

## **DETERMINING THE EFFECTS OF VARIOUS LAND USES WITHIN MICHIGAN STATE UNIVERSITY'S WATERSHED ON WATER QUALITY IN THE RED CEDAR RIVER**

**S.P. MCELMURRY<sup>1</sup>, I. ASLAM<sup>1</sup>, A.U. SYED<sup>2</sup>, T.C. VOICE<sup>1</sup>, D.T. LONG<sup>3</sup>,  
M.S. PHANIKUMAR<sup>1</sup>, D.P. LUSCH<sup>4</sup>, and W.J. NORTHCOTT<sup>5</sup>**

<sup>1</sup>Department of Civil and Environmental Engineering, <sup>3</sup>Department of Geological Sciences, <sup>4</sup>Center for Remote Sensing and Geographic Information Science, <sup>5</sup>Department of Agricultural Engineering; Michigan State University; East Lansing, Michigan 48824 USA

<sup>2</sup>U.S. Geological Survey; 6520 Mercantile Way, Suite 5; Lansing, MI 48911 USA  
E-mail: [long@msu.edu](mailto:long@msu.edu)

### **EXTENDED ABSTRACT**

Traditionally, the influence of land use on the quality of surface and subsurface water is evaluated through studies of sub-watersheds or source sheds at the regional scale. These source sheds are typically quite heterogeneous, with wide variability in hydrologic characteristics, in land use activities, in the pollutant loads generated, and in the impacts on water quality. As a result, these large-scale watersheds require the use of broadly averaged hydrologic and chemical loading parameters. Thus, it is difficult to delineate specific cause-and-effect relationships necessary to efficiently achieve specific water quality goals through land-use management strategies. This problem becomes particularly acute in urban and suburban environments because of the very high density and wide diversity of small-scale land uses (e.g., roads, parking lots, buildings, landscaped zones and natural areas).

Working within the Michigan State University Red Cedar River Project (MSU Water [http://www.hydra.iwr.msu.edu/msu\\_ws/](http://www.hydra.iwr.msu.edu/msu_ws/)) we have developed an approach for understanding how specific land uses affect water quality using the MSU campus as a pilot study area. The foundation of our approach is to understand how water and chemicals are transported throughout the campus land area using a combination of deterministic and stochastic methods. Creating mathematical models of the hydrology present within the MSU campus involves delineating micro-watersheds, defined by topography and the storm sewer collection system, modeling the complex network of storm drains and outfalls, and accurately portraying the physical characteristics of the Red Cedar River (RCR). Once these models adequately describe water flow from the MSU campus and within the RCR, then chemical transport and transformations can be added to fully depict how chemical inputs from different land uses affect water quality.

Initial results of hydrologic dynamics and chemical sampling suggest detailed modeling and intensive sampling are required to accurately characterize this complex watershed. Ultimately, results from this project will aid in current and future land use planning issues, locally and regionally; provide a framework for designing watershed management plans, locally and nationally; and assist regulatory agencies to clarify and prioritize monitoring requirements aimed at improving watershed conditions.

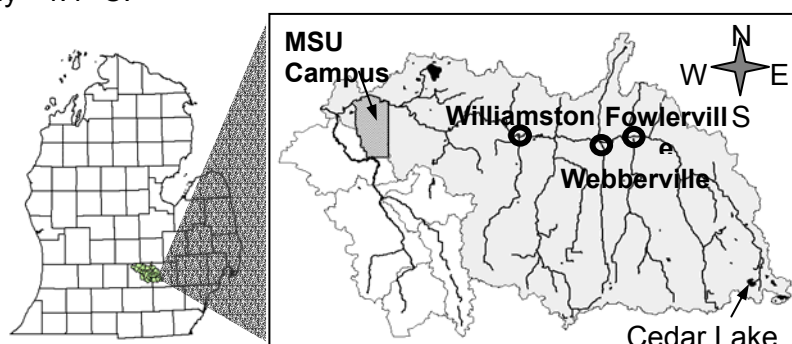
**Key words:** Urban storm water, land use, modeling, watersheds

## 1. INTRODUCTION

Understanding the effects of land use on water quality is based upon detailed understanding of connections between contaminant chemistry, watershed hydrology, and land use. The chemistry of the contaminant determines the potential hydrologic transport pathways for that chemical. For example, contaminants with low sorption coefficients can potentially be leached from soil into groundwater and moved within water columns (e.g., Cl). Transport for highly sorbed contaminants (e.g., PAHs) relies almost exclusively on sediment transport. Hydrology provides the mechanism for pollutant transport. Of prime importance, is determining the proportion of precipitation that becomes surface run-off. Finally, the land use itself determines the chemistry and hydrology of micro-watersheds and is capable of causing a variety of effects depending on the system. Land use is recognized as the single greatest factor in determining the what type of pollutants are released from the landscape and how they are transported [1].

The ultimate goal of this research is to model the transport of chemical and biologic pollutants introduced to surface waters by different land uses. In order to achieve this objective, it is first necessary to accurately describe the hydrologic characteristics of the watershed system. This includes describing sediment transport, due to the high proportion of constituents that are most likely sorbed to particulate matter. This paper highlights some of the initial steps taken while working towards this goal. Relevant observations and results are discussed pertaining to the application of a micro-watershed scale routing model including sewer transport, and the river hydrodynamic model. Initial chemical observations are also discussed in order to better define the system.

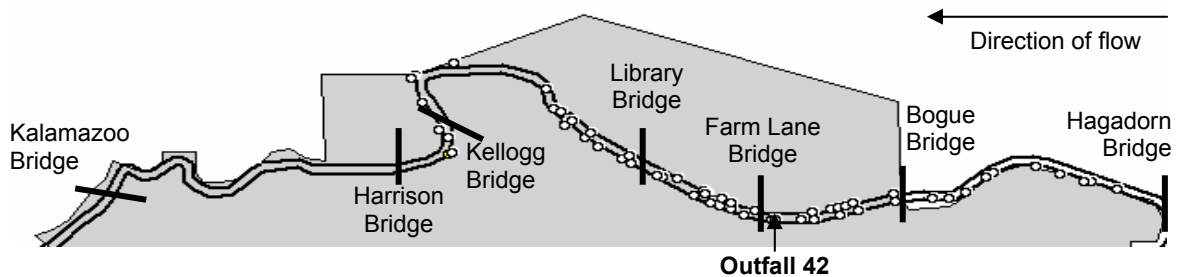
The Red Cedar River (RCR) is a warm-water stream in south central Michigan, U.S. It originates as an outflow from Cedar Lake, located in Marion Township, Michigan. The stream flows past the communities of Fowlerville, Webberville, Williamston and Okemos before entering the East Lansing and Michigan State University (Figure 1). It then connects with the Grand River in Lansing, Michigan (Ingham County). The total stream length is slightly greater than 70 km. The river and its tributaries drain an area of about 1,230 km<sup>2</sup>, one fourth of which is drained by Sycamore Creek, which enters the river downstream from MSU's campus. The river has an average gradient of approximately 0.5 m/km, with about one-half of this occurring within the uppermost third of the river. The river reach within MSU's campus has an average gradient of about 0.4 m/km. The elevation of Cedar Lake is about 285 m above sea level and the confluence of Cedar River with Grand River is at an elevation of 249 m above sea level. A U.S. Geologic Survey (USGS) gauging station is located at the southwest abutment of the Farm Lane Bridge (Figure 2). The gauge measures the runoff from about 75 % of the basin (919 km<sup>2</sup>). The mean annual temperature for the area is 8.2 °C, with a winter mean of approximately -4.4 °C.



**Figure 1:** The complete Red Cedar River watershed, including the Sycamore Creek watershed (white).

MSU's campus is slightly more than 22 km<sup>2</sup> in size. Land use within MSU's campus can be divided into 6 major categories: agricultural (46%), forested (9%), urban (36%), open fields (7%), wetlands (1%) and water (1%).

The RCR meanders through the campus of Michigan State University over a stretch of approximately 5 km (Figure 2). This section of river is unique due to numerous outfalls, also shown in Figure 2, that direct surface water runoff to the river from multiple types of land uses within the campus watershed. The nature of this runoff varies depending on the areas being drained by the outfall. The storm water may be from parking lots, walkways, lawns or agricultural farms, which enter the RCR at multiple points. The reach also offers a unique study area due to the number of bridges spanning the river, which makes sampling possible on at many points throughout campus. This allows the hydrodynamics and contaminant transport within the river to be studied over short distances.



**Figure 2:** The Red Cedar River as it passes through the northern portion of the MSU campus with outfalls (circles) and sampling locations (bridges) described.

## 2. METHODOLOGY

In order to describe contaminant transport it is necessary to develop a comprehensive understanding of many complex processes of chemical transport and transformation during various times within the overland and stream flow phases. The fate of a contaminant, after entering the naturally flowing surface waters is mainly controlled by physical and chemical mechanisms. The physical process can be split into various sub processes such as advection, dispersion, and diffusion and chemical processes such as sorption/desorption, transformation reactions, and volatilization. Although these processes are essentially three-dimensional in nature, their representation in mathematical terms can initially be described using a one-dimensional representation. The successful coupling of overland flow, sewer, and river models with chemical kinetics is essential to account for most, if not all, of the physical and chemical processes that undoubtedly occur within the system.

### 2.1. MICRO-WATERSHED ROUTING MODEL

For this project, the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) is being used as the overland flow routing model. Campus maps in AutoCAD format with a resolution of about 0.3 m contour interval were used for delineating the micro-scale watersheds. These micro-watersheds were developed base on sewer networks and the area that drained into the storm sewer network ultimately being discharged to a single outfall to the RCR. The sub-watershed for Outfall 42 was selected as the first outfall/watershed to be modeled and was divided into 145 micro-watersheds. Each micro-watershed represented a microwatershed contained its own defined input parameters such as slope, hydraulic length, SCS lag and curve number. The coordinates generated through the delineation of the Outfall-042 watershed were used as an input into HEC-HMS for independent micro-watersheds. The overland flow model was driven

by rain gauge data collected on campus from the MSU Agricultural Weather Office ([www.agweather.geo.msu.edu](http://www.agweather.geo.msu.edu)) and was calibrated using the flow data measured using an ISCO 4150 flow logger (Lincoln, Nebraska USA) installed at the outfall.

The Soil Conservation Service (SCS) method was used to create a BASINS (Better Assessment Science Integrating point and Nonpoint Sources) model for the Outfall 42 watershed with three antecedent soil moisture conditions. These basins were connected through a series of pipes, simulating the storm sewer network. There were a total of 244 pipe segments and 95 junctions in the Outfall 42 sub-watershed. Flows generated from runoff simulations were routed through the storm sewer network using the Kinematic Wave Method. Each pipe segment utilized an inflow hydrograph at the upstream section of the pipe and produced the routed outflow hydrograph at the downstream end of the pipe. The model adds flow generated from microwatersheds as it travels towards the outfall which discharges into the RCR. A five-minute interval, 2-hour precipitation data for October 4, 2002 was used to simulate a precipitation event the watershed discharged from Outfall 42. The computed unit hydrograph, generated using the SCS method for the October 4 rain event, was calibrated against the Unit hydrograph generated from the observed hydrograph (direct runoff hydrograph). Since the Outfall 42 watershed is mainly in an urban setting with a large impervious area, it was assumed that no base flow contributed to the outlet discharge from the watershed.

The effects of model complexity were also studied by comparing the simulation results from a lumped parameters model and an event based semi-distributed parameter model the Outfall 42 watershed. In the lumped parameter model, the complete sub-watershed for Outfall 42 was assigned a single set of parameters to include curve number, SCS lag, initial abstraction, hydraulic length and slope.

## **2.2. RIVER HYDRODYNAMIC MODEL**

Hydrodynamic models are deterministic in nature but range considerably in complexity and level of mathematical sophistication. A hydrodynamic model can be a simple one-dimensional model with vertical and lateral averaging and on the other hand, can also be a complex three-dimensional model taking into account the lateral and vertical variations. The majority of these models, whether one, two or three-dimensional, rely on the numerical solution of the basic hydrodynamic equations of flow and continuity, commonly known as St. Venant (or shallow water) wave propagation equations [2].

The U.S. Environmental Protection Agency's DYNHYD model was used as the in-stream hydrodynamic model with an ultimate aim of driving the Water Quality Analysis Simulation Program (WASP) model. The model framework for the in-stream hydrodynamic model was built using bathymetry described in flood insurance data. The entire length of the river in the study section was divided into 102 segments. A 50 m segment length was used to conform to the computational stability criteria commonly known as the Courant condition. The head, velocity and discharge were measured from April 4-11, 2002 at the two intermediate stations, the Library and Kellogg bridges, using standard USGS equipment and were used to calibrate the model. The mid-section method [3] was used to calculate the cross-sectional areas and discharges. The model was checked for numerical stability by using various combinations of space and time discretizations.

Dispersion results from the mechanical mixing of substances as they advance downstream. Mixing takes place vertically, transversely and longitudinally. Once the cross-sectional mixing is complete, the process of longitudinal dispersion is the most important mechanism, erasing all longitudinal concentration gradients [4]. Therefore in order to apply any model for the prediction of concentrations at a distance downstream

from the point of discharge, selection of a proper dispersion coefficient is most a important and difficult task [5]. Three tracer tests were conducted for different flow conditions ranging from approximately 14 to 19 m<sup>3</sup>/sec. Dye was released in the middle 75% of the channel width to ensure nearly instantaneous horizontal mixing. Extensive sampling was conducted at the three sampling points at the middle of the cross section during these tests, in which the flow were 16.8, 14.4 and 19.1 m<sup>3</sup>/sec. A fluorescein solution (179 g/l) was used for in all tracer tests. The volume of the dye used varied each time based on a desired peak concentration range of 10-20 µg/l at the last sampling point located at a distance of 5.1 km from the release point.

### **2.3. CHEMICAL INVESTIGATION**

Limited chemical sampling was conducted to better define the water quality within MSU's watershed system. Samples were collected during different types of flow events, at different locations and were analyzed for different parameters. Some of the parameters sampled for include: anions (Cl, Br, NO<sub>3</sub>, PO<sub>4</sub> and SO<sub>4</sub>), cations (Ca, Mg, K, Na), total inorganic carbon (TIC), total organic carbon (TOC) and total suspended solids (TSS), dissolved oxygen (DO), pH, conductivity, water temperature and turbidity. Between three and six sets of sampling data were collected where the RCR enters and exits campus on the same day. These sampling dates were collected in spring (Jan. 29, Feb. 6 & 9, 2002), summer (June 6, 2002- base flow conditions) and fall (Oct. 11 & 19, 2001).

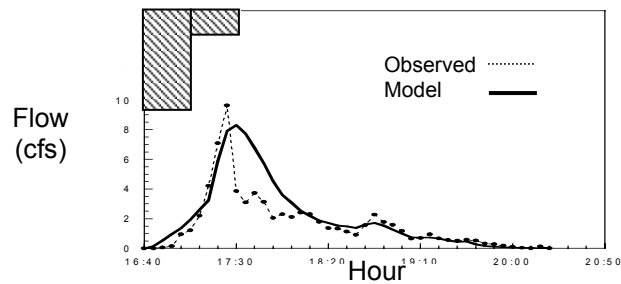
In an attempt to understand the inherent variability of the system, three different types of samples were collected for chemical and physical parameters. Two types of samples were collected from storm sewer outfalls that discharged directly to the RCR: (1) "Outfall" samples were those that could be collected directly from the outfall without interference from other water bodies (required free falling outfall) and (2) "Mixing Zone" samples were samples that were collected at the end of piper but were below the surface of the RCR. All attempts were made to collect mixing zone samples in such a way that they represented primarily storm water discharging from outfalls, such as collecting samples from within the submerged storm sewer. The third type of samples collected, "River" samples, were collected as grab samples from the center of bridges crossing the RCR were intended to represent actual river conditions.

### **3. HEC-HMS ANALYSIS**

HEC-HMS model results for the October 4, 2002 rain event at Outfall 42 showed a peak flow of 0.8 m<sup>3</sup>/sec (28.2 ft<sup>3</sup>/sec) and a flow volume of 0.27 hectare-m (2.2 acre-ft). Adjusting initial abstractions and curve numbers refined the hydrograph. A storm hydrograph from the computed HEC-HMS unit hydrograph was generated using the convolution method. This hydrograph was superimposed on the observed flow hydrograph of the same storm event and it was found to closely match (Figure 3).

A comparison between the lumped parameter model and a semi-distributed model for the same Outfall 42 watershed showed the semi-distributed model was capable of generating a more accurate hydrograph than the lumped parameter model. Three main conclusions were derived from this exercise: (1) the semi-distributed model is more sensitive to the rainfall distribution pattern than the lumped parameter model, (2) errors are introduced using the lumped parameter model that will delay the peak discharge and underestimate flow, and (3) the identification of flows or the sources of contaminants are only possible using the semi-distributed model because results are obtained on a micro-watershed scale and in the lumped parameter model no relationships can be established. These results were demonstrated by adjusting only 1/6 of the watershed discharging from Outfall

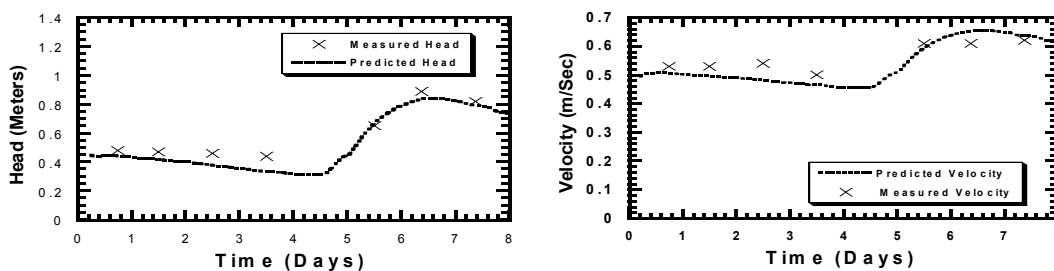
42. The small differences observed will be amplified for larger-scale watersheds, such as the entire MSU campus. The major limitation to both models is their inability to predict the hydrograph produced by intense storm events. This is due to the fact the routing method (kinematic wave) does not accurately describe pipe flow under pressure conditions.



**Figure 3:** Observed flow versus modeled flow for the storm event of October 4, 2002, at Outfall 42. Precipitation excess was approximately 0.5 cm (0.2 in) during the first hour, and 1.3 cm (0.05 in) during the second hour.

#### 4. RIVER HYDRODYNAMIC MODEL

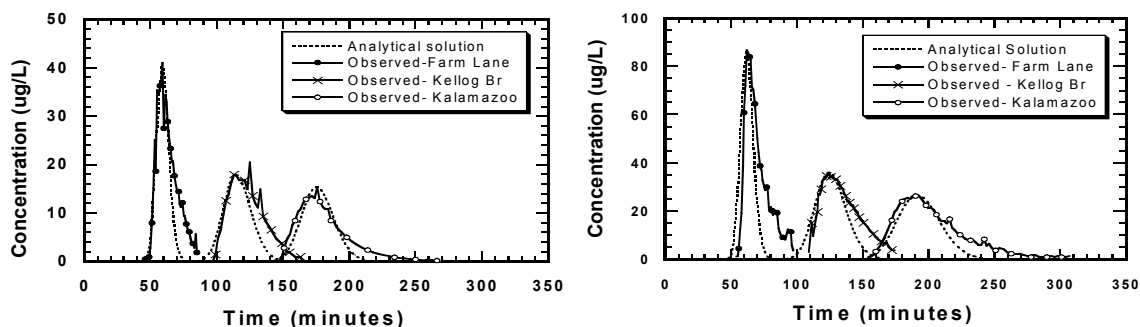
The velocities and heads at the Library and Kalamazoo bridge (not shown) predicted by the river hydrodynamic model were generally consistent and in agreement with the observed values for all type of flow conditions (Figure 4). However, velocities were under-predicted when the observed flow was lower than 14 m<sup>3</sup>/sec.



**Figure 4:** Predicted and measured velocity and head at the Library Bridge on April 4 through April 11, 2002.

Guidance criteria for error statistics for estuarine water quality model have been reported in the literature by Wu [6] but no specific criteria exists for small streams resembling the RCR. This was the guidance criterion used while developing this model. According to this criterion, the correlation coefficient should be greater than 0.94 for hydrodynamic variables, 0.84 for transport of a conservative water quality variable and 0.60 for water quality variables. Comparison of the model predictions and observed data was performed using linear regression techniques [7]. Three standard linear regression statistics were computed: (1) the square of the correlation coefficient, (2) the slope of the regression line, and (3) the intercept of the regression line. The slope of the regression line represents how well trends can be projected with the calibrated model and the intercept indicates if any systematic error is present. The square of the correlation coefficient for all the hydrodynamic variables, velocity, head and discharge, were calculated between 0.92 and 0.99 at the Library Bridge and 0.72-0.90 for the Kellogg Bridge.

A series of tracer tests conducted provided insight into one of the most important parameters for contaminant transport modeling, the dispersion coefficient. The three sampling sites used were the Farm Lane, Kellogg and the Kalamazoo bridges (Figure 2). A USGS gauge located at the Farm Lane Bridge was used as an index gauge. The results of the tracer tests compared with the analytical solution for the one-dimensional Fickian model are presented (Figure 5). The resulting dispersion coefficients were found to be appropriate for the RCR through MSU's campus and will aid in future transport modeling.

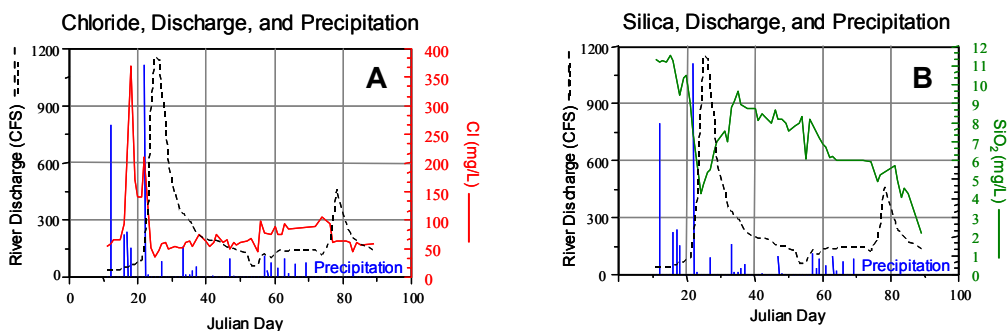


**Figure 5:** Predicted and observed concentration for the first two tracer tests.

## 5. CHEMICAL SAMPLING

The anthropogenic influence of surface waters discharged from MSU's campus into the RCR did cause a change in the chemical composition of water collected from upstream (Hagadorn Rd) and downstream (Kalamazoo St.) sampling locations. During base flow, parameters can be assumed to resemble natural or "background" conditions, as if there were no anthropogenic sources of surfacewater runoff from MSU's campus. Typically, TSS, water temperature, bromide, nitrate, calcium, magnesium, potassium, sodium, TOC, TIC, and TSS increase within MSU's campus. Those parameters that decreased were: DO, pH, conductivity, chloride, phosphate, sulfate, and alkalinity.

Spring rain events remove chloride from paved surfaces via urban storm water flow as shown on the Figure 6-A. During the largest rain event (around day 20), chloride concentrations increase rapidly before there is the expected increase in river discharge. This supports the "first flush" phenomena described by Hewitt and Rashed (for metals) [8] and Deletic and Maksimovic (for sediments) [9]. Correspondingly, silica concentrations can decrease rapidly due to dilution from surface water inputs (Figure 6-B). Seasonal effects are also noticeable as biotic growth within the river, increases from spring to summer causing a reduction in silica concentrations until concentrations are nearly undetectable levels during mid-summer months (Figure 6-B).



**Figure 6:** Physical and chemical variations observed collected in the center of MSU's campus near the library bridge from the Red Cedar River during the spring of 1999.

Substantial variability was also observed during preliminary sampling. This supports previous findings that suggest nearly 20 samples are necessary to adequately provide a reasonable estimate of the mean concentration for constituents in runoff from paved areas [10]. The variance observed between different sampling methods was found to be less than the variance among samples collected by the same method (F-test, 95% confidence) for all parameters except for sodium, TIC, and TOC. Most importantly, this preliminary analysis confirms that chemical inputs discharging from the MSU campus watershed to the RCR are difficult to accurately measure, differing considerably within time, under assorted weather conditions and between different land uses, as previously reported [11], [12]. Additionally, this data suggests that the watershed does indeed have a significant effect on the water quality within the RCR. Determining what influences chemical transport and relating this to specific types of land use will ultimately help to define future planning issues.

## 6. CONCLUSIONS

Initial results show that lumped parameter models, typically used in watershed modeling, will not help to resolve flow at the microwatershed scale necessary to decipher differences between specific land uses. Additionally, the high variability observed in the chemical data will require intensive, event-based sampling to accurately describe storm water runoff. Future work will attempt to link mechanistic understanding of contaminant transport to observations of actual urban storm water conditions.

## REFERENCES

1. Kibler, D.F., ed. *Urban Stormwater Hydrology*. Water Resources Monograph. Vol. 7. 1982, American Geophysical Union: Washington, D.C. 271.
2. Ambrose, R.B., Jr, *The Dynamic Estuary Model, Hydrodynamics Program, DYNHYD5, Model Documentation and User's Manual*. 1993, ASCI Corporation, Athens, Georgia.
3. USGS, *National handbook of recommended methods for water-data acquisition*. 1977, Washington, D.C.: U.S. Government Printing Office.
4. Fischer, B.H., et al., *Mixing in inland and coastal waters*. 1979: Academic Press, Inc., New York, N.Y.
5. Seo, W. and T.S. Cheong, *Predicting Longitudinal Dispersion Coefficient in Natural Streams*. Journal of Hydraulics Engineering, 1998. **124**(1): p. 25-32.
6. Wu, Y.t., *Calibration And Validation of The DYNHYD5 Hydrodynamic Model For The Delaware River Estuary*. 1995, Estuary Tixics Management Program, Delaware River Basin Commission: West Trenton , New Jersey.
7. Thomann, R.V., *Verification of water Quality Models*. Journal of Environmental Engineering, 1982. **108**(5): p. 923-940.
8. Hewitt, C.N. and M.B. Rashed, *Removal Rates of Selected Pollutants in the Runoff Waters from a Major Rural Highway*. Water Research, 1992. **26**(3): p. 311-319.
9. Deletic, A.B. and C.T. Maksimovic, *Evaluation of water quality factors in storm runoff from paved areas*. Journal of Environmental Engineering-Asce, 1998. **124**(9): p. 869-879.
10. Thomson, N.R., et al., *Highway stormwater runoff quality: Development of surrogate parameter relationships*. Water Air and Soil Pollution, 1997. **94**(3-4): p. 307-347.
11. Rossi, L., R. Slowinski, and R. Susmaga, *Rough set approach to the evaluation of stormwater pollution*. International Journal of Environment and Pollution, 1999. **12**(2-3): p. 232-250.
12. Osuch-Pajdzinska, E. and M. Zawilski, *Model of storm sewer discharge. I: Description*. Journal of Environmental Engineering-Asce, 1998. **124**(7): p. 593-599.