

**D.C. Water Resources Research Center
Annual Technical Report
FY 2008**

Introduction

This report summarizes the activities of the District of Columbia (DC) Water Resources Research Institute (the Institute) for the period March 1, 2008 through February 28, 2009. The Institute is one of a network of 54 such entities at land-grant universities in the nation which constitutes a federal/state partnership in research, information transfer and education regarding water related issues. The Institute provides DC with interdisciplinary research support to identify city water and environmental resources and problems and contribute to their solution.

The Institute continues to increase its internal collaborations and partnerships among Departments at the University of the District of Columbia to provide relevant water resources research results and transfer information to assist policy makers and residents in the District of Columbia. Faculty researchers from the Chemistry and Math Departments have participated in our Seed Grant program and were awarded grants for FY2009. This inclusive process has had an incredible impact on stimulating research activities at the University.

The Institute, in partnership with the Cooperative Extension Service Environment and Natural Resources/Pesticide Education Program, was awarded \$600,000 through an intra-district grant from the District Department of the Environment Toxic Waste and Hazardous Materials Branch to convert the Water Quality Testing Lab to an EPA Certified Testing Lab for measuring pesticide residues in the environment, provide technical assistance to community gardeners, and train eligible DC residents as certified pesticide applicators. The institute will purchase three pieces of equipment for the lab; a gas chromatograph-mass spectrometer (GC-MS), an inductively coupled plasma-mass spectrometer (ICP-MS) and an atomic absorption spectrophotometer (AAS) with a graphite furnace. This analytical lab will support inter-disciplinary graduate research and training programs in chemistry, engineering, environmental and biological sciences as well as statistics and computer sciences. This progress demonstrates an incredible transformation of the Institute from simply providing research and information transfer seed grants to building capacity for in-depth research and training future scientists in water resource management. The Institute aspires to return to the glory days under the direction of Dr. Hame Watts, by taking on more challenges to serve the training and research capabilities of students and faculty members in the consortium of universities in the District of Columbia.

Efforts to advocate for clean-up in the Anacostia Watershed are still very critical to pollution control in the Chesapeake Bay. Storm and wastewater management in Washington DC, however, has outgrown its handling capacity through the Combined Sewer Overflow system which now requires either reconstruction or support with creative low impact development projects. Unfortunately, mounting challenges, particularly with emerging contaminants such as pharmaceuticals and organics that are not easily detected analytically, and with increasing costs, increase the difficulty of measurement using standard methods. Nevertheless, the Institute will continue to identify means of coordinating and facilitating research projects related to water resources to assist in solving stakeholder-driven problems.

The Institute continues the effort to assist in ensuring high quality in the District's municipal drinking water by maintaining partnerships with the Cooperative Extension Service (CES) Water Quality Education Program, the Agriculture Experiment Station (AES), the School of Arts and Sciences, and the School of Engineering and Applied Sciences. Our water quality testing laboratory and environmental simulation and modeling labs are supporting research and extension projects especially relating to Storm and Waste Water Management. Integrating monitoring and mathematical modeling, both labs will continue to serve the research and training needs of faculty and students as well as water and wastewater operators in the District.

The Extension Agent in the Cooperative Extension Service/Water Quality Education Program continues to impact the Institute's information transfer and outreach capacity. Listed are some of her accomplishments in

conjunction with the Institute: Prepared and distributed water quality education brochures and fact sheets to DC residents; Conducted workshops on water quality education at various DC Recreation Centers and Public Schools; Visited DC Water and Sewer Authority (DCWASA) Water Quality Division for potential collaboration Periodically visited USDA\CSREES National Water Program to enhance Water Quality Education Program for future collaboration; and Participated on the Mid-Atlantic Regional Water Quality Program Steering Committee

The Institute website, <http://www.udc.edu/wrri/>, provides updated information about current activities. The Institute also completes bi-seasonal issues of the Water Highlights Newsletter. These documents are very informative and highlight current research and educational projects sponsored by the Institute along with interactions among faculty members and their student interns on projects and conferences.

An electronic mailing list of over 150 Water Resources faculty and experts in the consortium of universities in Washington DC is maintained and regularly updated and disseminated via email to report updates on local, regional, and national water issues received by the Institute. This line of information transfer has enhanced the visibility and credibility of the Institute among its stakeholders.

Research Program Introduction

The DC Water Resources Research Institute will continue to provide the District with inter-disciplinary research support to both identify and contribute to the solution of DC water resources problems. These research and educational projects provide students with essential practical skills required for future job opportunities and also allow faculty members access to new technologies and equipment that develop their expertise in water resource management. Reports for four of the five projects funded are included in this technical report. One progress report is also included to be completed after a three-month no cost extension while two projects were awarded funding to continue into Phase II.

In summary, Dr. Pradeep Behera's project, *Development of a Web-based Rainfall Statistical Analysis Tool for Urban Storm Water Management*, was awarded a grant to complete Phase II. His progress report demonstrated that the analysis of urban storm water pollution is a primary step in developing cost-effective solutions for wet-weather flow problems. A web-based statistical tool was developed to provide the user with increased functionality. This included (1) extraction of rainfall records from the NOAA and NCDC sites; (2) preprocessing of data for statistical analysis; and (3) fitting of probability distribution functions and estimation of their parameters. Phase II of this project will test and assess the effectiveness of the tool.

Dr. Karen Bushaw-Newton at American University submitted a six month progress report on her project, *Assessing the Distribution of Synthetic Organics and the Degradation of Polyaromatic Hydrocarbons in the Anacostia River through Microbial and Stable Isotope Studies*, indicating that synthetic organics are a serious form of pollution affecting the biological life of the Anacostia River. Polycyclic Aromatic Hydrocarbons (PAHs), a by-product of engine combustion, are distributed throughout the sediments of the river system and have been linked to cancer in higher organisms including catfish.

Drs. Byunggu Yu and Pradeep Behera were awarded a grant to continue Phase II of their project, *Application of Spatiotemporal Informatics to Water Quality*. Their progress report showed that recent developments and innovations in spatiotemporal informatics (storage, update, and retrieval of continuously changing data) and relevant sensor technologies can provide exciting opportunities and innovations in urban water resource management and decision making applications. In Phase I of the project, a competitive proposal was developed and submitted to NSF for extramural funding. The peer review identified this work as one of the innovative proposals with intellectual merit, and recommended that the proposal include more preliminary experimentation prior to funding. Phase II of the proposal includes the laboratory experimentation and the development of an improved proposal with a submission to the NSF Sensor Network program in year 2009.

Dr. Tolessa Deksissa, in his project, *Modeling of Integrated Urban Wastewater System in the District of Columbia*, developed an integrated mathematical model that takes into account the interaction of all urban wastewater system components, i.e., sewer, wastewater treatment plant and river. An appropriate modeling approach was selected for each sub-model as well as model connector. A conceptual sewer model and model connectors to link the three sub-models were developed. Potential application of the current version of the proposed model was also evaluated on the basis of hypothetical data. Results of the study show the usefulness of the proposed modeling approach for a real time control, and therefore helpful for researcher, planner and regulator to detect weak points in the system. Furthermore, brief discussion of model formulation, model implementation and model evaluation as well as the preliminary monitoring data collected in the Rock Creek watershed is presented. Dr. Deksissa is collaborating with Dr. Valbona Bejleri, a UDC Statistician, on a FY2009 104B grant titled *Modeling Model Uncertainty for Storm Water Quantity and Quality Analysis in DC Urban Area*, to calibrate and continue testing the integrated model for effectiveness and efficiency.

Dr. Li Chen, along with his student intern, Travis Braham, published one article from his project, Gradual Variation Analysis for Groundwater Flow of DC. He established a mathematical model based on gradually varied functions for groundwater data volume reconstruction. These functions do not rely on the rectangular Cartesian coordinate system. A gradually varied function can be defined in a general graph or network. Gradually varied functions are suitable for arbitrarily shaped aquifers. Two types of models are designed and implemented for real data processing: (1) the gradually varied model for individual (time) groundwater flow data and (2) the gradually varied model for sequential (time) groundwater flow data. In application, we also established a MySQL database to support the related research.

Listed below are the six grants awarded to researchers for FY 2009 104B grants.

Title: Development of Web-based Rainfall Statistical Analysis Tool for Urban Stormwater Management Analysis Phase II, Dr. Pradeep Behera, Associate Professor Department of Engineering, Architecture & Aerospace Technology, University of the District of Columbia

Title: Application of Spatiotemporal Informatics to Water Quality Phase II, Dr. Byunggu Yu, Associate Professor, Department of Computer Science and Information Technology, University of the District of Columbia

Title: Modeling Model Uncertainty for Storm Water Quantity and Quality Analysis in DC Urban Area, Dr. Valbona Bejleri, PhD, Associate Professor, Department of Mathematics, University of the District of Columbia

Title: Clam Active Biomonitoring and POM Passive Monitoring for Anacostia Watershed Contaminant Point Sources, Dr. Harriette L. Phelps, Professor Emeritus, Dept of Biological and Environmental Sciences, University of the District of Columbia

Title: Speciation of Some Triorganotin Compounds in Anacostia and Potomac River Sediments using NMR Spectroscopy, Dr. Xueqing Song, Associate Professor, Department of Chemistry, University of the District of Columbia

Title: Development of a Fast Optimization Technique using Interactive Spatial Join for GIS Application in Water Resources, Dr. Seon Ho Kim, Associate Professor, Department of Computer Science and Information Technology, University of the District of Columbia.

Matching requirements were met with non federal in-kind contributions from the indirect cost waived by each university and cash match from the University of the District of Columbia. These research projects will provide water quality training for graduate and undergraduate students in the District of Columbia.

Modeling of Integrated Urban Wastewater System in the District of Columbia (Pase II)

Basic Information

Title:	Modeling of Integrated Urban Wastewater System in the District of Columbia (Pase II)
Project Number:	2008DC92B
Start Date:	3/1/2008
End Date:	2/28/2009
Funding Source:	104B
Congressional District:	District of Columbia
Research Category:	Water Quality
Focus Category:	Surface Water, Models, Toxic Substances
Descriptors:	None
Principal Investigators:	Tolessa Deksissa, Pradeep K. Behera

Publication

Modeling of Integrated Urban Wastewater System in the District of Columbia (Phase II)

Progress Report for FY2008



Principal Investigators: Tolessa Deksissa, Ph.D
Research Associate
University of the District of Columbia
E-mail: tdeksissa@udc.edu

Pradeep K Behera, Ph.D., P.E.
Associate Professor
Engineering, Architecture & Aerospace Technology
University of the District of Columbia
Email: pbehera@udc.edu

Date: June 2009

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Modeling of Integrated Urban Wastewater System in the District of Columbia: Progress Report (Phase II)

Tolessa Deksissa^{1,2} and Pradeep K. Behera^{1,3}

*University of the District of Columbia*¹*Water Resource Research Institute*²*Agriculture Experiment Station,*³*School of Engineering and Applied Science*

ABSTRACT

The goal of this study is to develop an integrated mathematical model that takes into account the interaction of all urban wastewater system components, such as sewer, wastewater treatment plant and river. Despite the fact that these three components interact in various ways, they are often considered separately. Recent development in modeling urban wastewater system and increase of the demand for holistic approach indicates that considering all three components as one system is needed. This approach allows evaluation and optimization of system performance in terms of environmentally and economically sound planning and management. In phase I, appropriate model selection and implementation procedures were discussed, including sub-model selection and implementation of the selected sub-models in appropriate software platform. A conceptual sewer model and model connectors to link these three sub-models were applied. In phase II, further development and refining of the hydrologic as well as water quality model was carried out. Furthermore, potential application of the current version of the proposed model was further evaluated on the basis of hypothetical data. The effect of retention basin on the quantity and contamination frequency of the receiving water body was analyzed. The preliminary results of the study show the usefulness of the proposed modeling approach, and if verified with the monitoring data, it is applicable for a real-time control and therefore helpful for researcher, planner and regulator to detect weak points in the system. It is quite useful for designing as well as evaluating the effectiveness of the best management practices to reduce the problem of combined sewer overflows in older cities in general, and in the District of Columbia in particular. Further research includes demonstration of the effect of best management practice on the water quality of the urban wastewater system, water quality data collection and model calibration and verification.

INTRODUCTION

In the older cities where the sewer system was designed to convey both wastewater and storm water runoff, the existing sewer system has no longer has a capacity to accommodate the combined wastewater flows. The combine sewer systems were designed to collect rainwater runoff and all types of wastewater, domestic as well as industrial, in the same pipe. When there is no heavy rain, combined sewer systems transport all of their wastewater to a sewage treatment plant. The runoff quantity during storm event combined with all wastewater currently generated in most of older city is by far much higher than the sewer flow rate of several decades ago. Subsequently, during periods of heavy rainfall or melting snow excess volume of wastewater discharged directly into the nearby streams, rivers, or other water bodies.

Like in the other older cities of the United State, frequent Combined Sewer Overflows (CSOs) are the main problem in the District of Columbia, where one third of the city is served by a combined sewer system (USEPA, 2004). During storm events, the excess flow, which is a mixture of sewage and storm water runoff, is discharged into the receiving waters: Anacostia and Potomac Rivers, Rock Creek and tributary waters. For every inches of rain, there will be a combine sewer overflows somewhere in the Rock Creek or other water shed. This shows that there would be a frequent contamination from CSOs, which affects surface water quality in the District. According to the District of Columbia water quality standards, the designated use of these receiving waters is Class A, i.e. they must be suitable for primary contact recreation. However, their actual use is Class B, i.e. they are suitable for secondary contact recreation and aquatic enjoyment (DC, 2000). Mainly because of the problem of frequent CSOs, the water quality of these receiving waters does not currently meet the designated standards.

To address the CSOs problem in the District, a holistic approach must be taken into account. In addition to monitoring, appropriative mathematical model must be applied. In urban wastewater system, model integration is paramount of importance, as all three components - sewer, wastewater treatment plant, and the receiving water bodies - interact various ways. Such interaction is better described by the integrated mathematical model of the urban wastewater system as a whole than considering it as a separate system. Integrated approach may assist the water quality regulator in making decision. For example, before making major investment on the upgrading of the existing physical infrastructure, the evaluation of the system as a whole using an integrated model might be of worthwhile. In those cases, integrated models allow cost effective analysis and evaluation of system performance as a whole, as it takes into account all the three components (sewer system, wastewater treatment plant and river) as one system rather than traditional way of individual-system analysis.

In urban wastewater management, the receiving water must be considered as a subsystem that fully interact with the other subsystems, i.e. the catchment, the sewer system and wastewater treatment plant. It is well recognized that urban wastewater management cannot rely upon uniform, simple emission standards from sewer and wastewater treatment plant. For best management, the uniform emission standard must be complemented by the environmental quality standard or the local condition of the receiving water quality (Tyson *et al.*, 1993). Integrated modeling of the three components is a holistic approach that applies for both types of the standards. The usefulness of the proposed approach has also been demonstrated in the previous studies (Meirlaen *et al.*, 2002; Vanrolleghem *et al.*, 2005).

The goal of this study is to develop an integrated mathematical model that consists of sewer, treatment plant and river, and evaluate its application in the case study of the District of Columbia. The primary objective of this work includes appropriate model selection and modeling tool, and development of interfaces or model connectors.

METHODOLOGY

The proposed integrated model includes three components such as sewer, Wastewater Treatment Plant (WWTP) and river. Schematic representation of integrated urban system is illustrated in Figure 1.

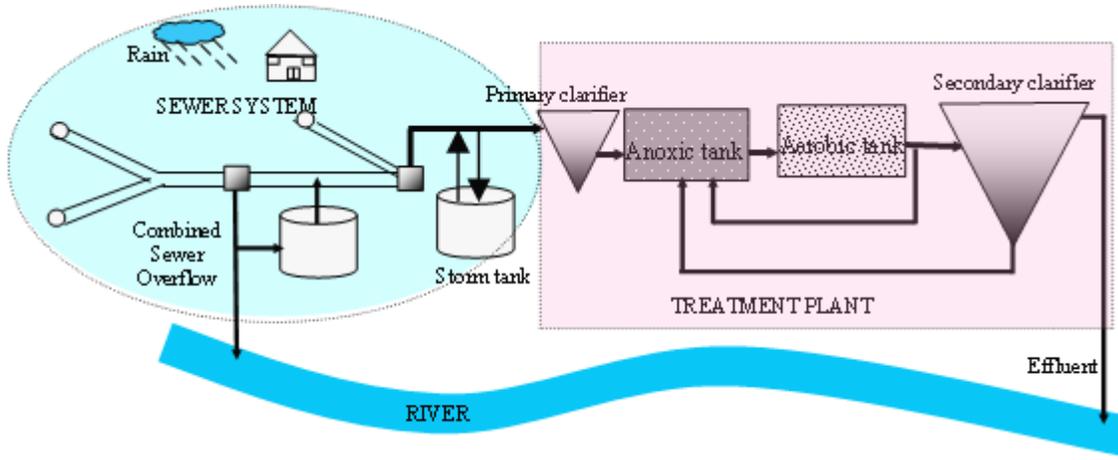


Figure 1. Schematic representation of integrated urban wastewater system

As indicated in the previous report (Phase I), the integrated urban wastewater system modeling approach consists of seven steps: (1) model selection, (2) program platforms, (3) rainfall-runoff and dry weather flow, (4) hydraulic modeling, (5) pollutant accumulation and wash-off, (6) water quality and pollution transport, and (7) model connectors. Detail description of each step is given in the following subsection.

Model selection

In modeling integrated urban wastewater system, making use of the available models that have already been well established for individual component is preferred to developing a completely new model. For each sub-system, there are several mathematical models available in literature. The challenge is, therefore, how to select the appropriate model that applies for the management of integrated urban wastewater system.

In this study, model selection and implementation was conducted on the basis of three key factors. First, model complexity – mathematical model under consideration must be complex enough to describe the real situation. Second, appropriate process description and state variables of the model need to be selected. All selected sub-models (sewer, treatment plant and river) need to have similar description of state variables. For example, in QUAL2E (Brown and Barnwell, 1987) bacterial biomass is not described as a state variable. In addition this model is based on Biological Oxygen Demand (BOD) rather than Chemical Oxygen Demand (COD). Hence QUAL2E is not compatible with the Activated Sludge Model (Henze *et al.*, 1987), as the latter is based on COD as well as considers bacteria as state variable. The third important factor in model selection is mass conservation. The model needs to maintain close mass and elemental balances (Reichert *et al.*, 2000). Furthermore, the proposed integrated model needs to be applicable for a

scenario analysis ‘what if’. Subsequently, a dynamic mechanistic mathematical model was developed for the proposed integrated model on the basis of complete mass and elemental balances as well as model compatibility.

Program platforms

Despite the fact that the idea of integrated modeling was made about 30 years ago (Beck, 1976), an appropriate software platforms became available only recently. Selection of simulation software or program platform was conducted on the basis of four main criteria. First, open model structure in which the user can modify or add a new model in the model bases of the platform. Second, parallel or simultaneous simulation, which allows real time control of the interaction of the whole system. Third, simulation of long time series feasibility. Fourth, reported integrated use of the software at a real case study. As it fulfils these criteria, the WEST[®] simulator (Wastewater treatment plant Engine for Simulation and Training) (MOSTforWATER N.V., Kortrijk, Belgium) version 3.7.5 was selected as a software platform for this study. Detail information about the WEST[®] simulator is presented in Vanhooren *et al.* (2003).

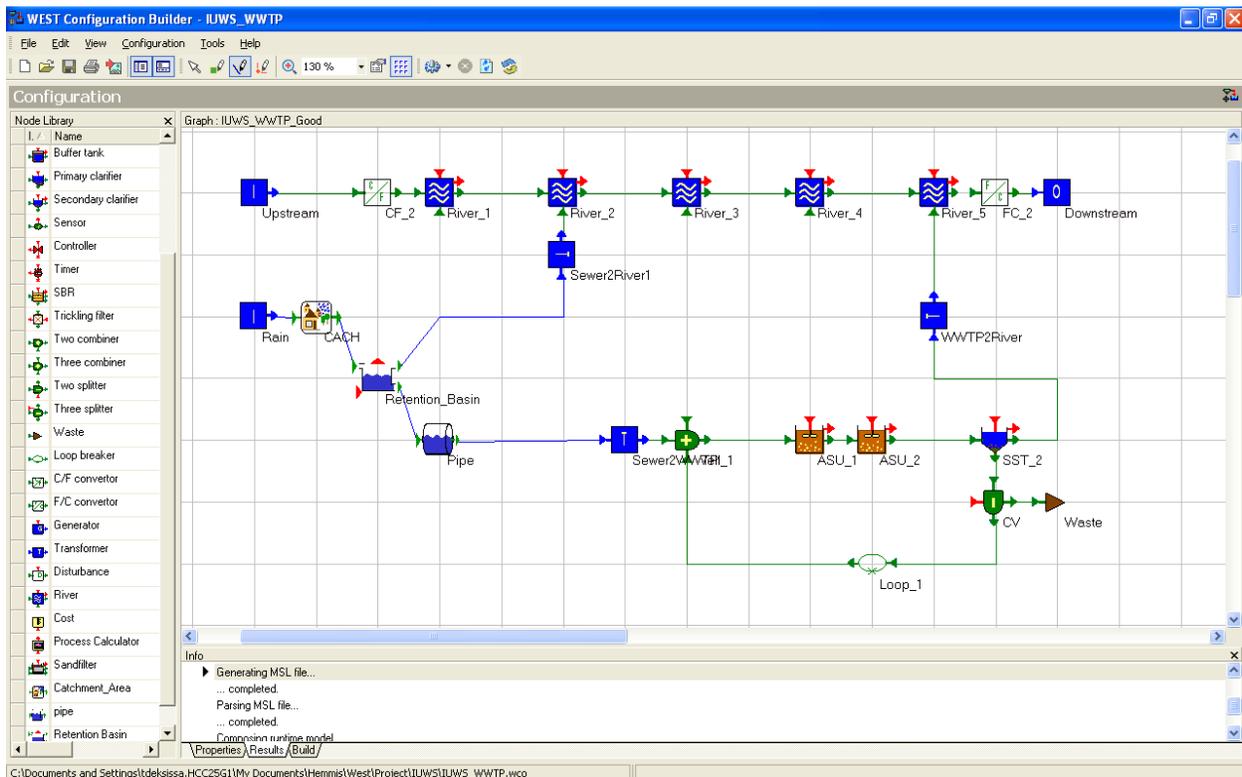


Figure 2. Integrated Urban Wastewater System in the WEST simulator

Rainfall-runoff and dry weather flow

Both rainfall-runoff and dry weather flow are the integral part of hydrologic modeling of integrated urban wastewater system. As they are affected by various factors, their estimation should include at least the major once. In this study, a conceptual rainfall-runoff model has been

proposed for the integrated model. The runoff volume can be estimated based on rainfall volume, catchment characteristics such as imperviousness and abstraction losses which include depression storage, infiltration and evaporation. After meeting the depression storage volume, a fraction of the difference between rainfall volume and depression volume become runoff. The runoff volume is collected and conveyed through the urban drainage system (curb gutters, catch basins, storm sewers and outfalls) and ultimately end up to the receiving water, which is in this case river.

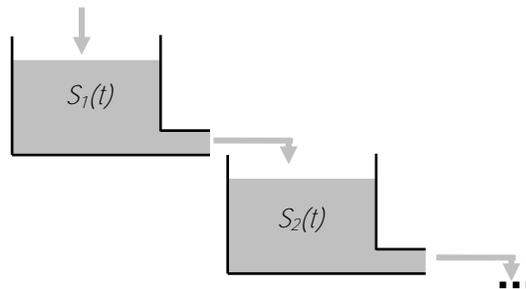
The urban dry weather flow is estimated from the different land uses. The residential dry weather flow is estimated based on the population served and per capita water use. The estimation of dry weather flow from other land uses such as institutional and commercial is based on the literature values.

Hydrological modeling

The mechanistic modeling of time varying hydraulics in open channel is often made on the basis of the state-of-the-art approach of Saint Venant equations (Deksissa, 2004a). Since their approximation is computationally demanding, the application of state-of-the-art kinematics approach of hydraulic model on the integrated model is limited. Subsequently, a conceptual flow routing model was selected. This conceptual hydrological model generally respects the continuity equation but replaces the conservation of momentum with some conceptual relationship. The underlying concept is a cascade of linear reservoir model or tanks-in-series model with the water being routed downstream. This method works for both fixed as well as variable volume tanks. Under gradually-varied flow conditions, stage-discharge relationship can be used to route variable flow through the tanks. Being simple, it allows rapid simulation, but can not simulate, at least directly, effects such as backwater effect and pressurized flows. Each of the reservoirs can be described by a storage equation and continuity equation as follows:

$$\frac{dS(t)}{dt} = Q_{inflow}(t) - Q_{outflow}(t) \quad (1)$$

$$Q_{outflow}(t) = \frac{1}{K} S(t) \quad (2)$$



Where:

$S(t)$ Storage at time t [m^3]
 Q_{inflow} Inflow at time t [$m^3 d^{-1}$]

$Q_{outflow}$ Outflow at time t [$m^3 d^{-1}$]
 K Storage constant [d]

Pollutant accumulation and wash-off

Both pollutants accumulation and wash-off depend on many factors that need to be taken into consideration while modeling these processes. Pollutants are accumulated on the catchment during dry weather period before they are transferred into and along the sewer system. The accumulation processes occur not only on the catchment surfaces, but also in the sewer pipes. The amount of accumulation depends on street nature, particle size, duration of the dry weather period etc., and whereas pollutant accumulation in sewer pipes is due to the sedimentation of particles that cannot be kept in suspension by the flow energy. These processes may be described by linear or exponential asymptote.

Pollutant wash-off during rain event involves a series of parameters: rainfall intensity, height and duration, particle characteristics, type and condition of the surface. Taking into account the street dirt loading, the pollutant wash-off during rain event may be calculated on the basis of exponential relationship.

In this model an exponential buildup function and exponential wash-off function will be used as described in previous works (Behera et. al, 2006; Alley and Smith, 1981; Alley, 1981).

Water quality and pollution transport

The state-of-the art water quality and pollution transport is utilizing the de Saint Venant equations, also termed as diffusion and dispersion equations, which are computational demanding, and applying such a complex modeling approach is not convenient for fast simulation and parameters estimation of an integrated model (Meirlaen *et al.*, 20002). Subsequently, conceptual mass balance approach consists of two terms (transport and biochemical reactions) was applied. On the basis of Equation 1, the pollutants mass balance in an open channel flow can be described as follows:

$$\frac{dM(t)}{dt} = \underbrace{Q_{inflow}(t)C_{inflow}(t) - Q_{outflow}(t)C_{outflow}(t)}_{\text{Transportation term}} \pm \underbrace{RV(t)}_{\text{Reaction term}} \quad (3)$$

Where:

$M(t)$ Accumulated mass at time t [g]
 $C_{inflow}(t)$ Concentration in the inflow [$g m^{-3}$]
 $C_{outflow}(t)$ Concentration in the outflow [$g m^{-3}$]
 R A source or sink reaction rate [$g m^{-3} d^{-1}$]
 V Flow volume of the tank [m^3]

Biochemical reaction

In describing the pollutants mass balance, the term R in Equation 3, the biochemical reaction term is an integral part of mass balance that must be taken into consideration while modeling a non-conservative pollutant in all three components. The number of biochemical reactions depends on the number of processes that dominate the system behavior of the component. For example, photosynthesis is not relevant in the activated sludge unit, but is one of the governing processes of oxygen balance in river.

There are two general approaches of modeling biochemical reactions. The first approach is based on open mass balance, both mass and elemental balances are not taken into account, e.g. QUALE2 (Brown and Barnwell, 1987). In this approach the model may fit well with a given set of monitoring data, but the mass balance remains incomplete. In the second modeling approach, both mass and elemental balances are conserved, e.g. RWQM1 (Reichert *et al.*, 2000). In this study, the second approach, complete mass and elemental balances, was applied. To maintain conservation of mass and elemental composition of organic matter, Chemical Oxygen Demand (COD) rather than Biological Oxygen Demand (BOD) modeling approach was applied. For the wastewater treatment plant and river components, state-of-the art water quality models have been reviewed and an appropriate modeling approach was selected. Subsequently, the selected modeling approach for those two components has been implemented in the WEST[®] simulator including ASM1 for activated sludge modeling and RWQM1 for river water quality modeling. Similar concept was also applied to build a sewer water quality model.

Model Reduction

In modeling water quality, model reduction is of paramount importance when the available model is too comprehensive and complex to be used in the modeling of integrated urban wastewater system. Integrating modeling of the three components using the state-of-the art sub-models without model reduction is actually not practically applicable. Subsequently, in the water quality sub-models of this study, appropriate model reduction has been made. Under sewer system, there are two major subcomponents: rain fall runoff simulation and pipe network that collects and conveys storm water as well as wastewater (dry weather flow) into the treatment plant. Both subcomponents were modeled such that the proposed model need to have a minimum complexity, but should be able to describe the real situation. Model reduction was done on the basis of prior knowledge and appropriate process description or selection (Deksissa *et al.*, 2004b; Vanrolleghem *et al.*, 2001). For example using a one-step instead of two step nitrification process reduces a model complexity and model parameters otherwise need to be determined. Such consideration depends on the characteristics of the system under consideration. In all cases, dominant processes must be taken into consideration first and evaluated for appropriate description of the system behavior. The number of process and reaction parameters must be kept

to the minimum, as the higher the number of model parameters to be considered, the larger the size of monitoring data it will require for the model calibration.

Model connectors

Model connectors are required to create an integrated sewer-WWTP-river model in which model variables described in sub-models need to be linked. In order to do that the model connector/interface must respect closed mass and elemental balances. Detail description of the method that was applied in this study was given in the previous work (Benedetti *et al.*, 2004). For the proposed model, three model connectors were considered: sewer –river, sewer – WWTP, and WWTP-river. All three model connectors are being built and incorporated in the integrated model.

MODEL IMPLEMENTATION

After selecting an appropriate modeling approach, the model has to be built in an appropriate program platform as described in the previous sessions. Prior to putting all sub-models together, each sub-model for each component was tested for quality assurance. Brief discussion about how the implementation of each sub-model and integrated model was done in the WEST[®] simulator is given in the next session including (1) sewer, (2) wastewater treatment plant, and (3) river, and (4) integrated urban wastewater system.

Sewer

Before compiling/integrating all the model components of urban waste water system together as one model, each sub-model was implemented first and tested for quality assurance. For example Figure 3 indicates the model configuration for sewer system. In this example, the retention basin is installed in order to slow down and reduce the peak flow of storm water in the sewer. Overflows from the retention basin can partly be discharged to the receiving water, and partly be conveyed to the treatment plant. The retention basin can be storm tank, tunnel or pond. The usefulness of such a best management practice was illustrated in this study.

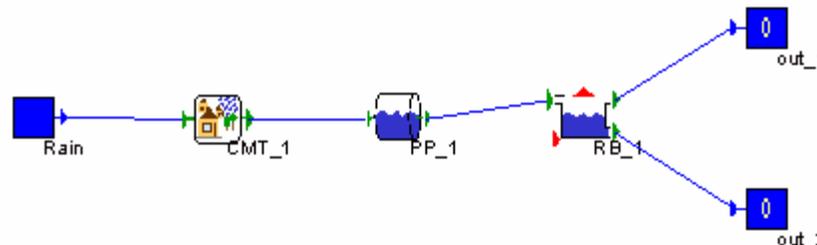


Figure 3. Urban catchment and pipe connected to the storm water retention basin

Wastewater Treatment Plant

In modeling biological Wastewater Treatment Plant (WWTP), similar approach (tank-in-series) was applied. The state-of-the-art Activated Sludge model 1 (Henze *et al.*, 1987) is available in the modelbase of the WEST[®] simulator. For example, model configuration of WWTP in the WEST[®] simulator can be expressed as indicated in Figure 4. In this example, the secondary settler (SSR_1) is included. Primary settler may be included when a full scale or plant wide modeling is desired. In addition to liquid part, the solid part (sludge) is also considered in this example. While large part of the sludge is wasted from the secondary settler (Waste_2), the remaining part of sludge is recycled.

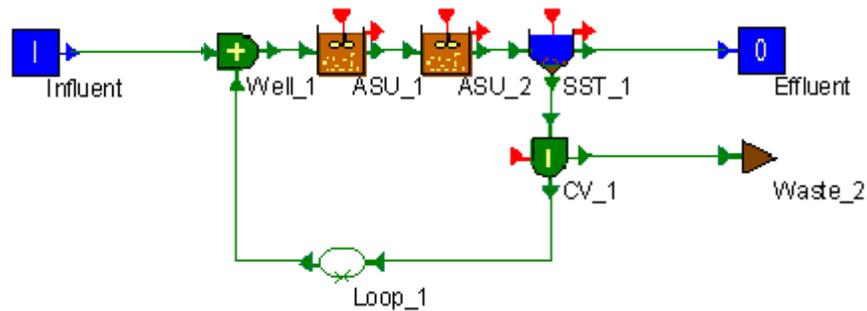


Figure 4. Wastewater Treatment Plant with two tanks of activated sludge units

River

The river model is implemented in the WEST[®] simulator as indicated in Figure 5. It shows a series of tank-in-series, a cascade of linearly reservoir model, in which the outflow of the upstream river stretch or reservoir becomes the inflow of the downstream river stretch or reservoir. If there are any side streams, one can add as many additional inputs, as a side stream (Figure 5) as possible at particular location along the river under consideration, depending on the number of side streams.



Figure 5. Model configuration: River stretches in the WEST[®] simulator

Integrated urban wastewater system

In the WEST[®] simulator, the proposed integrated model of urban wastewater system can be described as indicated in Figure 6. In this example, the model input for the sewer system includes rainfall, residential or industrial wastewater discharge connected to the sewer system. In case of river, two main inputs of wastewater discharges were considered: runoff from urban catchment and the wastewater treatment plant effluent. Inputs for the wastewater treatment plant include a combination of runoff from the urban catchment and dry weather flow. In this model, three model connectors or transformer (T) were also incorporated: Sewer2River, Sewer2WWTP and WWTP2River (Figure 6). For the sake of demonstration, few numbers of tanks-in-series were used. In the real situation, the optimum number of tank-in-series depends on the mixing condition of the system, which can be determined on the basis of monitoring data and model calibration.

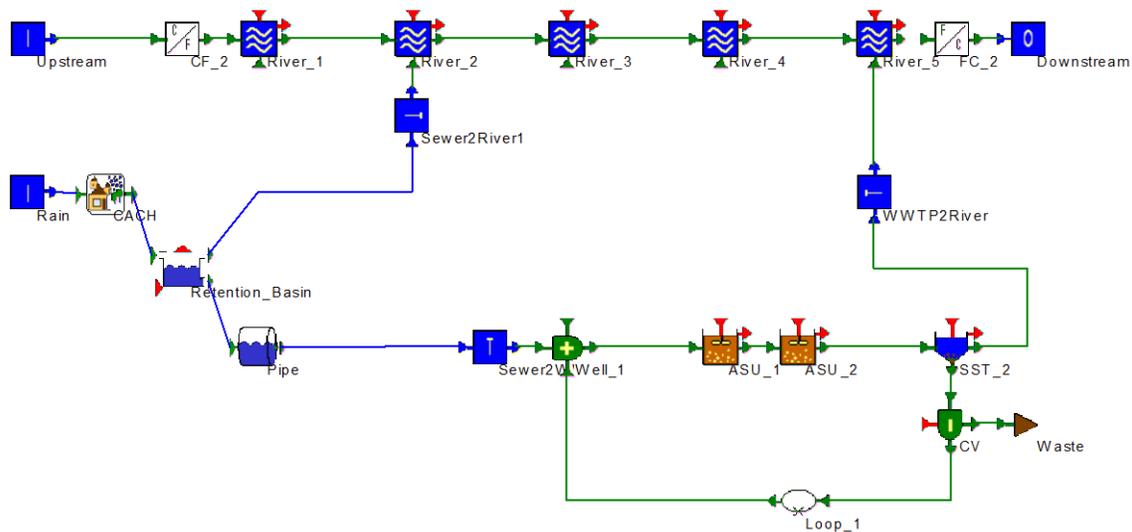


Figure 6. Integrated model configuration in the WEST[®] simulator

Data requirements

Data requirement is one of the driving forces for reducing model complexity to the minimum. It increases with the line of model complexity. Developing an appropriate integrated model taking into account the limitation of data requirements, collecting minimum data required to calibrate and evaluate each submodel or all model components as a whole is in progress. As generating monitoring data requires laboratory test, a new water quality testing lab is being established at the University of the District of Columbia. As of now important lab equipment and supplies have been purchased, and preliminary water quality data were also collected and presented herein.

In order to apply the proposed integrated model to simulate conventional pollutants (nutrients) in all components, minimum required data set in general is indicated in Table 1. The level of model complexity together with the amount of data required actually determined by the purpose of model application. If one wants to simulate the pH change in the river or sewer, more chemical water quality data needs to be collected other than just major plant nutrients. In this

work, as monitoring is relatively expensive, minimizing the data requirement of the model is taken in to consideration.

Table 1. Minimum data requirements for modeling of integrated urban wastewater system

Water Quality and Quantity Variables	System		
	Sewer	Treatment plant	River
<i>Hydrologic variables</i>			
• Water flow	✓	✓	✓
• Flow velocity	✓		✓
• Flow and gage relationship	✓		✓
• Hydro morphological or physical dimension	✓	✓	✓
• Water temperature	✓	✓	✓
• Solar light intensity	✓	✓	✓
• Catchment area	✓		✓
• Rainfall	✓		✓
• Population equivalent	✓		
<i>Chemical variables</i>			
• Carbonaceous Biological Oxygen Demand (BOD)	✓	✓	✓
• Carbonaceous Chemical Oxygen Demand (COD)	✓	✓	✓
• Total nitrogen	✓	✓	✓
• Total phosphorus	✓	✓	✓
• Total Suspended Solids	✓	✓	✓
• Nitrate plus nitrite	✓	✓	✓
• Ammonia plus ammonium	✓	✓	✓
• Dissolved Oxygen	✓	✓	✓
• Carbonates and bicarbonates		✓	✓
• pH		✓	✓
<i>Biological variables</i>			
• Hetrotheroph microbial biomass	✓	✓	✓
• Authotheroph microbial biomass		✓	✓
• Algal biomass			✓

MODEL EVALUATION

In phase I, few applications of the proposed model were presented. Using hypothetical data, illustration of pollutant transport, in this example total dissolved solid, in the river sub-model was discussed. Using 15 km of river stretch, the plum propagation is similar to a typical spill model (Figure 7). Practical application of the reduced river model applied in this study was presented in Deksissa *et al.* (2004b and 2004c). In addition, the effect of storm water runoff into the river was simulated, and the application of best management practices, e.g. retention basin is demonstrated herein.

In Phase I, on the basis of hypothetical data the effect retention basin on the sewer overflows was simulated was demonstrated. The result shows that, depending on the size of retention basin, the

frequency of river contamination by sewer overflows can be reduced. The larger the size of retention basin, the lesser the frequency of contamination it would cause to the river. In addition, the wastewater treatment plant bypass was also included in the simulation. Depending on the capacity of the wastewater treatment plant, the diluted wastewater may be bypassed to the river and its impact on the river water quality can be simulated as well.

In this study, further scenario analysis was conducted in order to evaluate the effectiveness of putting retention basin on the combine sewer line: (1) effect of the volume of retention basin on the flow volume of CSOs into the receiving stream, and (2) effect of the volume of retention basin on the water quality of the receiving water as well as wastewater treatment plant. The latter scenario analysis is in progress. Using the rainfall and runoff simulation illustrated in Figure 8, the effect of retention basin size on the flow volume of CSOs is demonstrated in Figure 9.

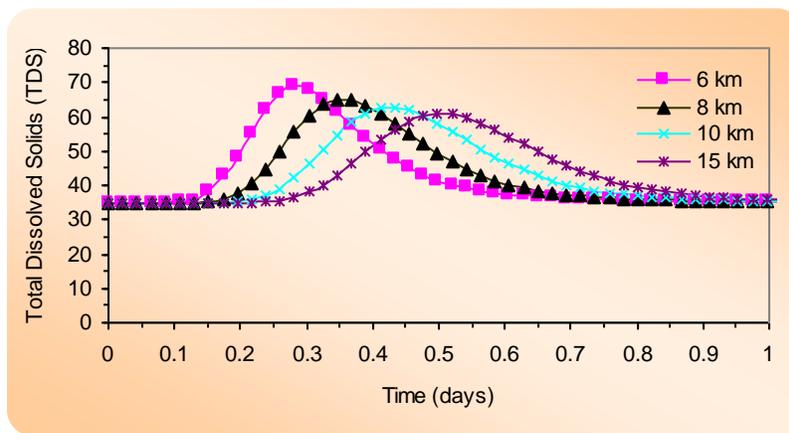


Figure 7. Simulating pollutant transport in river

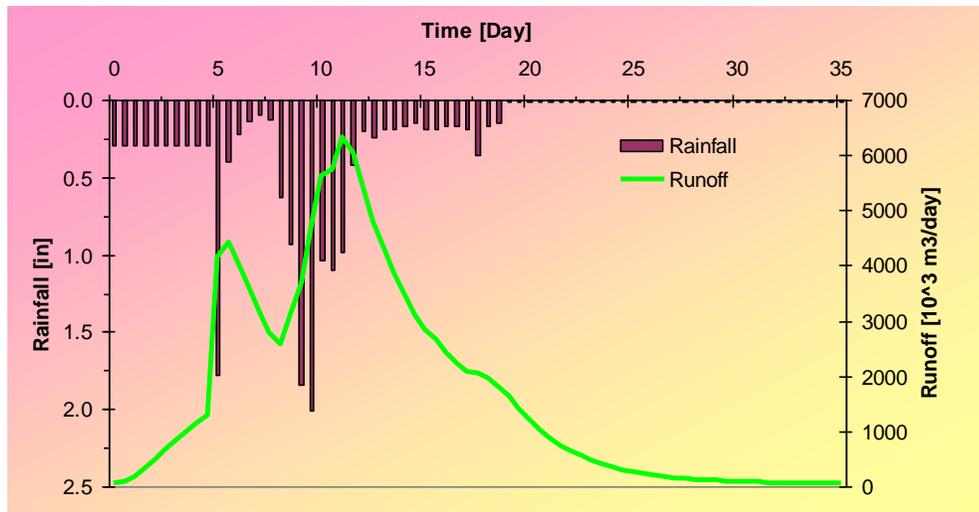


Figure 8. Example of Rainfall runoff using model configuration indicated in Figure 6

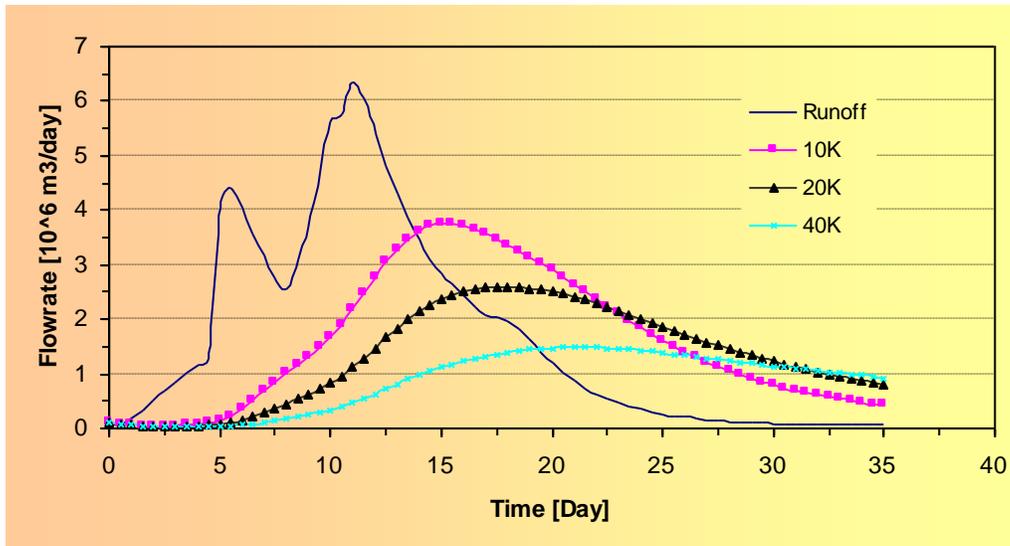


Figure 9. Effect of Maximum volume of retention basin on the volume of river flows: 10K = 10,000 m³; 20K = 20,000 m³; 40K = 40,000 m³

PRELIMINARY DATA COLLECTION

Preliminary monitoring data have been collected at the outfalls draining into Rock Creek in Washington DC (Figure 9). Duplicate water samples were collected two different times (October 12 and 27, 2007) from seven outfalls, and analyzed for limited water quality variables (Table 2). The amount of rainfall on those two days was 0.41 and 4.36 inches, respectively. The result shows that storm event has resulted in higher pollution load except BOD₅, which was diluted. It is evident that Combined Sewer Overflows (CSOs) are the reason for contamination of the Creek during storm event. Rock Creek is a shallow fast flowing stream, but violates the District water quality standards due to CSOs. There are about 28 outfalls that drain into the Rock Creek, unless addressed it continues to affect the water quality of the Creek.

Table 2. Preliminary data collection in the Rock Creek watershed

Parameters	After storm (4.36")		Before storm (0.41")	
	Average	Standard deviation	Average	Standard deviation
BOD ₅ [mg O ₂ l ⁻¹]	39.44	29.52	57.60	10.94
Total Coliform [PN/100 ml]	6516.56	1818.12	786.30	472.34
Fecal Coliform [PN/ 100 ml]	180.86	97.68	29.53	24.25
PO ₄ [mg l ⁻¹]	2.97	0.44	1.31	0.23
Nitrate [mg l ⁻¹]	0.47	0.14	0.82	0.06



Figure 10. Monitoring outfalls in the Rock Creek watershed

The preliminary data set presented herein (Table 2) is not enough to run the proposed integrated model; however it confirms the importance of CSOs in the restoration plan of the Creek. To reduce effects of CSOs best management practices are being implemented in the District as part of a long term control plan recommended by the District of Columbia Water and Wastewater Authority. The proposed integrated model can be used as a tool to evaluate the effectiveness of the best management practices as well as optimization of the system as a whole (Muschalla, 2008).

CONCLUSION

In this preliminary study, attempt was made to develop an integrated model of sewer-WWTP-river. Although the model is continuously being updated on the basis of available knowledge about the system, the proposed integrated model was successfully implemented in the WEST[®] simulator. The current version of the model can simulate rainfall runoff, sewer system, river and wastewater treatment plant in parallel. However, more work needs to be done to describe the actual wastewater discharge from residential as well as industrial sites. On the basis of preliminary model evaluation and preliminary monitoring data presented herein, one can conclude that the proposed model has a potential to be applied as a tool for urban wastewater management. Full application of the model requires time series monitoring data of each sub-model. Further researches include model refining, collection of monitoring data and model calibration.

KNOWLEDGE TRANSFER/PRESENTATION

Important parts of the result of this project were presented at different conference and meetings, such as the DC Water Resource Research Institute ‘brown bag’ seminar, June 11,

2008, 2008 Mid-Atlantic Regional Water Resources Research Conference, WV, November 17-19, 2008, and 2009 DC WRI advisory board meeting, April 7, 2009, Washington, DC.

Papers presented:

- Deksissa, T. 2009. Model Integration. 2009 DC WRI advisory board meeting, April 7, 2009, Washington DC
- Deksissa T. and Behera P. (2008). Modeling Integrated Urban Wastewater System: Model Selection and Implementation. In: *proceedings of the 2008 Mid-Atlantic Regional Water Resource Research Conference: The Energy & Water Nexus: Water's Role in the Challenges of Energy Production in the 21st Century, November 17–19, 2008, Shepherdstown, WV.*

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Development of Web-based Rainfall Statistical Analysis Tool for Urban Stormwater Management Analysis

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Publication

Development of Web-based Rainfall Statistical Analysis Tool for Urban Stormwater Management Analysis (Phase I)

Progress Report



UNIVERSITY OF
THE DISTRICT
OF COLUMBIA



Pradeep K. Behera, Ph.D., P.E., D. WRE
Travis Branham, CS Major

School of Engineering and Applied Sciences
University of the District of Columbia

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Content

Abstract	3
1.0 Introduction.....	3
2.0 Analytical Probabilistic Model	5
2.1 The Rainfall Event.....	5
2.2 The Rainfall Record.....	6
3.0 Requirements of the Application	8
3.1 The Parsing Engine.....	8
3.2 The Statistical Analysis.....	11
3.2.1 The Exponential PDF	11
3.2.2 The Gamma PDF.....	12
3.3 The User Interface	13
3.3.1 A Web-based Interface.....	13
3.3.2 A Command-line Interface	14
3.4 Output	15
3.4.1 Text-based Output	15
3.4.2 Graphical Output.....	16
4.0 Conclusions.....	20
5.0 Acknowledgements	21
6.0 References.....	21

Abstract

The analysis of urban stormwater pollution is a primary step in developing cost-effective solutions for wet-weather flow problems. Often the solutions are proposed based on limited monitoring and modeling efforts due to their exorbitant cost. Continuous simulation models have been used to analyze the existing watershed and stormwater pollution condition and to develop alternative solutions. The example of continuous simulation model includes *EPA Storm Water Management Model*. As these models are resource intensive, often development of watershed-wide simulation models is avoided during planning-level analysis. On the other hand analytical probabilistic models are computational efficient compared to continuous simulation models and can be easily used to develop the watershed-wide model.

Especially, for the District of Columbia sewer system, analytical models can be easily applied to analyze the existing water pollution problem and to develop alternate solutions. The primary input to the analytical stormwater model is statistical parameters of the long-term rainfall record. The federal agencies such as NOAA and NCDC provide the meteorological data which are typically used by the continuous simulation models. The rainfall records are generally pre-processed for the use in the stormwater models. However, analytical models use the same long-term rainfall records in a different manner. The long-term rainfall records are statistically analyzed and fitted with several probability distribution functions. The parameters of best fitted probability distribution functions for the rainfall characteristics such as storm event volume, event duration, event intensity and inter-event time, are used in the analytical models in lieu of continuous record.

The proposed web based statistical tool will provide the user much functionality. They include (i) extraction of rainfall records from the NOAA and NCDC sites; (ii) preprocessing of data for statistical analysis; (iii) fitting of probability distribution functions and estimation of their parameters.

1.0 Introduction

In order to protect society and environment adequately from the stormwater impacts such as flooding, erosion and receiving water problems engineers and professionals use stormwater

management models. These models require adequate representations of both hydrologic and hydraulic behavior of the drainage system (both sewer system and watershed) in order to size and configure control system elements. Typically stormwater management models are mathematical models which use continuous simulation approach rather than single design event approach. There are two major methods used to model urban drainage needs: event-based models, continuous simulation models. Event-based modeling represents the simplest approach commonly used for analysis and design drainage systems based on the design storm approach. Continuous simulation modeling falls at the other end of the spectrum. The complexity of this method is significant, in contrast to Event-based modeling, but the quality of the information derived from this method is vastly superior in predicting the optimal requirements of the drainage infrastructure required to maintain an acceptable level of performance.

Continuous simulation models are physically based use a long-term rainfall records to simulate catchment hydrology and hydraulics, and pollutant processes with long-term meteorological records as model input. However, the use of continuous simulation during screening-level analysis is relatively cumbersome, time consuming and very expensive.

An alternative approach to continuous simulation for screening-level analysis is using analytical approach. It is an approach based on analytical models formulated with derived distribution theory. The input to the model uses the probability distributions of rainfall characteristics: rainfall volume, duration, intensity and inter-event time and simpler hydrologic and pollutant processes that are similar to continuous simulation models. Since these analytical models are often closed form algebraic equations, they are more computationally efficient compared to simulation models. These models can be used to analyze the runoff pollution condition for each of the sub-catchments within a large watershed.

In order to use analytical records, a statistical analysis of long-term rainfall record is necessary. The proposed research will develop a tool to conduct the statistical analysis of rainfall records and estimate the parameters of fitted probability distribution functions.

The remainder of this report will describe the implementation of an analytical probabilistic modeling tool which can be used by civil engineers to address the concerns for urban stormwater management in a simple, cost-effective manner.

2.0 Analytical Probabilistic Model

Analytical Probabilistic models for urban stormwater analysis are derived using the Derived Distribution Theory. As per the theory, the probability density function (PDF) of a dependent variable can be derived from the PDFs of the independent variables using the transformation function which is the relation between the independent and dependent variables. In this model, the rainfall characteristics constitute the independent variables such as rainfall event volume, event duration, event average intensity and interevent time constituting as the primary input to the model. These are treated as random variables as rainfall is a random phenomenon. In the continuous simulation approach, long-term rainfall record is used as the input the model, whereas in the analytical model the PDFs are used as input the model which are developed from the long-term rainfall record.

Therefore in order to use or develop the analytical probabilistic models, the inputs must first be defined. The following sections will describe the details derived from the rainfall records which will be analyzed by the tool.

2.1 The Rainfall Event

A chronological rainfall record may be split up into two distinct groups of time periods: rainfall “events”, and the intervening times between rainfall “events”. Here, a rainfall event is characterized by some measurable precipitation. The granularity by which we may identify an event depends on two factors: first, the inherent granularity of the rainfall record (the frequency with which the precipitation levels are recorded); and second, the user-defined minimum interval without rainfall, known as the Interevent Time Definition (IETD) (Adams and Papa, 2000). Once one has defined an event delimiter (in this case an IETD), each event can be scrutinized to determine the following additional characteristics:

- 1) the volume of precipitation recorded for the event,
- 2) the duration of the event, and
- 3) the intensity of the event (volume per unit time).

Thus, each rainfall event that is found within the record may be described by these four parameters (volume v , duration t , average intensity i , interevent time b). The following Figure 1 helps to depict the role of the IETD in determining the boundary between events and the time between the events:

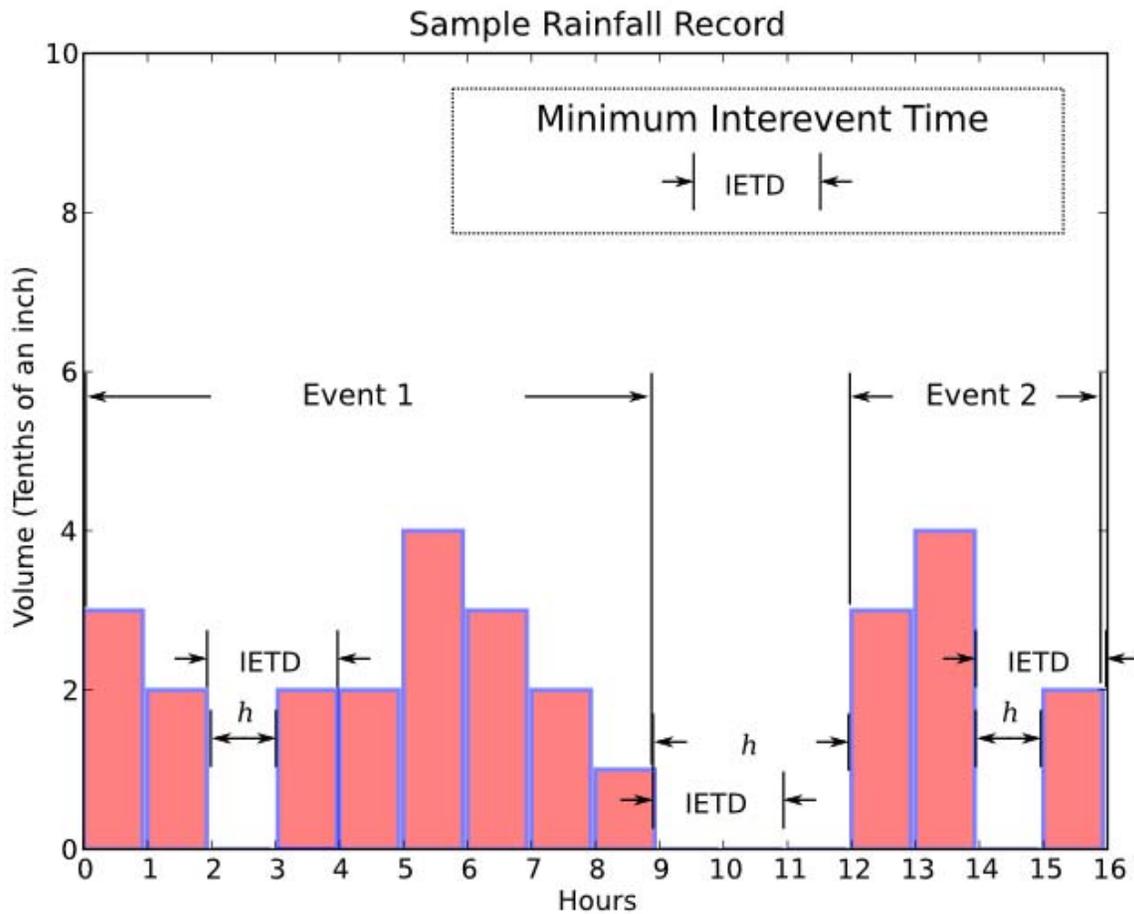


Figure 1: Delineation of Long-term Rainfall Records through IETD

In this example, the rainfall record granularity was given in one-hour intervals, and the volume measurements were given in tenths of inches. The IETD was defined to be two hours. The volume and duration parameters are simply the sum of the volume of rain recorded during the event, and the number of hours that the event lasted respectively. The intensity parameter is therefore given by volume divided by duration of the event. :

2.2 The Rainfall Record

The first, and most important, design consideration when writing the Rain Event Parser was to determine the likely source material for rainfall records. A decision was made to build the utility to parse the hourly precipitation data files produced by the National Climatic Data Center

(NCDC, see: <http://www.ncdc.noaa.gov/oa/ncdc.html>). These files catalog hourly precipitation information, and present the records in a comma-delimited ASCII text file. The advantage of supporting files from the NCDC is that there is a great deal of coverage, both geographically and historically, in their database; a disadvantage is that the actual formatting of the data within each file is somewhat cumbersome to parse effectively.

Below are the first two lines of data from a sample rainfall record from the NCDC, along with the header rows which contain the column descriptions:

```
COOPID,CD,ELEM,UN,YEAR,MO,DA,TIME,HOUR01,F,F,TIME,HOUR02,F,F,TIME,
HOUR03,F,F,TIME,HOUR04,F,F,TIME,HOUR05,F,F,TIME,HOUR06,F,F,TIME,HO
UR07,F,F,TIME,HOUR08,F,F,TIME,HOUR09,F,F,TIME,HOUR10,F,F,TIME,HOUR
11,F,F,TIME,HOUR12,F,F,TIME,HOUR13,F,F,TIME,HOUR14,F,F,TIME,HOUR15
,F,F,TIME,HOUR16,F,F,TIME,HOUR17,F,F,TIME,HOUR18,F,F,TIME,HOUR19,F
,F,TIME,HOUR20,F,F,TIME,HOUR21,F,F,TIME,HOUR22,F,F,TIME,HOUR23,F,F
,TIME,HOUR24,F,F,TIME, TOTAL,F,F
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,-----,-----,-----,-----,-----,-----,-----,-----,-----
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-----,-----,-----,-----,-----,-----,-----,-----,-----
448906,00,HPCP,HI,1948,05,01,0100, 00000,g, ,0200, 00000, , ,0300,
00000, , ,0400, 00000, , ,0500, 00000, , ,0600, 00000, , ,0700,
00000, , ,0800, 00000, , ,0900, 00000, , ,1000, 00000, , ,1100,
00000, , ,1200, 00000, , ,1300, 00000, , ,1400, 00000, , ,1500,
00000, , ,1600, 00001, , ,1700, 00002, , ,1800, 00000, , ,1900,
00000, , ,2000, 00000, , ,2100, 00000, , ,2200, 00000, , ,2300,
00000, , ,2400, 00000, , ,2500, 00003, ,
448906,00,HPCP,HI,1948,05,02,0100, 00000, , ,0200, 00000, , ,0300,
00000, , ,0400, 00000, , ,0500, 00000, , ,0600, 00000, , ,0700,
00000, , ,0800, 00000, , ,0900, 00000, , ,1000, 00000, , ,1100,
00000, , ,1200, 00000, , ,1300, 00000, , ,1400, 00000, , ,1500,
00002, , ,1600, 00012, , ,1700, 00001, , ,1800, 00002, , ,1900,
00000, , ,2000, 00000, , ,2100, 00000, , ,2200, 00000, , ,2300,
00000, , ,2400, 00000, , ,2500, 00017, ,
```

3.0 Requirements of the Application

The Rain Event Parser was designed from the beginning to be an easily accessible utility. First and foremost, the application must correctly parse the rainfall events from the provided rainfall record; this requirement is crucial, because it is the basis by which all of the other functions will perform their duties.

The long-term rainfall record has been discretized into individual events through defining an IETD. Then the time series of rainfall event characteristics (volume, duration, intensity and inter-event time) were used to develop the histogram by selecting appropriate intervals. The histograms were fitted with several probability density functions, particularly exponential and Gamma distributions. Therefore, ultimate result of this application is to produce the necessary input parameters for the Exponential and Gamma PDF functions, which will allow engineers and researchers to use these values to help design urban stormwater infrastructure elements.

The Rain Event Parser has three main elements: An engine for parsing rain events from supplied rainfall records, a front-end application interface, and a series of utilities to aid in performing statistical analysis on the parsed events. These aspects will be described throughout the rest of this report.

3.1 *The Parsing Engine*

Following the decision to support rainfall records from the NCDC, a preliminary parsing engine was developed using the Python programming language (see: <http://www.python.org/>). Python was initially chosen because of its efficient text processing capabilities, and because it is a fully Object Oriented language. The former consideration is obvious, given the nature of the input medium; the latter consideration was made in order to use high-level abstractions to treat all of the input parameters. The chief goal of the parsing engine was to build a series of objects which describe the main characteristics of the problem domain, and to define a series of methods which access, modify, or compute intermediary results related to those objects. The parsing engine uses three primary classes to abstract the data:

- 1) Event
 1. Attributes and Accessor Methods:

1. date (The date the event began)
2. hour (The hour the event began)
3. inter_time (The number of hours elapsed between the prior event and the current event)
4. values (A list containing the hourly recorded rainfall measurements)
2. Methods:
 1. volume() (Returns the total volume of precipitation for the event)
 2. duration() (Returns the total number of hours recorded for this event)
 3. intensity() (Returns the volume/duration for the event)
 4. retrieve(parameter) (Returns the value for a given parameter [used for output routines])
 5. append() (Add another hourly rainfall measurement to this event)

2) EventContainer

1. Attributes and Accessor Methods:
 1. ietd (The current IETD being used to delimit the events)
 2. events (A list containing each Event object parsed for the supplied IETD)
 3. avgs (A dictionary containing average values for each parameter)
 4. sds (A dictionary containing the standard deviations for each parameter)
 5. ex_vrs (A list containing the input parameters for the Exponential PDF for each of the usual parameters)
 6. rhos (A list containing the rho input parameter for the Gamma PDF for each of the input parameters)
 7. taus (A list containing the tau input parameter for the Gamma PDF for each of the input parameters)
2. Methods:
 1. append() (Add an event to the current list)
 2. avg() (Calculate the average for the desired parameter and populate 'avgs')
 3. sd() (Calculates the standard deviation for the desired parameter and populate 'sds')
 4. rho(), tau(), and ex_vr() (Responsible for calculating the values required to compute the Gamma and Exponential PDF's)

3) RainDataParser

1. Attributes and Accessor Methods:

1. infile (NCDC file to be parsed)
2. ec (Holds the EventContainer instance for each supplied IETD)
3. winter (A list which holds the numerical values for months that are to be ignored each year, due to poor weather)

2. Methods:

1. parse(ietd) (Read the file, and fill the container with the parsed events)

These three classes handle virtually all of the functions required to effectively parse the rainfall events present in the files from the NCDC.

The Event class is the fundamental building block by which the rest of the application is built. An Event object captures the hourly rainfall found for a rainfall event from the NCDC record, along with the date and time that the event began. Every entry in the list stored within the Event object represents one hour of rainfall data. Hours during the event which had no recorded rainfall (but were below the IETD event delimiter) are stored as zero values, to preserve the average intensity calculations.

The EventContainer class is used to store all of the events which were found within the input file for the desired IETD delimiter. Objects of this type are also used to compute several useful statistics related to the sample. The EventContainer is not, however, responsible for the actual parsing of the input file; this design feature allows the class to be used potentially to capture events recorded in other formats at a later date.

Finally, the RainDataParser has the task of parsing the actual events from within the NCDC data record. The method for extracting the events from an input file is complicated by several factors: first, dates for which no rainfall was measured are not present in the file; second, records where a “trace” amount of rainfall was recorded are present in the file; and third, events may span across several days, where each day is represented by a different record. None of these issues are, in and of themselves, difficult to overcome, yet it should be noted that extreme caution was taken to ensure that these issues were addressed to preserve proper event recognition within the application.

3.2 The Statistical Analysis

In order to provide the requisite series of statistical parameters to the researcher, some basic analysis must be performed on the parsed events. Specifically, the average and standard deviation must be acquired for each of the four main event parameters.

The methods for computing the average (the arithmetic mean) is as follows:

$$\mu_X = \frac{1}{n} \sum_{i=0}^n x_i$$

Where n represents the number of items in the sample, and x represents each sampled value.

Similarly, the method for computing the standard deviation is straight forward:

$$\sigma_X = \sqrt{\sigma^2} = \sqrt{\frac{\sum_{i=0}^n (x_i - \mu_X)^2}{n-1}}$$

As previously stated, the analytical probabilistic model which is being implemented by this tool needs to deliver the Exponential and Gamma PDF's. The following two sections illustrate the method by which the application generates these functions.

3.2.1 The Exponential PDF

The Exponential PDF is given by:

$$f_X(x) = \gamma e^{-\gamma x}, \quad x \geq 0$$

and

$$\gamma = \frac{1}{\mu_X} = \frac{1}{\sigma_X}$$

where μ_X is the mean, and σ_X is the standard deviation. Usually, the following variables are used to describe the Exponential PDF for each of the four parameters ($\lambda, \zeta, \beta, \psi$):

$$f_V(v) = \zeta e^{-\zeta v}, \quad v \geq 0, \text{ where } \zeta = \frac{1}{v} \quad (\text{mm}^{-1})$$

$$f_T(t) = \lambda e^{-\lambda t}, \quad t \geq 0, \text{ where } \lambda = \frac{1}{t} \quad (\text{h}^{-1})$$

$$f_I(i) = \beta e^{-\beta i}, \quad i \geq 0, \text{ where } \beta = \frac{1}{i} \quad (\text{h/mm})$$

$$f_B(b) = \psi e^{-\psi b}, \quad b \geq 0, \text{ where } \psi = \frac{1}{b} \quad (\text{h}^{-1})$$

To return the proper value for the input parameters, one must simply return the inverse of the average for each parameter to the researcher.

3.2.2 The Gamma PDF

The Gamma PDF is given by:

$$f_X(x) = \frac{x^{\rho-1} e^{-x/\tau}}{\tau^\rho \Gamma(\rho)}$$

where,

$$\rho = \mu_X^2 / \sigma_X^2, \quad \text{and} \quad \tau = \sigma_X^2 / \mu_X$$

and,

$$\Gamma(\rho) = \int_0^{\infty} z^{\rho-1} e^{-z} dz$$

is the Gamma function.

In contrast to the Exponential PDF, the Gamma PDF requires more in the way of computation to produce the result. The SciPy Python package (see: <http://scipy.org/>) is used to provide useful statistical support for this project; specifically, the Gamma function defined in the package is used to generate the curve for the graphical representations (described in a subsequent section).

3.3 The User Interface

There are currently two different methods for accessing the utility: a web-based front-end application, and a command-line driven application. Each interface will be described in the following two sections.

3.3.1 A Web-based Interface

Since the goal of the utility is to help relieve some of the difficulty in modeling stormwater management scenarios, it was important to account for the user-friendliness of the application. The initial design considerations for the Rain Event Parser were to either build a Graphical User Interface (GUI) or a web-based interface; the web-based interface eventually took precedence, as it appeals to a broader audience, and requires no additional software to be installed on the researcher's computer. There are two possible avenues one can choose from when designing a web-based application of the type required for the Rain Event Parser: A Common Gateway Interface (CGI) script, or a Web Application Framework. CGI scripts provide a simple interface which communicates directly with a user's web browser. These scripts require very little in the way of special software, yet they make more complex tasks (such as database access) somewhat more complicated. In order to provide a scalable application, it was decided to use a Web Application Framework to build the Rain Event Parser. This application allows the engine of the Rain Event Parser to be run in a browsing session; it handles user input/output routines, builds customized HTML pages, and allows for simple database access (note: a database feature was not part of the original specification, but the chosen framework enables one to be used in the future with a minimum impact).

As a web-based application, the Rain Event Parser is extremely simple to use. Once a researcher acquires a properly formatted file from the NCDC (there is a tutorial document, in Portable Document Format, to aid an individual in requesting the correct information) they may upload the file into the interface, choose the options that they want, and hit the 'Submit Query' button. The web based GUI of the software is presented in the following Figure 1.

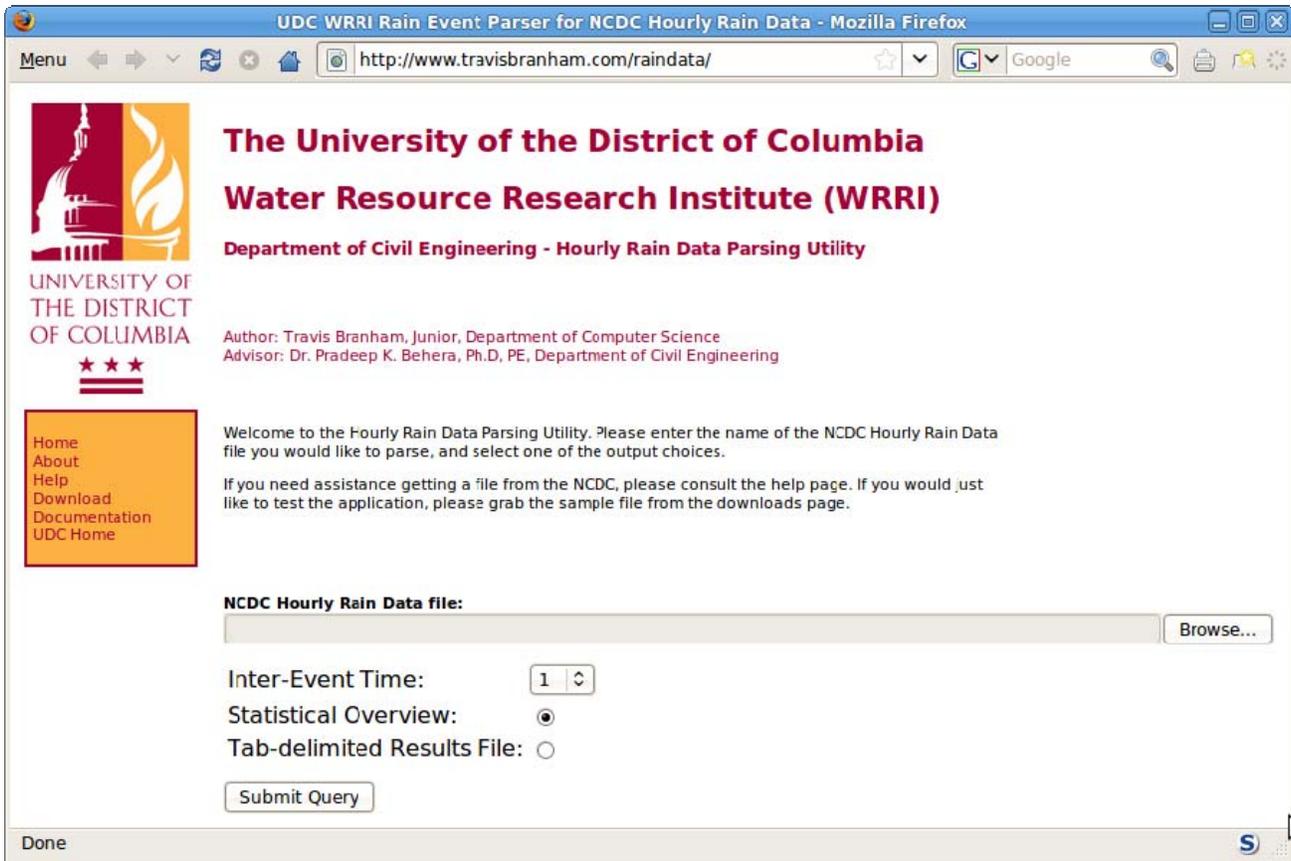


Figure 1: Web-base Graphical User Interface

3.3.2 A Command-line Interface

Prior to developing the web-based front-end, a simple command-line utility wrapper was created around the core parsing engine to enable for testing and debugging of the application. This version has an advantage over the web-based front-end in that it is capable of running directly on the researcher's machine, provided they have the Python Programming Language and the SciPy library installed. Both Python and SciPy are free, open-source software packages, which means that there is no additional monetary cost associated with running the application in this manner.

In its current incarnation, the command-line interface utility is extremely simplistic: it accepts the name of the NCDC rainfall record file to be parsed at the command line, along with the list of IETD's that the researcher is interested in using to parse the file.

3.4 Output

Both the command-line and web-based utilities are capable of generating several types of output, in order to best serve the needs of researchers. Currently, due to limitations on the testing server which the web-based application is running, the graphs which are generated for the parsed events, and the associated plots for the PDF functions, are not being provided. Researchers using the web-based interface will, however, receive the input parameters for the Exponential and Gamma PDF's so that they may plot these functions in a spreadsheet application themselves. The command-line interface utility, however, does generate full plots, as well as text-based output. Both output types are described in detail in the following sections.

3.4.1 Text-based Output

There are two primary text-based output types associated with the web-based Rain Event Parser: the Statistical Overview, and the Tab-delimited Results File (suitable for opening in a spreadsheet application). If one chooses the statistical overview, they will be presented with the relevant statistics related to the input file, such as the number of events, the averages and standard deviations for the four main parameters. The tab-delimited results file provides a comprehensive list of all of the events, and associated statistics, which were parsed from the file. The former output method is only beneficial for performing quick calculations on the aggregate: calculations which only require knowing, say, the number of events in the period, or the average amount of rainfall; the latter output method is useful for importing into a spreadsheet application so that the researcher may scrutinize the parsed events.

The following is an example of the type of statistics generated in the overview from a sample rainfall record:

```
IETD: 2
Total Events           : 6887 (Winter months stripped)

Hours (Hours)
- Average              : 4.14142587483665
- Standard deviation  : 4.51319186850992
- Lambda              : 0.241462730523806
- Rho                 : 0.842038969594977
- Tau                 : 4.91833041507412
```

```
-----  
Volume (Hundredths of inches)  
- Average : 29.5273704080151  
- Standard deviation : 48.7076649376923  
- Zeta : 0.0338668830370534  
- Rho : 0.367497953162945  
- Tau : 80.3470336470771  
-----
```

```
Intensity (Hundredths of inches per hour)  
- Average : 6.91519290491069  
- Standard deviation : 10.372495929665  
- Beta : 0.144609125696243  
- Rho : 0.444469590591927  
- Tau : 15.5583037653967  
-----
```

```
Inter-event Time (Hours)  
(Based on 6827 events)  
- Average : 59.0519994140911  
- Standard deviation : 78.3340571853644  
- Psi : 0.0169342276285632  
- Rho : 0.568287328178645  
- Tau : 103.912222719011  
-----
```

3.4.2 Graphical Output

The web-based utility provides the simplified statistical output directly on the output web page as shown in the following Figure 2:

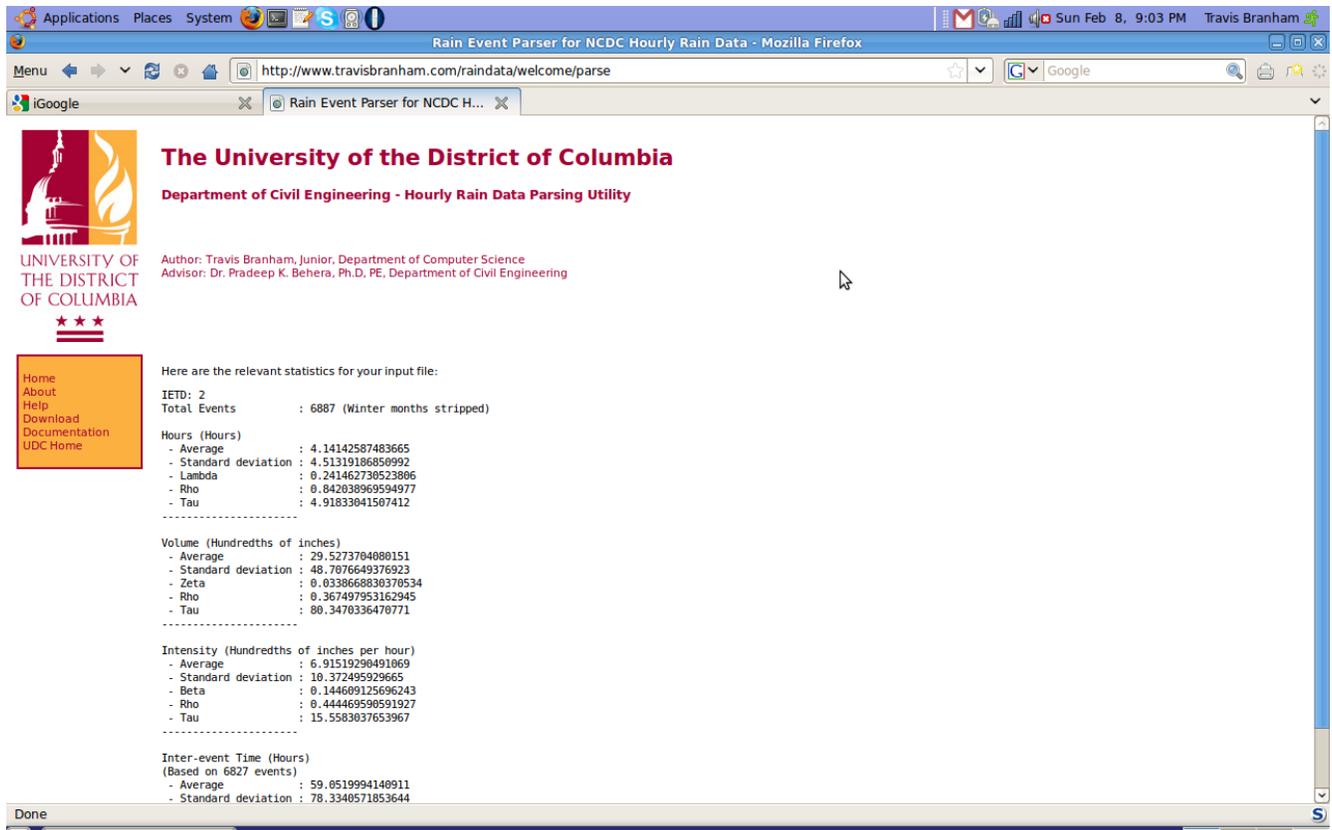


Figure 2: Output Web Page

As was mentioned previously, the web-based interface does not currently support the generating of graphs. The command-line utility, however, is capable of generating sophisticated graphs of the rainfall parameter histograms, in addition to plots of the Exponential and Gamma PDF functions. The following Figure 3 contains a typical image generated by the Rain Event Parser:

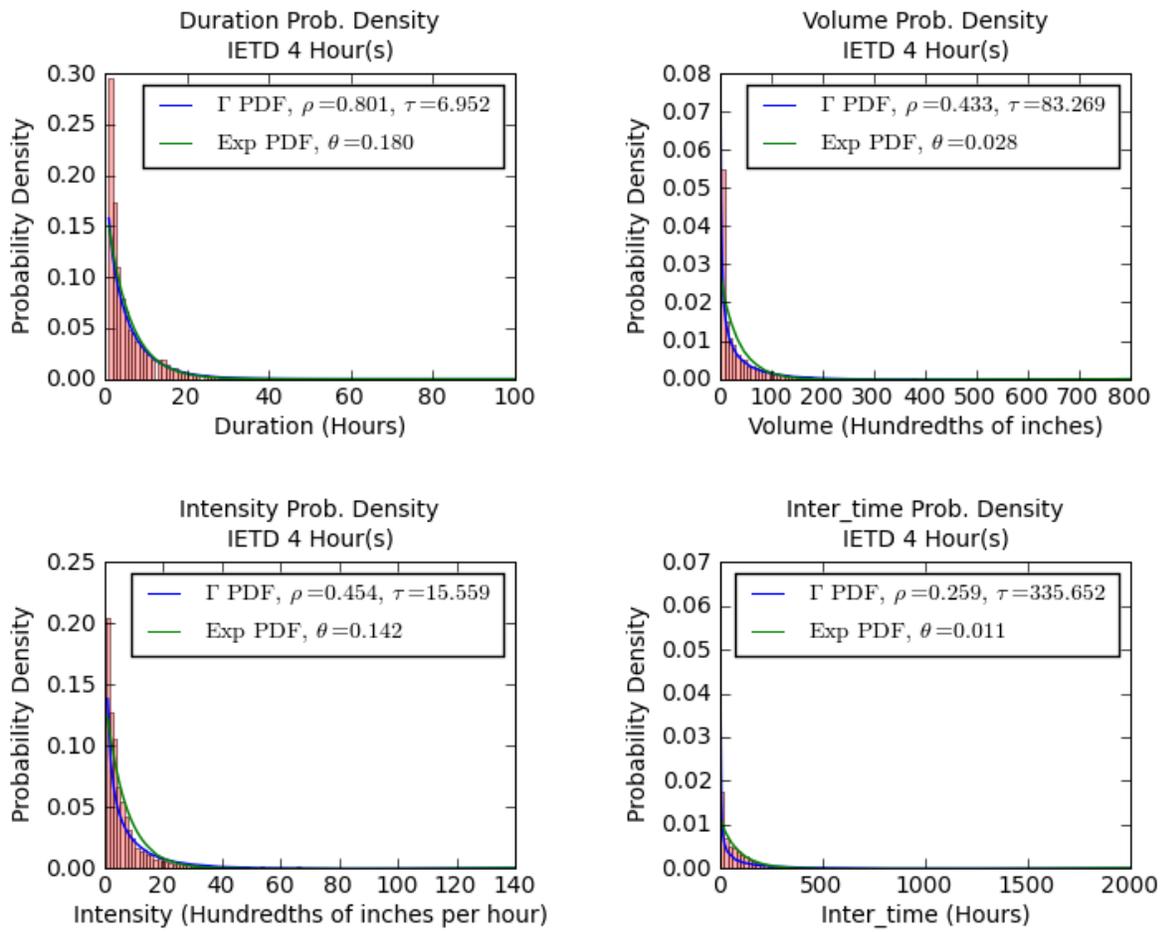


Figure 3: Graphs with Fitting Distributions

The command-line utility also allows for individual graphs to be generated:

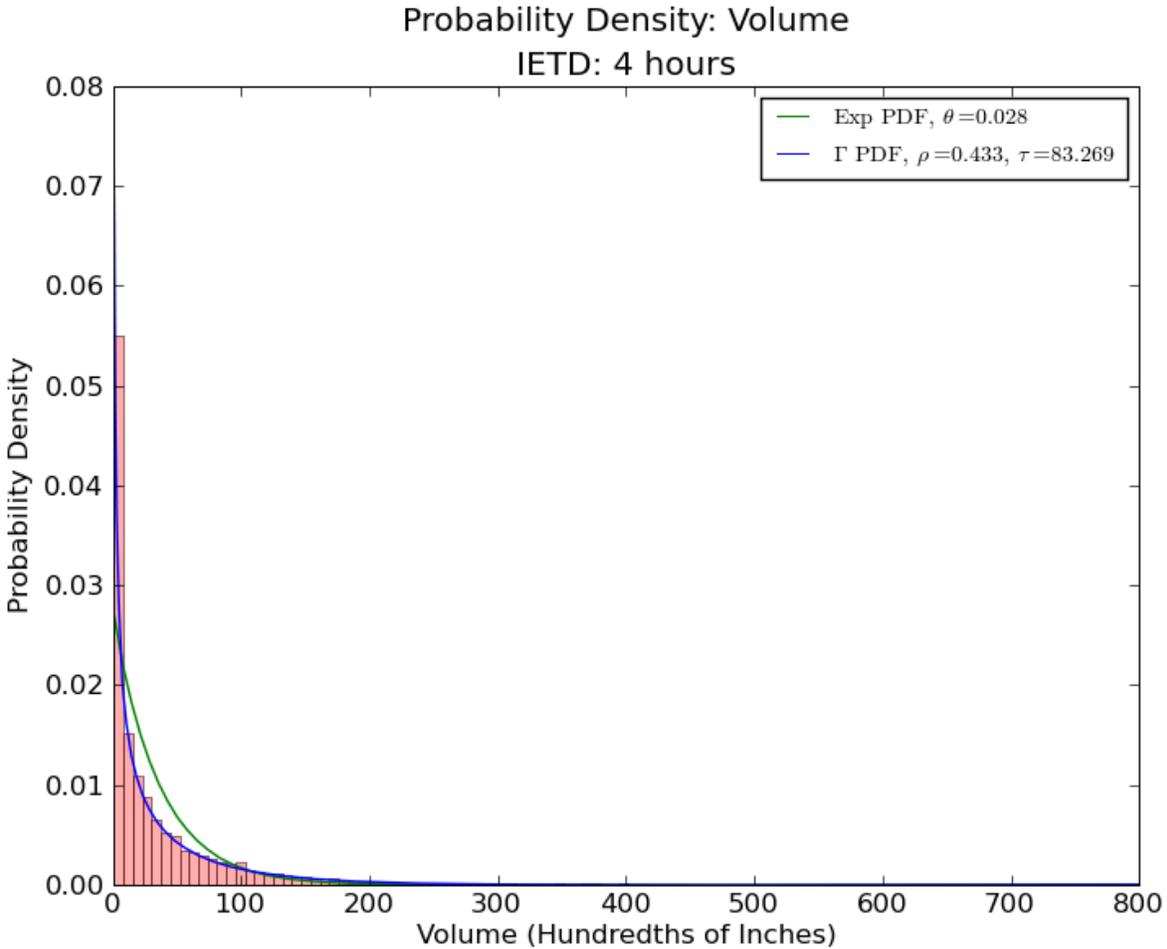


Figure 4: Exponential and Gamma PDF of Rainfall Event Volume with IETD 4 hours

The plots are generated with the help of the matplotlib Python library (see: <http://matplotlib.sourceforge.net/>). Further, since the core parsing engine is written in Python, a researcher familiar with mathematical and statistical packages such as Matlab will be able to use the core parsing engine as a module in the iPython interface, which allows for interactive graph manipulation. For example, one can dynamically change the output parameters on the generated graph to zoom into an area of interest. The following Figure 5 shows the same graph above, but with different x and y limits specified:

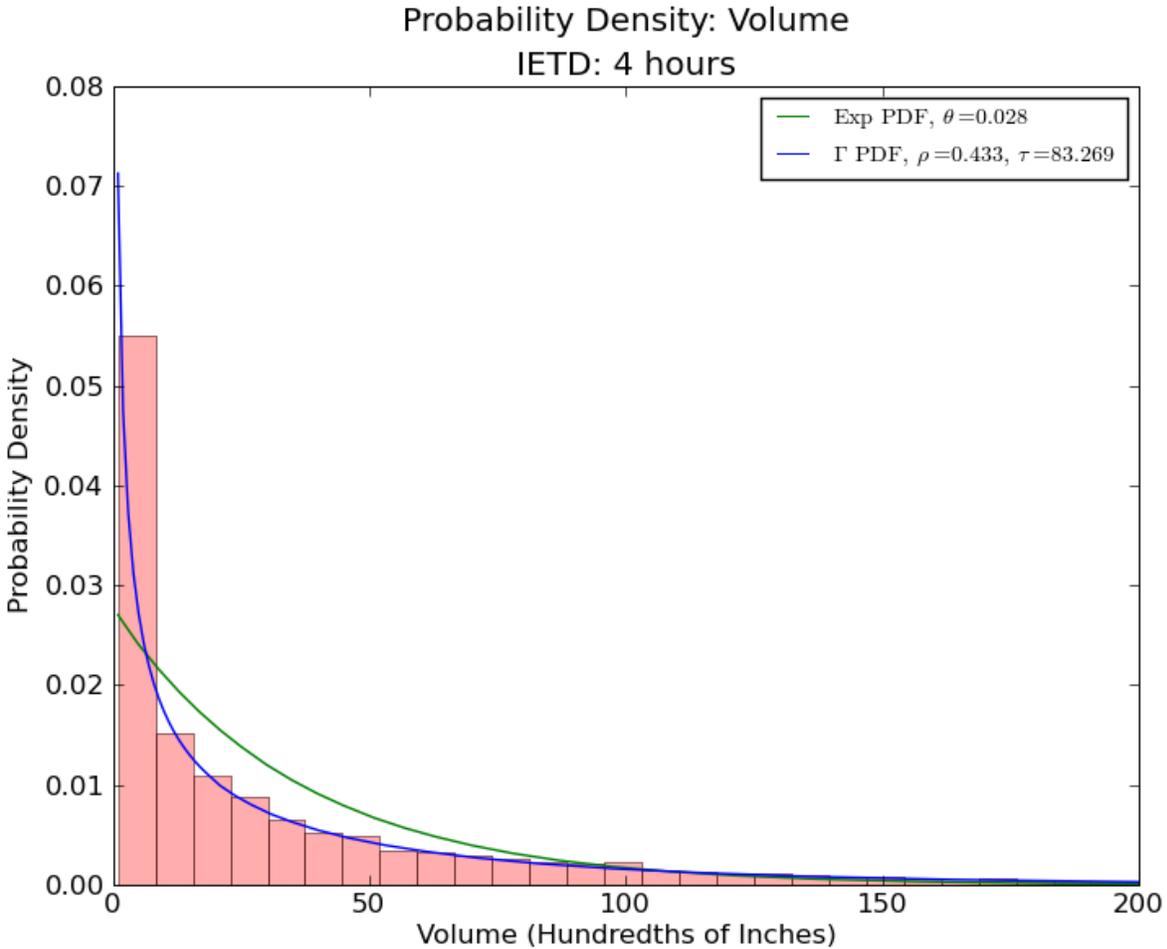


Figure 5: Exponential and Gamma PDF of Rainfall Event Volume with IETD 4 hours

4.0 Conclusions

The Rain Event Parser application, as described throughout this report, is capable of delivering the statistical parameters necessary for researchers to implement an analytical probabilistic model for urban stormwater management. Further, students will be able to analyze the effect that the runoff coefficient plays when designing areas of varying imperviousness. By developing web-based statistical rainfall analysis tool, the water resources engineers, researchers and regulatory authorities can easily use the NOAA NCDC data effectively. The statistical tool will provide the parameters of probability distributions of rainfall characteristics such as storm event volume, duration, intensity and inter-event time of long-term rainfall record. The fitting of different probability distribution functions to rainfall characteristics will provide a number of useful information such as magnitude-frequency relationship of rainfall volumes and extreme event analysis can easily be conducted. The outcome of this research will benefit the use of

analytical probabilistic models for urban stormwater management analysis. Analytical models uses continuous simulation approach and are computational efficient compared to available continuous simulation models such as U.S. EPA SWWM. The development of this tool benefit to the students as it can be used for demonstration of statistical analysis. Since the application will be primarily for web-based users, the scope of the application will reach civil engineers from around the country that are interested in implementing this type of analytical probabilistic modeling in their own research.

5.0 Acknowledgements

This research is possible through the funding support from the DC Water Resources Research Institute, National Water Resources Institutes and U.S. Geological Survey.

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Assessing the Distribution of Synthetic Organics and the degradation of Polyaromatic Hydrocarbons in the Anacostia River through Microbial and Stable Isotope Studies

Basic Information

Title:	Assessing the Distribution of Synthetic Organics and the degradation of Polyaromatic Hydrocarbons in the Anacostia River through Microbial and Stable Isotope Studies
Project Number:	2008DC94B
Start Date:	3/1/2008
End Date:	2/28/2009
Funding Source:	104B
Congressional District:	District of Columbia
Research Category:	Biological Sciences
Focus Category:	Ecology, Sediments, Toxic Substances
Descriptors:	None
Principal Investigators:	Karen L. Bushaw-Newton, Stephen E. MacAvoy

Publication

Over the past six months research has been conducted to demonstrate bacterial utilization of several different PAH compounds commonly found in the Anacostia River system. Three sites were chosen based upon previous research (MacAvoy et al. submitted, Bushaw-Newton et al. submitted) and represent different regions of the tidal portion of the Anacostia River

system. Dr. Bushaw-Newton's lab comprised of a graduate student (Evan Ewers) and undergraduate student (Huyen Nguyen) has successfully demonstrated using microplate assays that communities from three regions of the Anacostia River are able to breakdown a variety of PAH compounds (Figure 1). Further, her lab has also

Site	Fluorene	Fluoranthene	Pyrene	Phenanthrene
UP	+	-	+	+
MID	+	+	+	-
DOWN	+	+	+	+

demonstrated through preliminary molecular analyses the presence of three different types of genes known for PAH degradation including monooxygenases (*tmoA*) and dioxygenases (*ndo* and *nid*-like) within the three different regions of the river. Work is ongoing on isolating individual bacteria from the Anacostia River system and sequencing some of the community DNA to determine the novelty of the bacteria within the system. In Fall 2008, we presented research on microbial aspects of PAH degradation in the Anacostia system at the Atlantic Estuarine Research Society Meeting (abstract below). Further, in the spring we will be sampling the river for different biogeochemical profiles.

Professional Presentations

Bushaw-Newton, K.L. and E. Ewers. 2008. Presence and Metabolic activities of bacteria that degrade polycyclic aromatic hydrocarbons in sediments of the Anacostia River. Fall Meeting of the Atlantic Estuarine Society-Nov 7-9, George Mason University, Oral Presentation.

The Anacostia River (Washington, DC) is an urban river rich in organic contaminants, particularly polycyclic aromatic hydrocarbons (PAHs). However, the potential of PAH remediation through the local microbial population has not been investigated. Twenty-one strains representing three different regions (upstream, middle and downstream) of the Anacostia River system were capable of degrading either the PAHs or BTX compounds, with many strains able to utilize multiple PAHs as the carbon source. In addition, a microtiter plate method was employed to examine sediment community degradation capacity using the WST-1 respiration indicator. Community analysis using the WST-1 respiration indicator showed potential for utilization of all tested PAHs. The upstream community favored phenanthrene and pyrene as carbon sources, while the

midstream and downstream communities utilized fluoroanthene and fluorene more readily. PCR using primers for the *tmoA*-like genes yielded product in samples from all sites, with greater presence in the upstream and downstream communities. PAH and BTX-utilizing isolates showed the ability to utilize multiple PAHs as the sole carbon source, suggesting the presence of genes capable of breaking down multiple hydrocarbons in the community, such as the *tmoA*-like genes. Overall the Anacostia River system possesses bacteria within the sediment capable of degrading PAHs.

Citations

Bushaw-Newton, K. L., E. C. Ewers, D. J. Velinsky, J. T. Ashley, C. S. Fortunato, and S. MacAvoy. *Submitted*. Microbial community snapshots from sediments of the Anacostia River using metabolic and molecular analyses. *Microbial Ecology*

MacAvoy, S.E., E. Ewers, and K. L. Bushaw-Newton. *In review*. A Biogeochemical Survey of the Anacostia River, Washington DC. *Environmental Monitoring and Assessment*. (Corresponding author)

Gradual Variation Analysis for Groundwater Flow in the District of Columbia (Phase II)

Basic Information

Title:	Gradual Variation Analysis for Groundwater Flow in the District of Columbia (Phase II)
Project Number:	2008DC96B
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Focus Category:	Groundwater, Models, Methods
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Publication

DC Water Resources Research Institute Progress Report

Gradual Variation Analysis for Groundwater Flow of DC (II)

March 1, 2008-February 29, 2009

Li Chen

Department of Computer Science and Information Technology
University of the District of Columbia

Email: lchen@udc.edu

(202) 274-6301

Abstract

Groundwater flow in Washington DC greatly influences the surface water quality **in urban areas**. **The current methods of flow estimation, based on Darcy's Law and the groundwater flow equation**, can be described by the diffusion equation (the transient flow) and the Laplace equation (the steady-state flow). The Laplace equation is a simplification of the diffusion equation under the condition that the aquifer has a recharging boundary. The practical way of calculation is to use numerical methods to solve these equations. The most popular system is called MODFLOW, which was developed by USGS. MODFLOW is based on the finite-difference method in rectangular Cartesian coordinates. **MODFLOW can be viewed as a "quasi 3D" simulation since it only deals with the vertical average (no z-direction derivative)**. Flow calculations between the 2D horizontal layers use the concept of leakage.

In the project, we have established a mathematical model based on gradually varied functions for groundwater data volume reconstruction. These functions do not rely on the rectangular Cartesian coordinate system. A gradually varied function can be defined in a general graph or network. Gradually varied functions are suitable for arbitrarily shaped aquifers. Two types of models are designed and implemented for real data processing: (1) the gradually varied model for individual (time) groundwater flow data, (2) the gradually varied model for sequential (time) groundwater flow data. In application, we also established a MySQL database to support the related research.

In the year of 2008-2009, we mainly investigated new approaches and modify the programming code for year of 2007-2008: (1) Theoretical algorithm design with consideration of harmonic analysis, (2) Discrete algorithm testing and modification. We still need more time to finish the final report. These functions do not rely on a rectangular Cartesian coordinate system. A gradually varied function can be defined in a general graph or network. Gradually varied functions are suitable for arbitrarily shaped aquifers.

Research Team Members: Li Chen (Professor), Travis L. Branham(Student)

1. Introduction

Groundwater flow in DC has greatly influenced the surface water quality in urban areas. The current method of flow estimation mainly uses the ground flow equation, which is a partial differential equation. Software systems such as MODFLOW can only solve 2D equations and pass the data vertically to form a 3D volume. The research on the 3D models of groundwater flow has fundamental and practical importance to hydrogeology. A method used to establish a true 3D Groundwater flow will be very useful to groundwater related research in DC. The new method can also be extended for use in other regions.

A feasible and true 3D model for groundwater flow is essential to groundwater research. This project attempts to establish a 3D model using discrete mathematics, especially graphical and graph-theoretical methods, to compute groundwater flow. It is called the gradual variation method. This method can be combined with the existing technology such as MODFLOW for more accurate results. The research is focused on the groundwater flow of the DC area. We have established a connection to use gradually varied functions in groundwater research. We have accomplished three tasks: (1) extracting of real data from databases of DC areas, (2) storing the data into local database, (3) reconstructing the water-head surfaces for time sequences using gradually varied surface fitting. We have also completed the design of the combined gradually varied fitting using the finite difference method.

The results of the research will provide a reliable source to better understand the groundwater of DC. The images of data flow will indicate the activity of the groundwater flow. Beyond the theoretical achievements, the undergraduate and graduate students of computer science will have the opportunity to learn how to conduct state of the art groundwater research and use various software systems. These students could work in the environmental sciences in the future.

2. The Problem, Methods and the Research Path

In order to use discrete methods for Groundwater Modeling, we need to solve the following problems: (1) Groundwater flow equations and its discrete forms, (2) Gradually varied functions for groundwater data, (3) Real data preparation, (4) Algorithms, especially fast design, (5) Real data processing and applications.

Much research has already been done to find a discrete model for the groundwater flow equations. So our first task is to investigate the suitability of gradually varied functions for groundwater data. Then, we must find a connection between the flow equations and gradually varied functions. We also need to design an input data format to store the data in a database.

A gradually varied function is for the discrete system where a high level of smoothness is not a dominant factor. It can be used in any type of decomposition of the

domain. It is more flexible than rectangle-cells used in MODFLOW and triangle-cells used in FEFLOW. Because gradual variation does not have strict system requirements, the other mathematical methods and the artificial intelligence methods can be easily incorporated into this method to seek a better solution. Based on the boundary conditions or constraints of the groundwater aquifer, the constraints could be in explicit forms or in differential forms such as the diffusion equations. The gradually varied function exists based on the following theorem: The necessary and sufficient condition of the existence of a gradually varied function is that the change of values in any pair of sample points is smaller or equal to the distance of the points in the pair.

3. Background and Related Research

The research of groundwater flow is one of the major topics in groundwater research [1] [2] (this sentence does not make sense and just repeats itself). The groundwater flow equation **based on Darcy's Law** usually describes the movement of groundwater in a porous medium such as aquifers. It is known in mathematics as the diffusion equation. The Laplace equation (for a steady-state flow) is a simplification of the diffusion equation under the condition that the aquifer has a recharging boundary. The conservation of mass states that for a given increment of time (Δt) **“the difference between the mass flowing in across the boundaries, the mass flowing out across the boundaries, and the sources within the volume, is the change in storage.”**[2]

$$\frac{\Delta M_{stor}}{\Delta t} = \frac{M_{in}}{\Delta t} - \frac{M_{out}}{\Delta t} - \frac{M_{gen}}{\Delta t} \quad (1)$$

Its differential form is

$$\frac{\partial h}{\partial t} = \alpha \left[\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} \right] - G \quad (2)$$

To solve this equation, a grid method is usually used, such as the finite difference or finite element method [3] [4]. Other methods including the analytic element method attempt to solve the equation exactly, but need approximations of the boundary conditions [5][6]; they are mainly used in academic and research labs.

The practical way of calculating is to use numerical methods to solve these equations. The most popular system is called MODFLOW, which was developed by USGS [7]. MODFLOW is based on the finite-difference method on rectangular Cartesian coordinates. **MODFLOW can be viewed as a “quasi 3D” simulation** since it only deals with the vertical average (no z -direction derivative). Flow calculations between the 2D horizontal layers use the concept of leakage.

Gradual variation is a discrete method that can build on any decomposition or networking. It was originally introduced to solve image processing problems and discrete surface reconstruction [8][9][21]. See Fig 1. When a boundary is known, it can be used to fit (solve) for the internal points in any type of linked connection. The original research

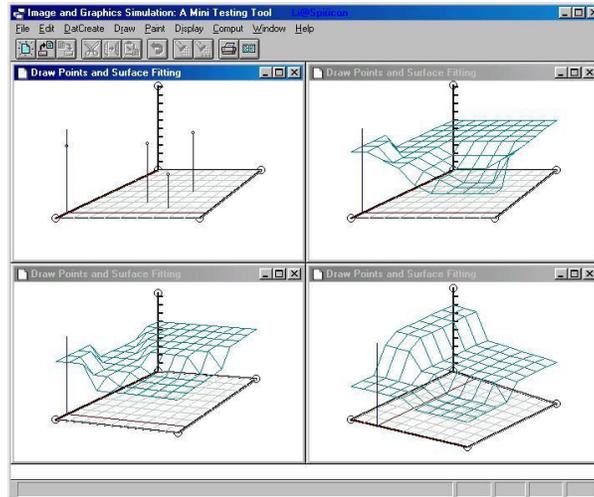


Fig 1. Gradually Varied Surfaces

of this project is to use **Darcy's Law or differential constrains to determine the value of** the unknown points instead of the random selection of the construction of gradually varied surfaces when there are more than one possible selections [10]. When the determination of the values are uncertain, we will try to use the artificial intelligence methods such as neural networks and genetic algorithms to help us to find near optimal solutions. These types of studies have already been done by many researchers in groundwater flow [11][12].

On the other hand, current research still showed considerable interest in establishing new modeling methods for groundwater flow [13-16]. Both the US and DC governments are concerned with the future of groundwater flow research [17][18]. This project on the 3D models of groundwater flow has fundamental and practical importance to hydrogeology. A method used to establish a true 3D model for groundwater flow will be very useful to groundwater related research in DC and in other urban areas.

4. Data Preparation

Data Preparation is a very important part of this project, please see appendix or [20] for more information. We have to use PHP to build a web application to access groundwater log data in Virginia and Maryland. Data is stored in MySQL databases.

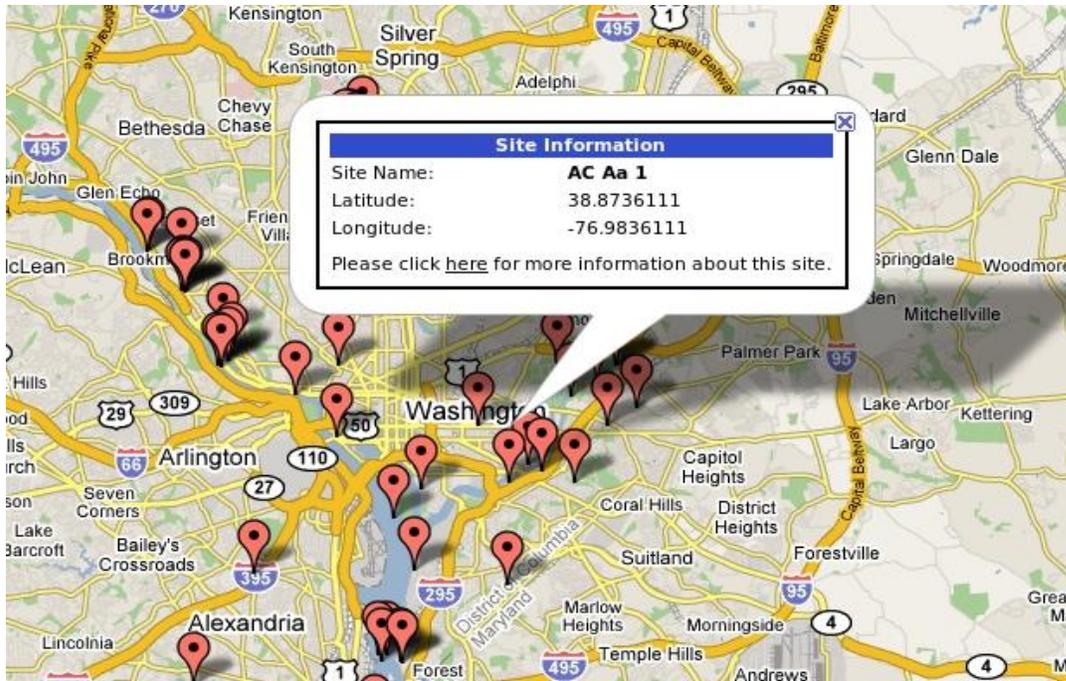


Fig. 2 Web based data collection

“A vast quantity of information, on many subjects that may be of interest to the general public, is offered, through various government agencies, free of charge; the methods for acquiring and understanding this data, however, can be difficult and troublesome for many individuals. The web-based application outlined in this paper attempts to address the difficulties inherent in the dissemination of data to interested members of the general public, and specifically data which has a geographical reference component.

This application deals specifically with water quality data in the metropolitan Washington, D.C. area, as reported by the U.S. Geological Survey (USGS). Interested individuals will access the web-based utility and, from there, easily navigate to the desired information. The data is presented initially by icons, representing water quality testing locations, plotted onto a map of the metropolitan Washington, D.C. region; as the user clicks an icon, he or she will be presented with a list of dates, with each date corresponding to an actual water quality test. By clicking on a date, users will then be presented with a page-by-page view of the values for each type of test performed at that time (e.g. lead, arsenic, etc.). In addition to the ability to browse these sites randomly, users may enter an address, and a radius, to find only the sites of closest geographical interest.” [20]

The application, in its current form, can be found at:
<http://www.travisbranham.com/waterquality/>

5. Ground Water Surface Fitting

We have done extensive research on data collection and initial data reconstruction using gradually varied functions that are for the discrete system where a high level of smoothness is not a dominant factor. Since they can be used on any type of decomposition of the domain, gradually varied functions are more flexible than rectangle-cells used in MODFLOW and triangle-cells used in FEFLOW. Because gradual variation does not have strict system requirements, the other mathematical methods and the artificial intelligence methods can be easily incorporated into this method to seek a better solution. Based on the boundary conditions or constraints of the groundwater aquifer, the constraints could be in explicit forms or in differential forms such as the diffusion equations. Again we select the gradually varied function because of the following theorem: The necessary and sufficient condition of the existence of a gradually varied function is that the change of values in any pair of sample points is smaller or equal to the distance of the points in the pair.

5.1 Individual surface fitting

Gradual variation is a discrete method that can be built on any graph. The gradually varied surface is a special discrete surface. We now introduce this concept.

The Concept of Gradual Variation: Let function $f: D \rightarrow \{1, 2, \dots, n\}$, if **a and b** are adjacent in D implies $|f(a) - f(b)| \leq 1$, point $(a, f(a))$ and $(b, f(b))$ are said to be gradually varied. A 2D function (surface) is said to be gradually varied if every adjacent pair are gradually varied.

Discrete Surface Fitting: Given $J \subseteq D$, and $f: J \rightarrow \{1, 2, \dots, n\}$ **decide if there is a $F: D \rightarrow \{1, 2, \dots, n\}$ such that F is gradually varied where $f(x) = F(x)$, x in J .**

Theorem (Chen, 1989) The necessary and sufficient conditions for the existence of a gradually varied extension F is: for all x, y in J , $d(x, y) \geq |f(x) - f(y)|$, where d is the distance between x and y in D .

The above theorem can be used for a single surface fitting if the condition in the theorem is satisfied. The problem is that the sample data does not satisfy the condition of fitting. So the original algorithm can not be used directly for individual surface fitting.

A new algorithm based on the sample point contribution to the fitting point is created. The core part of the program is given in the following code.

Algorithm Design

```
• for (k=0;k<nGuildPoints;k++){
•     ii=(latIndex[k]-latMin)/latDet;
•     jj=(longtIndex[k]-longtMin)/longtDet;

•     distance=sqrt((ii -i)*(ii-i)+(jj -j)*(jj-j));
•     temp_j=abs((array[i][j] - dat[k][time]))/Ratio-distance;
•     if(temp_j>0){ // not satisfy gvs condition

•     if( array[i][j] > dat[k][time])
•         temp=-temp_j *Ratio ;
•     else
•         temp= temp_j *Ratio;
•     array[i][j]=array[i][j]+temp ;
•     }
• }
```

5.2 Sequential surface fitting and involvement of the flow equation

The individual surface fitting in the above code is not an adequate method since the relationship of groundwater surfaces at each time is not accounted for in the calculation. In particular, we have to use the flow equation in the sequential surface calculation.

According to flow equation (2),

$$h_2 - h_1 = \alpha * (h_2(x-1,y) + h_2(x+1,y) - 2h_2(x,y) + h_2(x,y-1) + h_2(x,y+1) - 2h_2(x,y)) - G \quad (3)$$

We can let

$$f_4 = (h_2(x,y) - h_1(x,y) + G) / \alpha + 4 * h_2(x,y) = h_2(x-1,y) + h_2(x+1,y) + h_2(x,y-1) + h_2(x,y+1). \quad (4)$$

f_4 can also be viewed as the average of 4 times the center point. Using the gradually varied function, the average is $((h_2 - h_1 + G) / \alpha + 4 * h_2(x,y)) / 4$. Based on the properties of gradually varied functions, the maximum difference is three. For example, $h_{2_old}(x-1,y)$ is bigger, then $h_{2_new}(x-1,y)$ should be smaller.

The iterating procedure is to update the center point after the first fit.

6. Real Data Processing and Application

This results use an algorithm to fit the initial data set using an individualized fit, see Fig 3. This algorithm is also made by the rough graduate varied surface fitting by scanning through the fitting array. There are many clear boundary lines in the images. In order to reduce error, our new algorithm will use more accurate formulas to calculate the derivatives (1):



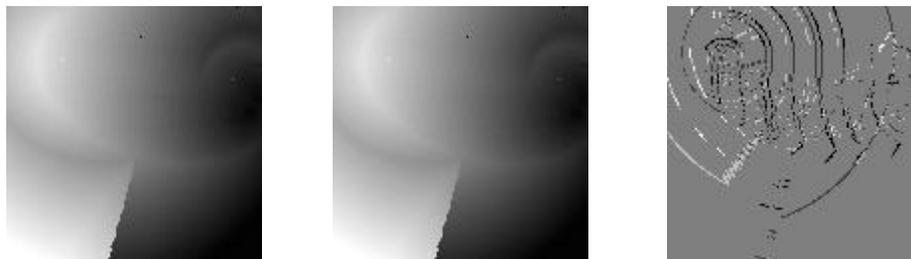
(a) day 1

(b) day 50

(c) day 100

Fig 3. Northern VA Groundwater distribution calculated by gradually varied surfaces date from 04/01/07. The intensity indicated the depth of the groundwater.

The following figures show the meaning of the sequential surface fitting after we have added the water flow equation. We also select the fitting order by the distance to the sample points. Therefore, the fitted images are much smoother.



(a)day1

(b) day 2

(c) enhanced difference



(d) Day 2 with flow equation iteration



(d) Day 3 with flow equation iteration

Fig 4. Northern VA Groundwater distribution calculated by gradually varied surfaces and the flow equation.

Future work: to ensure the accuracy of the calculation, we will add the finite element method to our research. We also want to use MODEFLOW to calculate local and small-region flow, and to use gradual variation to compute regional or global data.

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Application of Spatiotemporal Informatics to Water Quality

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Pradeep K. Behera, Ph.D., P.E., D. WRE
Byunggu Yu, Ph.D.

School of Engineering and Applied Sciences
University of the District of Columbia

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Content

Abstract	3
1.0 Introduction.....	4
2.0 Motivation and Research Objectives	5
3.0 Related Solutions	7
4.0 Analysis of SPOT.....	8
4.1 Introduction to SPOT.....	8
4.2 SPOT Package	10
4.3 SPOT Development process	10
4.4 SPOT Analysis.....	10
5.0 Project Development Planning & Analysis.....	11
5.2 Technical Approaches	13
6.0 Acknowledgements	17
7.0 References.....	17

Abstract

Recent developments and innovations in spatiotemporal informatics (storage, update, and retrieval of continuously changing data) and relevant sensor technologies can provide exciting opportunities and innovations in urban water resource management and decision making applications. For example, for the implementation of the Long Term Control Plan (LTCP) that addresses the combined sewer overflows and storm water discharges problems in the District of Columbia, such emerging technology and developments can significantly enhance and improve the monitoring and decision making processes.

The objective of this multidisciplinary (Civil Engineering and Computer Science and Information Technology) project is to devise a highly efficient and effective technology for stormwater quantity and quality monitoring by taking advantage of much emerging advances in spatiotemporal informatics and relevant sensor technologies.

The benefits of the project include the following: (1) highly cost-efficient and continuous monitoring of the runoff quantity and quality; (2) data and tools for real-time analysis and sharing of raw runoff data for better emergency and maintenance decisions; (3) lab and field training, education, and research.

Upon completion, this proposed project will benefit the District of Columbia in the development and implementation of a watershed wide innovative stormwater quantity and quality water quality monitoring system to measure flow and water quality parameters at the combined and separated sewer outfalls.

In the Phase I of the project, a competitive proposal was developed and submitted to NSF for extramural funding. The peer review identified as one of the innovative proposal with intellectual merit, however recommended that the proposal should include more preliminary experimentation. The Phase II of the proposal includes the laboratory experimentations and the development of an improved proposal with a submission to the NSF Sensor Network program in year 2009.

1.0 Introduction

Over the last couple of decades, it has been recognized that urban stormwater pollution is a large contributor to water quality problems of many receiving waters, as runoff transports a wide spectrum of pollutants to local receiving waters and as their cumulative magnitude is large [20].

The pollutants in urban runoff include visible matter, suspended solids, oxygen demanding materials, nutrients, pathogenic microorganisms and toxicants such as heavy metals, pesticides and hydrocarbons. These pollutants impose considerable physical, chemical, and biological stresses on the receiving waters that affect aquatic life and human health [12] and impair the designated uses of water resources. Typical urban stormwater-runoff-related receiving water quality problems include the degradation of aquatic habitats, degradation in water quality during and after wet weather events (e.g., rainfall and snowmelt), beach closures, and accelerated rates of eutrophication in lakes and estuaries, and thermal pollution [20]. These problems have been prevalent in most receiving water systems in the vicinity of urban or urbanizing areas.

In the District of Columbia, *combined sewer overflows* (CSOs) and *stormwater discharges* contribute significant pollution to the Anacostia and Potomac Rivers and Rock Creek, especially during wet-weather periods. These runoffs can adversely impact the quality of the receiving waters particularly Chesapeake Bay. The Anacostia River, a tributary of the Potomac River has been significantly impacted pollution, principally (Biannual Report, October 2005, WASA). To address these problems, District of Columbia is implementing a Long Term Control Plan (LTCP) which, over the next 20 years, will reduce the overall volume of overflow into waterways by 96 percent and the plan will cost approximately \$2 billion dollars.

This proposed project shall devise and verify such an efficient technology that can continuously monitor and measure the runoff quantity and quality in real-time.

To assist the decision-makers in implementing the LTCP, a real-time and continuous assessment of the severity of the runoff pollution in each sewer outfall (and the associated sub-catchment within the watershed) is necessary. The severity of the pollution governs the identification and prioritization of problems as well as the corresponding resource allocation and response decisions in LTCP. Hence, a continuous measurement of the quantity and quality of the runoffs is a key issue.

However, the management difficulties and high costs of any conventional human-involved data collection approach may pose major challenges. In the **application's backend, we see a timely** and critical demand for an innovative and cost-efficient approach to continuous and real-time measurements of the runoff quantity and quality.

This demand and effective environmental regulations, such as Total Maximum Daily Load (TMDL), give rise to the opportunities for the development of an effective stormwater and wastewater quality monitoring technology. The objective of this multidisciplinary (Civil Engineering and Computer Science and Information Technology) project is to devise such a monitoring technology by taking advantage of much emerging advances in spatiotemporal informatics and relevant technologies and to verify this deliverable technology.

2.0 Motivation and Research Objectives

Although various sensor technologies have been developed for water flow measuring, there is a marked lack of cost-efficient, continuous, real-time, long-term, autonomous, and scalable monitoring solutions for urban runoffs found at the discharge outfalls. Especially, manual methods and other sensor solutions require human labor for operation and maintenance, often incurring cumulative health risks to the field workers for directly accessing the pollution discharge points. This represents non-continuous and short-term/ad hoc monitoring solutions, **which degrade the overall reliability and responsiveness of the society's water resource** management and research.

To assist the decision-makers in realizing a long-term control plan (LTCP), a real-time, continuous, and cumulative assessment of pollution at sewer outfalls (and the associated sub-catchments within the watershed) is required. The severity of the pollution governs the identification and prioritization of problems as well as the corresponding resource allocation and response decisions in LTCP. However, the management difficulties and high costs of any conventional human-involved data acquisition approach pose major challenges.

Current environmental regulations, such as Total Maximum Daily Load (TMDL), require that the regulatory authorities must monitor receiving water bodies, such as streams, rivers, and lakes, for pollutant loads on a regular basis. This makes the motive of the project even more pronounced.

The project team has initiated this multidisciplinary project (comprising civil engineering,

electrical engineering, and computer science expertise) in order to investigate the following envisions:

- A wireless, autonomous, and tiny sensor-computer at each discharge/outfall location: the development of a cost-efficient (in terms of installation, operation, maintenance, and geospatial scalability) and tiny sensor-computer technology for autonomous, continuous, long-term, and real-time monitoring of urban runoffs and CSOs (Combined Sewer Overflows).
- An on-line information server – the development of a central on-line information server that can utilize such sensor-computer technology, that can continuously receive, record, and report runoffs with minimal human support, and that can actively alert human as necessary in real-time.

This multidisciplinary project is, by nature, explorative and includes untested and transformative elements mainly as innovative applications and study of emerging sensor-computer (small and highly programmable sensor objects) technologies and relevant informatics.

Long-Term Objective: Devise and verify a novel sensor-information system that can continuously monitor, record, and analyze urban wastewater and stormwater at sewer outfalls in a cost-efficient, autonomous, and highly scalable manner for long-term periods.

The scope of the current Phase I of the project is to experiment with newly developed Sun Small Programmable Object Technology (SPOT) computers and sensor technology to develop stormwater quantity and quality measurement techniques. The project will be implemented in three steps –

- (I) analysis of the SPOT and testing of programming ability to use as a monitoring device for water and wastewater;
- (II) development of a lab-based experimentation to verify the use of the SPOT to measure velocity and discharge rate of water;
- (III) development of a extramural funding for the installation of the equipment in the sewer outfall of the Rock Creek to measure water quantity and quality parameters. Few water quality parameters, such as water temperature and solid pollutants, will be tested. Based on the success of this project, more water quality parameters will be added on the availability of sensors.

3.0 Related Solutions

Flow monitoring for runoffs at sewer outfalls (discharge pipes along the receiving water) is complex because of the intermittent nature of the flow. The flow measurement techniques vary greatly in complexity, cost, and accuracy. The methods of runoff discharge monitoring technology can be classified, in a broad sense, into either direct or indirect.

A direct method measures the quantity (volume or weight) of the flow during a given time interval for closed conduits flow or pressurized flow. For gravity flow, the principle of open channel flow is typically used. The flow rate is computed by measuring the velocity of flow and by computing the area of flow. Hydraulic engineers have developed some equations -- given a depth of flow, there is a unique and predictable flow velocity (and flow rate) of water in the pipe, which can be derived **from Manning's Equation. Another standard pipe curve is known as the Colebrook-White Pipe Curve** [10].

Indirect methods measure pressure changes for closed conduits flow (or some other variable), which is directly related to the rate of flow. Examples include venturi meters, orifices, etc. Weirs are devices that employ indirect means to obtain partial flow rates. Some other types of indirect methods employ electro-magnetic flow meter device, which operates on a principle that a voltage is generated when a conductor moves in a magnetic field.

Among the simplest methods are the conventional methods that involve manual measurements of runoff quantity and quality (using various measuring tools, such as poles, bottle board and chalking, and dye testing). However, the manual methods rely extensively on labor-intensive field efforts during storm events and do not provide an accurate, continuous flow record [11].

Recently developed techniques employ flow devices, such as weirs, flumes, and orifice plates. The accuracy of flow calculations depends on the reliability of depth sensing equipments, since a small error in depth measurement can result in a large error in flow rate calculations. Some typical depth-sensing devices include the following:

1. Ultrasonic Flow Meters – employ a technique to measure the difference in travel time for a sound wave traveling upstream and downstream between two measuring stations. The difference in travel time is proportional to flow velocity. The other type of operation is based on Doppler Effect which is based on capturing the differential frequency (Doppler shift) during the

projection of ultrasonic beam into fluid. The measured frequency difference is related to the flow velocity.

2. Ultrasonic Sensors – are typically mounted above the flow. The depth is computed based on the time the reflected signal returns to the sensor. The depth measurements can be affected by the suspended solids of the runoff.

3. Pressure Sensors – sense the pressure of water above them. They are used along with a flow monitor that converts pressure value to a depth measurement and are hard to use at an open end of a pipe, such as a sewer outfall.

4. Bubble Sensors – emit a continuous stream of fine bubbles. A pressure transducer senses resistance to bubble formation, converting it to a depth measurement value. The bubble tube are often clogged, requiring frequent calibration

5. Electro-magnetic Flow Meters – operate on a principle that a voltage is generated when a conductor moves in a magnetic field.

4.0 Analysis of SPOT

4.1 Introduction to SPOT

SPOT (Small Programmable Object Technology) device is a HP product having 180 MHz 32 bit core, 512k RAM, 4Mb Flash drive, 2.4 GHz IEEE 802.15.4 radio, USB interface, light and temperature sensors, 2G/6G 3-axis accelerometer, 8 tri-color LEDs, 6 analog inputs, 2 switches, 5 general purpose I/O pins, 4 high current output pins, fully programmable operating system. The size is slightly bigger than the matchbox (41 x 23 x 70 mm) and it weights only 54 grams. This device is a new generation portable computing experimental platform designed in Sun labs. It is called Sun SPOT device.



Figure 4.1 : SPOT System

Such advantages of the Sun SPOT as small size, wireless communication, and battery power make it extremely useful as an experimental platform. “Sun SPOT devices include a flexible hardware platform as well as the software and tools to make it easy to innovate, experiment, and prototype whatever a developer can imagine.”(Sun SPOT FAQ) Sun Microsystems made the SPOT development available on almost every widely used operating system for both PC and Apple (Windows XP, Windows Vista, Macintosh OS X 10.4, Linux (Fedora Core 5, SuSE 10.1 and Ubuntu 6.06), and Solaris x86) There are more than 400 classes documented in Sun SPOT JavaDoc. Dun DSK provides us with more than 300 high level classes to access SPOT input and output hardware.

The area of Sun SPOT usage is amazingly wide. Some of them are(Figure 1):

- Education
- Medical Applications
- Industrial Research
- Government and Military Applications
- Robotics

The list can be continued on and on. The latest new from Sun Microsystems is that the SPOT project is going fully open source which opens even more opportunities for the developers. More information about SPOT projects can be found at www.sunspotworld.com/about/vision.php.

4.2 SPOT Package

The Sun SPOT package includes two Free-range Sun SPOTs (equipped with a battery), a base station, Software Development Kit CD, and USB cable. (Figure 4.2). The base station is used to connect to computer and wirelessly operate free-range device, though the free-range SPOT can be used as a base station as well. The SDK CD has detailed installation manual for both Linux and Windows. Each SPOT device **has its' own MAC address which is**



being used as a login when accessing Sun SDK updates. The MAC addresses in my case were:

- 0014.4F01.000.0734 (freelance device)
- 0014.4F01.000.070f (freelance device)
- 0014.4F01.000.0c9b (base device)

4.3 SPOT Development process

Sun SPOT SDK is a complex set of tools that include Java compiler Sun made the SPOT software development very simple as the programmers can use standard Java tools such as NetBeans or Eclipse. Currently, NetBeans **is the preferable development tool, due to its' tight** integration with the SPOT devices. The latest version of SDK is 4.0 (Blue).

4.4 SPOT Analysis

The project is subdivided into three major parts:

- Programming
- Analysis
- Laboratory testing.

The first part included development of software to sense and record several sensor readings such

as 3-dimensional position and velocity, temperature, and light values. Java Telemetry program was used as a base. It was modified to read light and temperature values, sense position instead of acceleration, calculate 3-dimensional velocity of object and store sensed values in a file. This part is mainly finished, though there is always a lot of space for the upgrades and improvements.

The second part is much more challenging as it involves the development of a formula (or variety of formulas with different precisions for various conditions) to approximate the amount of waste water based on the sensed values. This stage of the project is in active development and elaboration. Several approaches are used to accomplish the goal. Some results are already available in the attachment and ready to be tested in the lab.

The third part is the lab testing. It would require construction of the tube in the lab and testing the formulas in the real-world conditions. The implementation of the laboratory testing device is out of scope of this paper; though the testing results would be published as they would become available.

5.0 Project Development Planning & Analysis

Our proposed approach is based on a newly developed Small Programmable Object Technology (SPOT). This tiny sensor-computer platform consists of stacked three layers: Li-Po battery, sensor board, and tiny computer with a CPU (Java programmable), timer (AT91 timer for measuring time elapses), USB, power switch, and memory. The sensor board includes the following: 3-dimensional accelerometer (LIS3L02AQ), temperature sensor, light sensor, eight LEDs, two switches, five general-purpose I/O pins, and four high current output pins. Figure 1 shows SPOT devices in our laboratory.

The proposed methods of this project are as follows:

1. Instrumentation: Encase a SPOT computer inside a sealed sphere and tether it inside each target sewer outfall pipe as shown in Figure 5.2 (a lab-made pipe and artificial water input will be tested before actual field tests; before the field tests, the project will select target pipes in the Rock Creek region).
2. Runoff logging: The 3D acceleration data stream (swing motion sequence) from this sensor represents the runoff flow over time. The project will also try to see if some jerky and/or lateral motions caused by physical debris or sudden water bursts are usable for additional information. The project will also investigate possible uses of the temperature and light sensor of the SPOT for additional information. Connecting more sensors to the I/O port of the SPOT will be considered based on the results of this project.
3. Filtering and Aggregation: The programmable SPOT can filter-out insignificant events for optimal use of storage and communication bandwidth and provide representative summary data (pre-processing).

4. Students involved in the project will drive or walk by the sphere with a laptop computer equipped with a SPOT base station on a regular basis (again, lab tests will precede this field test). All logged data will be **automatically transmitted to the laptop's hard disk**. Then, the acquired data will be transmitted to the information server (running on the project server computers located in our laboratories) both manually and via WAN/Cell network interface to the Internet. **The server will also run the project's web site for the academic dissemination of the data, research, and findings.**

5. The project team will install a solar panel at each site and connect the charging mini USB cable to the SPOT. (SPOT can run on its battery for some days, just like cell phones; charging the battery takes a small number of hours.) This will eliminate the need for manually opening the sphere to replace or charge the battery.

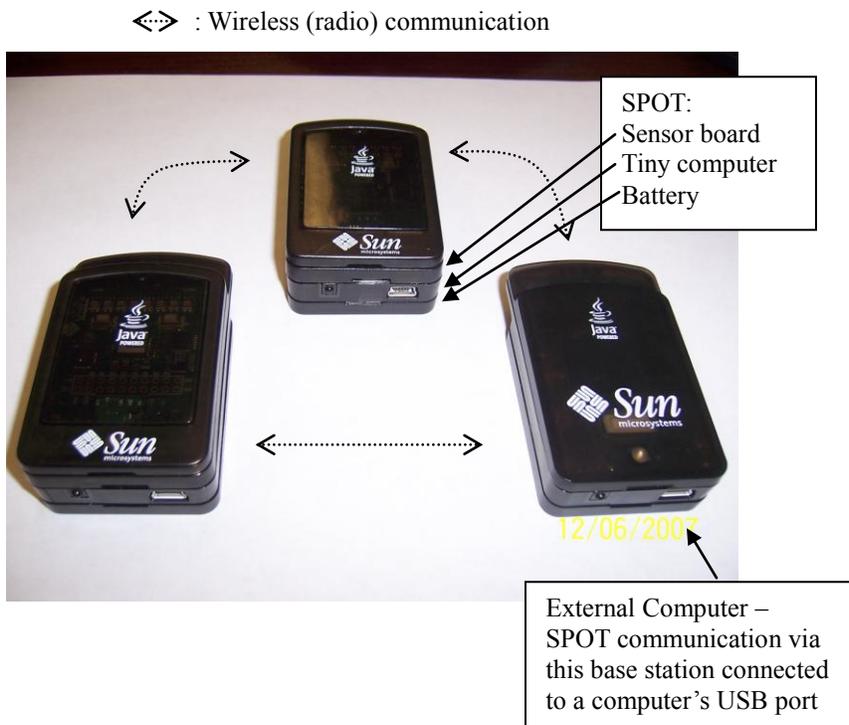
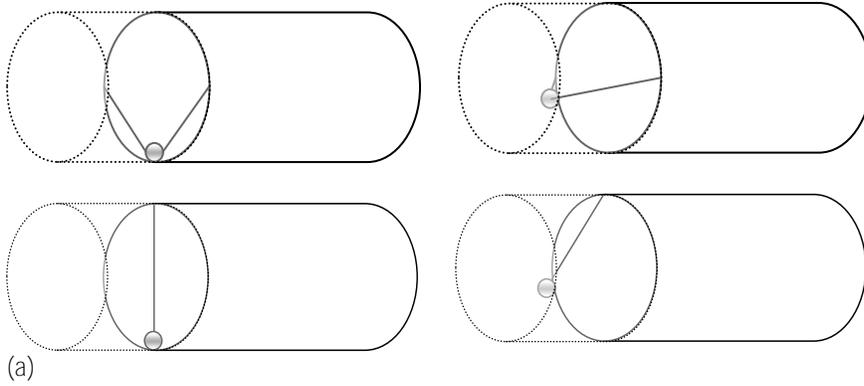
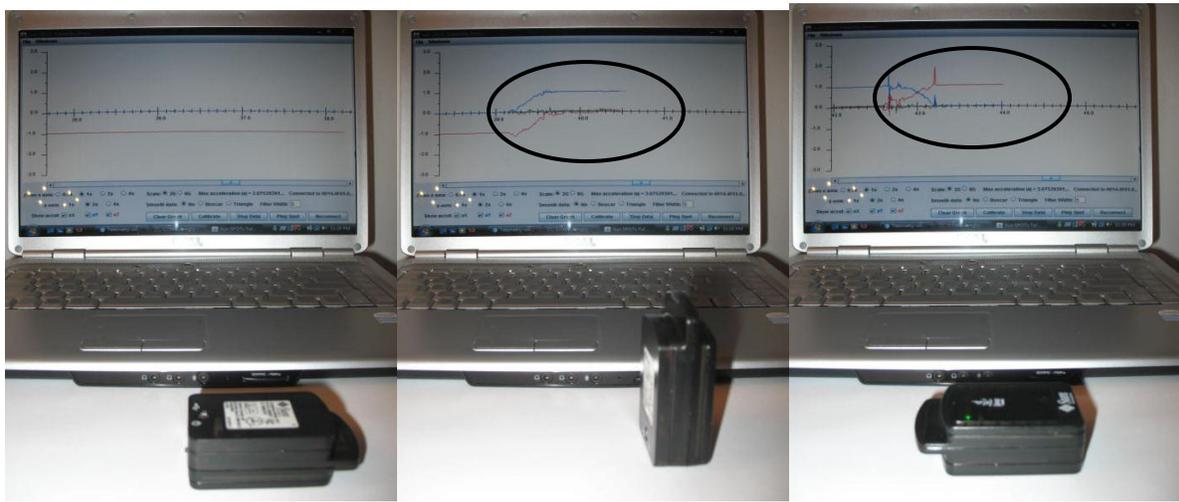


Figure 5.1. SPOT Computer: The physical dimensions in mm are 71mm×42.40mm×18mm. This tiny computer can run any Java program that accesses the sensor board.



180 degree turn on the YZ plane in two steps



Acceleration is measured in gravities (g)		Before	After		180 degree turn
			Step 1: 90°	Step 2: 180°	
Green	X-axis	0	0	0	
Blue	Y-axis	0	1g	0	
Red	Z-axis	-1g	0	1g	

(b) **Figure 5.2.** (a) Sphere's motion inside an outfall pipe (two of the possible configurations); (b) A sample of many accelerometer tests conducted in our lab

5.2 Technical Approaches

Calculation of the depth of flow in a pipe :

The SPOT device will be sealed inside a sphere made of appropriate material such as tin, or plastic and attached on the top of the pipe using one or two light solid bars or strings (alternative configurations will be tested). The sphere should provide enough buoyancy to float it on the surface of water. The device can compute the inclination, or tilt (θ in Figure 5.3), of an axis with respect to the total acceleration the device is experiencing [13]. In our application, the tilt is measured with respect to the gravity flow within the pipe. When there is no water in the pipe, the sphere is at

the bottom and the tilt is zero degree ($\theta=0^\circ$). When water flows, the sphere will float on the water and water level or height (h) is calculated using the tilt as follows (the buoyancy factor will be added after lab tests):

$$\theta' = \pi/2 - \theta,$$

$$\sin \theta' = \frac{d-h}{d},$$

$$h = d - d \sin \theta' = d(1 - \sin \theta'), \text{ where } d \text{ is the diameter of the pipe.}$$

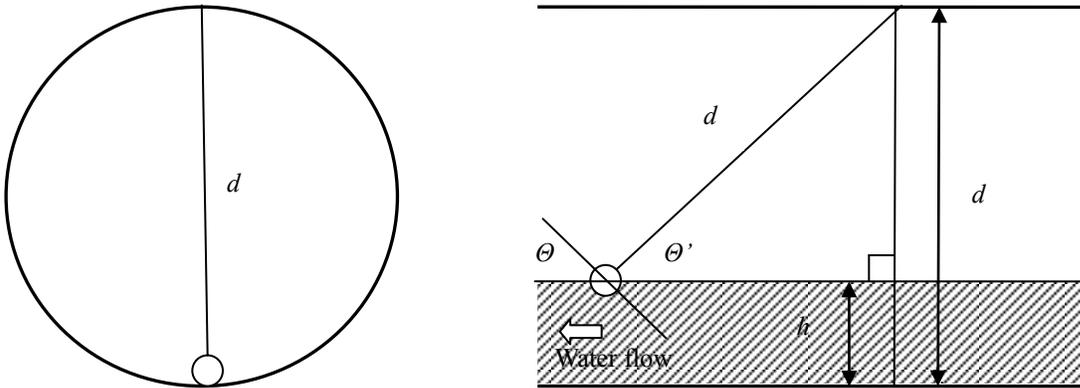


Figure 5.3. Calculation of water height using SPOT

Calculation of the flow rate, given a depth :

Given a depth of flow (h), the flow rate will be computed based on commonly used hydraulic principles. The flow rate (Q) will be computed from the continuity equation (conservation of mass principle) by the product of the water velocity (V) and the area of water flow (A), i.e., $Q = A \cdot V$. The partial flow area in a circular pipe can be calculated as follows and as depicted in Figure 4.

$$A = \frac{\beta}{360} \frac{\pi D^2}{4} - \sqrt{2rh - h^2} (r - h)$$

, which is the area of the arc with angle β subtracted by the area of the isosceles triangle. The velocity of water can be computed by using Manning's formula which is as follows:

$$V = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}}$$

, where n is Manning's roughness coefficient, R is hydraulic radius (flow area A divided by wetted perimeter p), and S is the slope of the pipe.

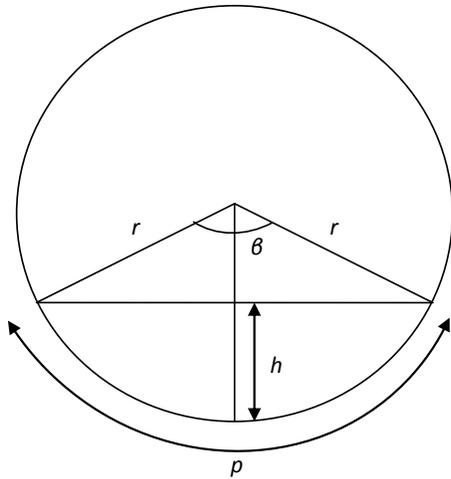


Figure 5.4. Calculation of area of water flow

Smart memory management:

SPOT is able to read samples at the maximum rate of 320Hz. SPOT will continuously monitor and record the water level (h), water temperature (t), and water clarity (c) with a predefined time interval I . Due to SPOT's limited memory capacity (4 Mbytes of flash memory [16]), it is important to know SPOT's maximum data acquisition period between two consecutive batch transmissions. First, suppose that SPOT is always collecting the data with a constant interval I regardless of water flow. This can be the worst case – maximum amount of data collected. For example, suppose that a sample of 5 bytes of data is collected at every certain time interval (2 bytes of real time data plus h , t , c , each one byte). Then the total collected data for a week amounts approximately 3 Mbytes of storage when the sampling interval is one second. SPOT's 4 Mbytes of memory could be enough for a week-long data acquisition without any data transmission.

Then there can be various techniques to extend this data acquisition period. One can store sample values only when they vary over a certain difference Δ . SPOT senses sample values at the beginning of every interval. However, if water level does not change much, it does not need to store the stimuli values until the change exceeds Δ . This approach can save significant amount of memory space in our application because 1) there would be no water flow under normal weather and 2) even in the presence of water flow, water level would not change abruptly in most time. Thus, the small amount of memory can possibly be sufficient to hold sample data for a far longer extended time period than a week, which will be investigated in this project.

Smart power management:

Without any external power, the SPOT battery can run up to 6-7 hours on the full power mode with wireless communication and LED on. Providing external power source is critical in the proposed long-term and continuous monitoring application. We propose a solar panel for the purpose due to its cost efficiency and reliability. However, even solar panel cannot provide sufficient power during night and cloudy day, especially during wet events. SPOT can be operated in three different modes to save its battery power, *Run*, *Idle*, and *Deep-sleep* mode [16]. In Run mode, SPOT performs basic operations with all processors and wireless communication running, just for 6-7 hours. Idle mode shuts off some unused circuits and the radio, which makes SPOT run three to five times longer than in Run mode. Deep-sleep mode shuts down all circuits except the minimal circuits to resume the operation when it is awakened. This mode consumes only 1/3000 – 1/4000 of the power comparing to Run mode. We can program SPOT

to sleep most time except when it actually collects data and communicates with server. By alternating Run and Deep-sleep mode based on the smart memory management and data sampling algorithms, SPOT can operate for weeks or a month without any external power. The project will investigate this smart power management.

Signal Processing :

In contrast to other sensors, SPOT contains a complete computer with built-in signal-processing and filtering functions that are further programmable. According to the PI's meeting with Sun Lab Scientists in 2006, the Kalman filter is worth a consideration in any motion/ trajectory estimation applications using SPOTs. In order to provide constantly accurate and continuously updated information about the position and velocity of the SPOT sphere given only a sequence of observations each of which can possibly includes some error, an additional digital filter algorithms, such as the Kalman filter, will be tested on top of SPOT's signal-processing functions. This will also help us filter out the sideway movements, fluctuations, and jerky motions of the sphere in the pipe.

The final algorithms will be adjusted in the lab and adopted and tested in a field scale experimentation set-up for optimal use of storage and communication bandwidth. The developed filters and other signal-processing/communication algorithms [5-9, 18] will mitigate inferences and further enhance the accuracy and reliability of the information.

Central Database Server

The project will develop a standard SQL/Relational database server using MySQL system to store, update, and retrieve remote sensor data at the central host server. The data transmission from sensors to the host will be accomplished via cellular network and the Internet. The remote database access programming will be based on Java's MySQL database connection library, a widely used and easy-to-use open database access toolkit on the field computer (laptop). The field computer paired with the sensor sphere will enable us to reprogram the sensors remotely without actually visiting the site.

The project's web site will be running on the data server machine hosting the database. The web site will academically disseminate project information, collected data, and research findings.

This permanent data store will bear innovations in water resource decision support applications and will help us develop significant research developing extensive research and iterative enhancements.

Lab and Field Experiments:

The project will test, enhance, and verify the proposed instrumentation both in a laboratory and in the field. The laboratory experiments and research will be performed in our lab (Bldg. 42, Room 111) at the University of the District of Columbia. The experiments will be conducted in a 1-foot diameter tilting pipe. In the first stage, the capsule of SPOT device will be designed with appropriate capsule material (plastic or tin), cushion material, and connection materials and mechanisms. Our experiments will verify their applicability. In the second stage, the instrumentation will be tested for several flow rates and associated velocities. The flow rates calculated by the proposed sphere solution will be compared with the actual flow rates (as shown in Figure 5, it is a closed circuit) as well as other existing technologies including flow meter and velocity meter.

The laboratory results will be further verified in the field. Two sewer outfalls along Rock Creek, which is an urban

stream passing near our lab in Washington, DC, will be selected. Generally, these pipes experience overflows when there is a rainfall of more than half an inch in the watershed. The instrumentation will be set up at the sewer outfalls by securing properly such that severe storms will not cause the instrument blow away. The data will be acquired for several storm events. The SPOT data will be compared with the data obtained from the parallel measurements employing existing technologies.

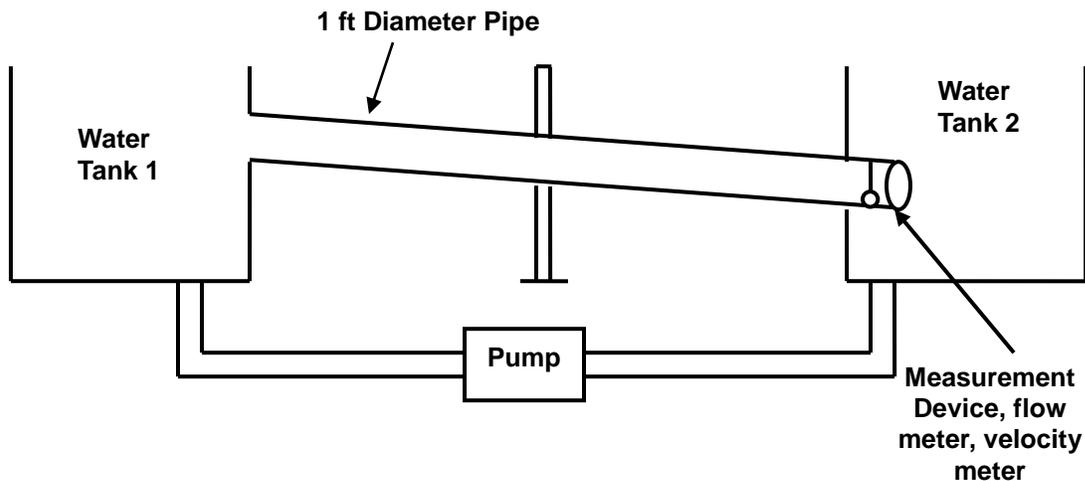


Figure 5. 5. Schematic Representation of Laboratory Experiments

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Information Transfer Program Introduction

The Extension Agent in the Cooperative Extension Service/Water Quality Education Program continues to impact the Institute's information transfer and outreach capacity. Listed are some of her accomplishments in conjunction with the Institute: Prepared and distributed water quality education brochures and fact sheets to DC residents; Conducted workshops on water quality education at various DC Recreation Centers and Public Schools; Visited DC Water and Sewer Authority (DCWASA) Water Quality Division for potential collaboration Periodically visited USDA\CSREES National Water Program to enhance Water Quality Education Program for future collaboration; and Participated on the Mid-Atlantic Regional Water Quality Program Steering Committee

The Institute website, <http://www.udc.edu/wrri/>, provides updated information about current activities. The Institute also completes bi-seasonal issues of the Water Highlights Newsletter. These documents are very informative and highlight current research and educational projects sponsored by the Institute along with interactions among faculty members and their student interns on projects and conferences.

An electronic mailing list of over 150 Water Resources faculty and experts in the consortium of universities in Washington DC is maintained and regularly updated and disseminated via email to report updates on local, regional, and national water issues received by the Institute. This line of information transfer has enhanced the visibility and credibility of the Institute among its stakeholders.

USGS Summer Intern Program

None.

Student Support					
Category	Section 104 Base Grant	Section 104 NCGP Award	NIWR-USGS Internship	Supplemental Awards	Total
Undergraduate	8	0	0	0	8
Masters	1	0	0	0	1
Ph.D.	0	0	0	0	0
Post-Doc.	0	0	0	0	0
Total	9	0	0	0	9

Notable Awards and Achievements

Publications from Prior Years