interception, infiltration, evapotranspiration, saturated flow, overland flow, and channel flow. The parameters of precipitation, solar radiation, DEM, land cover, ISA, vegetation index, and soil properties parameters are major inputs to the DORS model. All input parameters are spatially transformed to object level after the segmentation process. Other accessorial parameters such as manning coefficient for runoff routing are determined based on land cover types. The major output is discharge at the outlet of watershed.

3.2 Watersheds Characteristics

This study focused on the impact of ISA on watershed hydrology. We used the indicator of percentage of ISA to describe the watersheds characteristics. In addition, this study included another two indicators of distance from ISA to stream and stream density to explain the variance in hydrology pattern in study watersheds. We retrieved percentage of ISA and distance from ISA to stream from the high spatial resolution ISA data. We derived all of indicators for each study watershed.

3.3 Regression Analysis

We employed regression models to analyze the hydrologic response to spatial configuration and percentage of ISA. Changes of hydrologic pattern are directly connected to the percentage of ISA in watershed. Because of the assumption of independent observations in conventional regression techniques, this study used spatial lag and spatial error regression models (Anselin et al., 2006) as well as ordinary linear square (OLS) regression model.

We performed the regression analysis using the response variable, ratio of runoff to base flow, and a set of predictor variables including percentage of ISA, distance from ISA to stream and stream density. The equations for OLS, spatial lag and spatial error regression models are described as:

$$R = \beta_0 + \beta_1(ISA) + \beta_2(Dist) + \beta_3(Stream) + \varepsilon \qquad (1)$$

where R is the ratio of runoff to base flow, β_0 is the intercept, β_1, β_2 and β_3 are regression coefficients for the predictor variables, and ε is random error, ISA is the percentage of ISA, $Dist$ is the distance from ISA to stream, and $Stream$ is the stream density.

$$R = \rho WR + \beta_0 + \beta_1(ISA) + \beta_2(Dist) + \beta_3(Stream) + \varepsilon \qquad (2)$$

where WR is a spatially lagged dependent variable for weights matrix W and ρ is parameter.

$$R = \beta_0 + \beta_1(ISA) + \beta_2(Dist) + \beta_3(Stream) + \varepsilon \qquad (3)$$
$$\varepsilon = \lambda W\varepsilon + u$$

where W is the spatial weights matrix, ε is a vector of spatially auto correlated error terms, u is a vector of i.i.d. errors, and λ is parameter.

4. RESULTS

4.1 Model Validation

Change pattern of discharge is a critical index indicating the watershed hydrology, and is mainly affected by runoff that has important impact on the materials movement and associate pollution in watershed. The simulated and measured daily discharges at the outlet from March 20 to April 28 in 1997 are shown in Figure 3. The result indicates that the model performs reasonably well in simulating discharge in study watershed. The simulated and the measured daily discharge show similar temporal patterns. Simulated and the measured mean daily discharges at the outlet over the 40-day period are 1.30m^3/day and 1.25m^3/day. Total relative variation R_v of the simulated and the measured daily discharges during the period of study is -4.4%. The ratio of absolute error R_a which is used by World Meteorological Organization is 9.4%. The Nash coefficient $R2$ is 0.998.

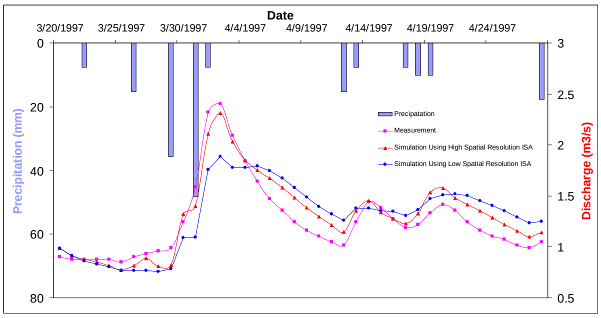

Figure 3. Simulated and measured discharge with and without high spatial resolution ISA in the study watershed

4.2 Regression Analysis

The result from the test of multi-collinearity indicates that the regression relationship between ratio of runoff to base flow, percentage of ISA and distance from ISA to stream has a lower score than that between ratio of runoff to base flow and percentage of ISA, distance from ISA to stream and stream density. Because of the possible spatial autocorrelation in measurements, we performed the diagnostics for spatial dependence. For the relationship between ratio of runoff to base flow and watershed characteristics, Moran's I score of 0.18 ($p<0.01$) is highly significant, indicating strong spatial autocorrelation of the residuals.

The comparison of three regression models between ratio of runoff to base flow and percentage of ISA, distance from ISA to stream and stream density is shown in Table 1, and the comparison of three regression models between ratio of runoff to base flow, percentage of ISA and distance from ISA to stream is shown in Table 2, and the comparison of three regression models between the ratio of runoff to base flow and percentage of ISA is shown in Table 3. The statistics analysis indicates that R^2 is 0.57, 0.56 and 0.31 respectively for OLS model. ISA can explain 31% variance in the observations, and the inclusion of distance from ISA to stream improves the explained variance. There is small difference in explained variance after the inclusion of stream density.

	OLS	Spatial Lag	Spatial Error
Constant	0.91^{*}	0.40	0.74^{**}
ISA	2.21^{***}	2.05^{***}	2.03^{***}
ISA Distance	-12.14	-9.23^{***}	-6.96^{**}
Stream Density	-0.52	-0.64	-0.39
R^2	0.57	0.73	0.70
AIC	-5.27	-10.96	-10.52

Table 1. The regression analysis between ratio of runoff to base flow and percentage of ISA, distance from ISA to stream, and stream density

	OLS	Spatial	Spatial Error
Constant	0.64^{***}	0.08	0.55^{***}
ISA	2.16^{***}	1.99^{***}	2.01^{***}
ISA Distance	-10.71^{***}	-7.54^{***}	-5.90^{**}
R^2	0.56	0.72	0.70
AIC	-6.87	-12.01	-12.14

Table 2. The regression analysis between ratio of runoff to base flow and percentage of ISA and distance from ISA to stream

	Ordinar	Spatial Lag	Spatial Error
Constant	0.52^{***}	-0.06	0.46^{***}
ISA	1.78^{*}	1.71^{***}	1.80^{***}
R^2	0.31	0.61	0.64
AIC	0.19	-7.04	-10.20

Table 3. The regression analysis between ratio of runoff to base flow and percentage of ISA

***, **, and * indicate 0.01, 0.05 and 0.1 significant levels.

The R^2 in spatial regression is a pseudo R^2, and it is not comparable with the measure in OLS regression. The pseudo R^2 serves as a rough estimate on explanatory power of the models. Compared with R^2, Akaike information criterion (AIC) is a more suitable performance measure for spatially correlated data. The model with the lowest AIC value is the best. According to AIC comparisons, the spatial regression models were generally superior to OLS in regression with different independents (Table 1, Table 2, and Table 3). The spatial error and lag models have similar performance.

With the comparisons between OLS and spatial regression models as well as the comparisons using different independent variables and the consideration of multi-collinearity, we selected spatial error model with percentage of ISA and distance from ISA to stream to analyze the relationship. Figure 4 illustrates the spatial error regression for the relationship between hydrology pattern and percentage of ISA and distance from ISA to stream. As expected, increases in percentage of ISA and/or decreases in distance from ISA to stream correspond to increases in ratio of runoff to base flow.

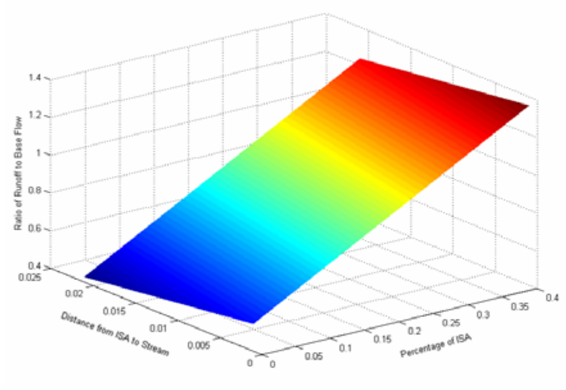

Figure 4. The relationship between ratio of runoff to base flow, percentage of ISA and distance from ISA to stream

5. DISCUSSIONS

5.1 Simulation without High Spatial Resolution ISA

In order to check the importance of high spatial resolution ISA in hydrologic modeling, we performed the simulation using the ISA derived from the Landsat land-cover data with 30-m spatial resolution. In the simulation, all other parameters except ISA were same as those in the simulation using high spatial resolution ISA. Figure 3 shows the simulation result using the land cover derived ISA in the study watershed. Total relative variation R_v, the ratio of absolute error R_a, and the Nash coefficient $R2$ are -3.7%, 16.4% and 0.995, respectively. The comparisons indicate the incorporation of high spatial resolution ISA improves the performance of simulation.

5.2 Relationship between ISA and Hydrology Pattern

Impervious surface increases runoff production and reduces the concentration time of surface runoff, therefore, changes the hydrology pattern in watershed. The change of hydrology pattern will bring the problems of soil erosion, water pollution and ecology degradation in streams. In all regression models, ISA has positive impact on the ratio of runoff to base flow. As spatial error model has the best fit for regression between the ratio of runoff to base flow and watershed characteristics, we used this model and the associated parameters to evaluate impact of ISA on hydrology pattern. The result indicates that increases in percentage of ISA and/or decreases in distance from ISA to stream correspond to increases in ratio of runoff to base flow. Compared with the spatial regression model, OLS model generally overestimates the coefficient of ISA in the relationship between hydrology pattern and percentage of ISA and distance from ISA to stream.

5.3 Other Factors Impacting Hydrology

The coefficient of determination in all regression models indicates that ISA explains important part of variance in hydrology pattern. This also implies that there are other factors contributing to the unexplained portion of the variance although percentage of ISA significantly impact hydrology pattern. In the regression analysis, the results indicate the inclusion of distance from ISA to stream increases the explained variance in hydrology pattern.

6. CONCLUSIONS

We developed a DORS model to simulate hydrologic processes at a watershed scale using spatial inputs of remote sensing data. This model combines three major sub-models which simulate surface runoff, groundwater and channel flow, and it has dynamic linkage between these sub-models. The model provides a framework to integrate remote sensing raw data and derived products in different scales for the simulation of hydrologic processes in a watershed, and the object-oriented algorithm reduces the simulation time and data volume. The complexity of the hydrologic models and their flexibility for representing spatial heterogeneity are important for simulation accuracy and model application. The simulation results indicate that the model performs well for the purpose of modeling the runoff and base flow in complex watersheds. The comparisons indicate the incorporation of high spatial resolution ISA improves the performance of simulation.

In this study, we analyzed the spatial autocorrelation in observations and compared 3 regression models in construction of relationship between hydrology pattern and predictor variables of ISA, distance from ISA to stream and stream density. Due to the existence of spatial autocorrelation in observations and best performance of spatial error regression model, we employed this model to explore relationship between hydrology pattern and predictor variables. We found that the percentage of ISA can explain important portion of variance in hydrology pattern although there are other factors impacting the hydrology pattern. This hydrologic model provides flexible tool to study the impact of complex practice of land management on watershed hydrology. The summarized relationship is useful for decision maker in land management and the method can also be extended to study other concerns in watershed hydrology with the extracted high spatial resolution ISA.

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