Final Report
Lake Houston Watershed Water Quality Prediction System

Project Number 2009TX324B

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Abstract

The increased degradation of influent to Lake Houston is causing increased water treatment cost for the City of Houston's Drinking Water Operations and has severe public and environmental health implications. The watersheds flowing into Lake Houston are impaired for bacteria and have concerns for nutrients. Therefore hydrologic models and water quality predictions concerning the influent from the watersheds to the lake are key to the operation of the City of Houston drinking water treatment plant. A water quality modeling system based on a distributed hydrologic model (*Vflo*$^{\text{TM}}$) that uses NEXRAD RADAR rainfall input, was proposed. The system is being tested in Cypress Creek Watershed as part of a wider Basin effort. Cypress Creek is an urbanizing watershed with significant agricultural activity. As such historic water quality data will be analyzed for loading relationships in conjunction with a wider literature review of land use pollutant loading rates for determination of water quality parameters. Then pollutant washoff and transport is modeled using land use parameters and hydrologic output from *Vflo*$^{\text{TM}}$. This output will then be evaluated using water quality sampling during storm events collected as part of the proposed project.

1. Introduction

Lake Houston is an important source of drinking water for the City of Houston, with approximately 300 million liters of water withdrawn daily (Chellam, 2008). Unfortunately, the lake experiences seasonal algal blooms and stratification during warm weather. This eutrophication is associated with nutrient inflow from the seven watersheds draining into the lake. Increasing urbanization within the watersheds is expected to increase urban runoff with loads of nutrients, suspended solids, and bacteria. The combination of nutrient enrichment combined with bacterial impairment increases the cost of water treatment for the drinking water purification plant on Lake Houston.

In order to address the rising water treatment costs, source protection measures need to be implemented within the watersheds draining into the lake. Source protection measures are designed structures and procedures devised to maintain the quality of a water resource and can include detention basins, vegetated stream buffers, pet waste pickup programs, and resident education programs. Seven watersheds, encompassing 1,939 mi^2, drain into the lake (See Figure 1). Cypress Creek, the most highly urbanized of these watersheds, is impaired for bacteria(TCEQ, 2008a) and listed on the 2008 303-d concerns list for nutrient enrichment (TCEQ, 2008b). Because of its contribution of urban and agricultural runoff to the lake, knowledge of the water quality in Cypress Creek is necessary for improved operation of the drinking water purification plant and future protection of the City of Houston's water supply.

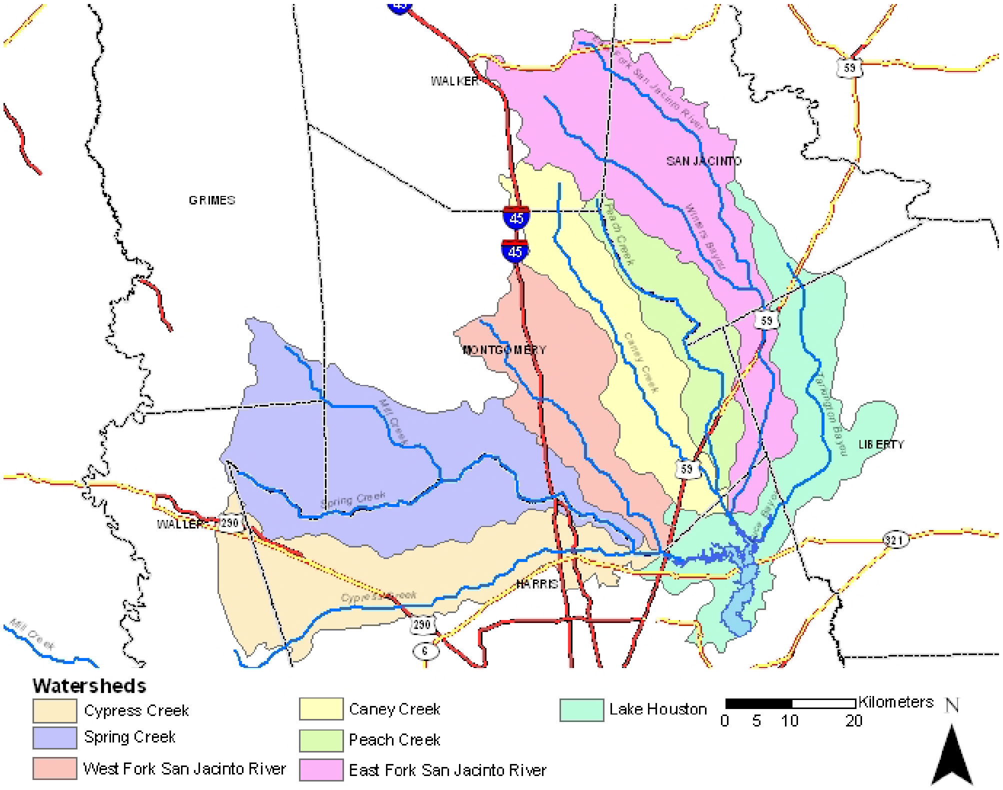

Figure 1 .Watersheds Flowing into Lake Houston

Efficient operation of the drinking water plant can be assisted by advance warning of pollutant loads entering Lake Houston from Cypress Creek. A predictive model that incorporates RADAR rainfall in real time and provides hydrologic and water quality output would provide information to the water treatment plant operators to use as a decision aid in the management of water purification processes.

2. Objectives

The goal of the proposed project was to develop a water quality management system based on a distributed hydrologic model for simulation and prediction of pollutant loads from Cypress Creek watershed to Lake Houston. The system can be expanded and applied to other watersheds, notably the other watersheds flowing into Lake Houston, for a comprehensive management plan for Lake Houston.

3. Study Area

Cypress Creek is a 308 mi^2 watershed north of the city of Houston in north Harris County with the upstream, western portion in Waller County. It flows 50 river miles to Lake Houston. The western upstream part of the watershed is undeveloped primarily as cultivated agricultural fields. The eastern portion of the watershed has primarily residential development and is home to most of 216,000 residents (ESRI, 2000). Based on the 2002 Land Cover analysis performed by the Houston-Galveston Area Council, low and high intensity development accounted for approximately 16% of the watershed. This development increased to approximately 39% by 2008. Additionally, forested and woody wetland decreased from 23% in 2002 to 11% in 2008 whereas grasslands decreased from 51% to 11% (See Figure 2). As such, the watershed has experienced rapid urban development in the past decade. Cypress Creek watershed is relatively flat with sandy loam soils. With sandy loam soils, there is greater infiltration potential and less erosion potential. As a result, increases in impervious cover would increase runoff and thus create greater loading of pollutants to the stream.

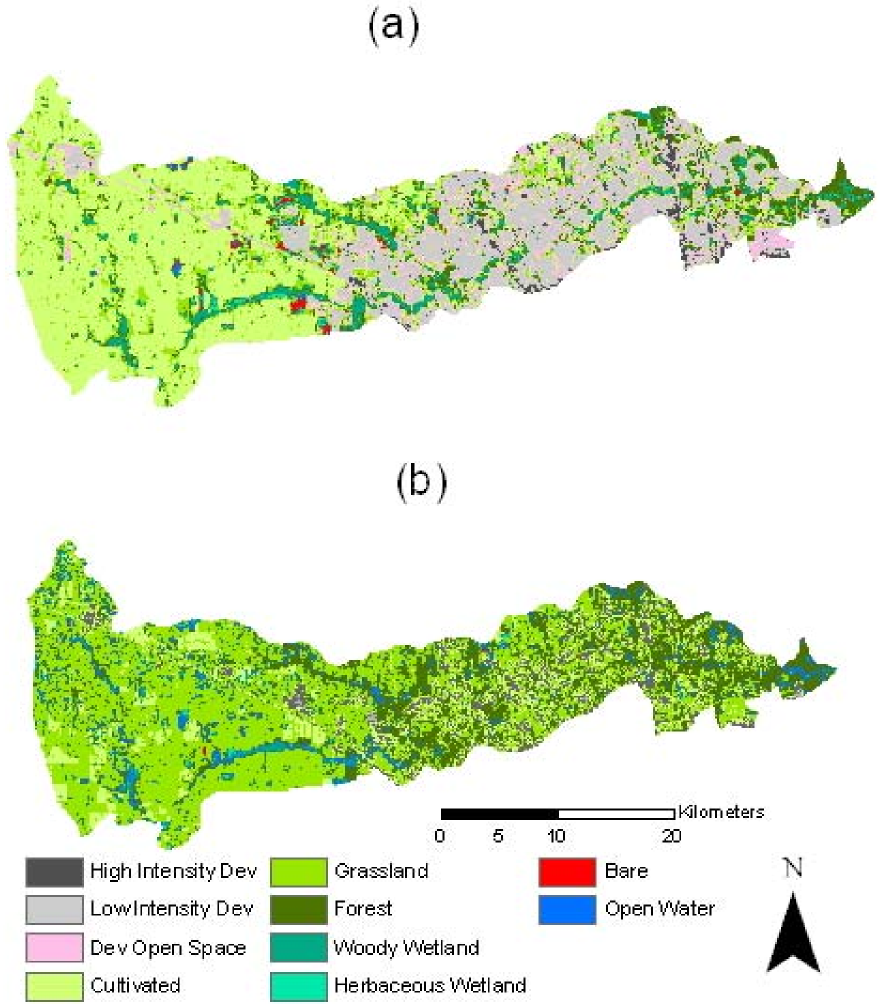

Figure 2. Land Cover for Cypress Creek in (a) 2008 and (b) 2002

4. Literature Review

The proposed water quality prediction system requires the development of a hydrologic model and a pollutant washoff and transport model using the output from the hydrologic model. The hydrologic model background as well as fundamental pollutant buildup, washoff, and transport relationships were reviewed in support of the project development.

4.1 *Vflo*^{TM} model

Vflo^{TM} is a distributed hydrologic model developed by Vieux et al. as a refinement of *r.water.fea* (Vieux and Gauer, 1994). The model uses finite element solutions of the kinematic wave equation for runoff routing. The solution for both overland and channel flow were derived from Saint Venant equations for unsteady fee surface flows. It is derived from the continuity and momentum equations (Borah et al., 2007). The one-dimensional continuity equation is

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} - q = 0 \tag{1}$$

Where Q is the flow rate, A is the cross-sectional area, and q is the lateral inflow, x is length, and t is time. The momentum equation is simplified to

$$S_0 = S_f \tag{2}$$

Where S_0 is the slope and S_f is the friction slope. The continuity and momentum equations are used to solve for discharge through

$$q = \alpha Q^{\beta} \tag{3}$$

Where β for overland flow is assumed to be 5/3 and the conveyance factor α is

$$\alpha = \frac{k_m}{n}\sqrt{S_0} \tag{4}$$

Where n is the Manning's coefficient, and k_m is the dimensionless kinematic flow number. Overland flow is calculated from the surface flow modeled by Manning's equation as

$$v = \frac{1}{n} S_f^{1/2} B h^{5/3} \tag{5}$$

Where is v is the flow velocity, S_f is the overland slope, B is the width of flow, h is the depth of flow, and n is the Manning's coefficient which is based on surface characteristics.

Runoff moves from overland cells into channel cells. Open channel flow is simplified to the form

$$q = \frac{\partial Q}{\partial t} + \alpha\beta Q^{\beta-1}\left(\frac{\partial Q}{\partial t}\right) \qquad (6)$$

which takes into account the change in portion of flow depth to flow width. This formulation can then be solved by finite element analysis, which is an efficient way to transform partial differential equations into ordinary differential equations in time (Vieux, 2004). By translating the 2-D grid into 1-D finite elements, or partial discretization, the system becomes computationally more efficient. The result is a system of equations for each element incorporating the boundary conditions of the grid cell, which can then be solved in matrix form by numerical methods.

The *Vflo*^{TM} model solves Green-Ampt infiltration and saturation excess equations for runoff generation (Bedient et al., 2003). Geospatial data representing elevation, soils, and land use are incorporated as parameters for the solution of these relationships. Precipitation input can be RADAR rainfall data, interpolated from rain gage data, or simulated design storms. The model is used to simulate runoff and other hydrologic quantities at any location within the study area, which supports the generation of hydrographs for the selected locations in the watershed.

Vflo^{TM} has been used to model multiple watersheds in Houston, Texas, including Brays Bayou, Whiteoak Bayou (Safiolea, 2006), and Cypress Creek (Zimmer, 2007). Previous applications in the Houston region have focused on flood prediction. Notably, a real-time flood alert system was developed for the Texas Medical Center using a Brays Bayou *Vflo*^{TM} model and NexRAD RADAR rainfall input (Fang et al., 2008). Furthermore the model has been applied to numerous other watersheds including the Yuna River in Dominican Republic (Robinson et al., 2009), Namgang and Yongdam River Basins, Korea (Vieux et al, 2009), and Blue River Basin, Oklahoma (Gourley and Vieux, 2006). It has been found that *Vflo*^{TM} produces highly accurate prediction of peak flows and simulation of the hydrograph (Bedient et al, 2003).

4.2 Pollutant Loading and Buildup Estimation

The type and rate of pollutant buildup is dependent on land use, human activities, and season (Overton and Meadows, 1976). The buildup of a pollutant on a surface can be modeled by different relationships such as linear, power, exponential, and Michaelis-Menton function (Barbe et al., 2006). Among the different modeling options, the first order relationship is the most commonly used and is integrated to an exponential form. The rate of accumulation of a pollutant can be modeled as

$$\frac{dP}{dt} = C - kP \tag{7}$$

Where P is the pollutant load, C is the constant rate of pollutant deposition, and k is rate of pollutant removal.. This can be solved (Haiping and Yamada, 1998) to the form

$$P = P_I \exp(-k * t) + C\left(1 - \exp\left(-k * t\right)\right) \tag{8}$$

which models the pollutant buildup behavior over time.

An alternative to assigning a general land use pollutant loading factor is to estimate potential loading through pollutant producing populations. For example, Paul et al.

(2006) estimated *E. coli* loads by spatially distributing the population of agricultural animals, wildlife, pets, septic systems, and sewage treatment. Based on this population distribution, a production rate is applied to the population. This produces a spatial distribution of *E. coli* potential loads. This is formalized through the Spatially Explicit Load Enrichment Calculation Tool (SELECT) methodology (Teague, 2009), which automates the process of spatial distribution of key populations, land use specific loading, and application of production rates. The SELECT method involves the steps of :

(1) Identify the potential sources of the pollutant
(2) Assess the population(s) of the pollutant sources
(3) Spatially distribute the population(s) of the pollutant sources to appropriate land use areas in order to determine the population densities
(4) Apply a loading rate or production rate to the population densities to calculate the average daily potential load.

The result is spatially distributed average daily potential load data, or a grid of the rate of load buildup in terms of mass per time for each grid cell.

4.3 Washoff and Transport Calculation

Pollutant washoff is the process of removal of soluble and particulate pollutants by rainfall and runoff (Vaze and Chiew, 2003). Falling raindrops create turbulence and overland flow loosens particles from the surface so that the particles can be transported through the watershed with water flow. Storm water quality models have traditionally conceptualized the washoff process as driven by the energy of raindrop impact or overland flow shear stress flow (Brodie, 2007).

The most common pollutant washoff model developed by Sartor and Boyd, assumes the mass of pollutant washed off is proportional to the runoff intensity (Patry, 1989) and has been incorporated into the SWMM and STORM models. The model is a first order equation describing the pollutant mass that remains on the surface at time *t* with the onset of a storm that can be simplified to exponential relationship between the pollutant washoff and runoff volume (Millar, 1999) and adequately describes the first flush phenomenon.

A variation of the Sartor and Boyd model assumes that shallow overland flow is satisfactorily approximated by assuming that washoff is proportional to the bottom shear stress of overland flow and the distribution of the pollutant (Nakamura, 1984). These assumptions were used to expand the model describing washoff by Akan (1987) and further elucidated by Singh (2002a; 2002b). Washoff is described by the model

$$\frac{\partial P}{\partial t} = -kShP \tag{9}$$

Where *P* is the mass of pollutant on the surface, *S* is the slope of the land surface, *h* is the depth of flow, and *k* is the washoff rate constant. The washoff rate constant is constant and is considered to depend only on pollutant characteristics with the dimensions Mass Length^{-3} Time^{-1}.

Pollutants can be transported through convection, dispersion, or diffusion. In addition, biochemical reactions degrade the pollutant. However, due to the time scale of a single storm, solutes are transported by shallow overland flow. This may not accurately represent the natural environment, where pollutants could be present in runoff in non-solute forms, such as adsorbed to particulates and organic matter. Despite these limitations, it is assumed that pollutant transport by diffusion and dispersion as well as biochemical reactions are negligible (Singh, 2002). Therefore, transport can be modeled based exclusively on convection. As such pollutant transport by overland flow can be represented by the dynamic equations of free-surface flow, the Saint Venant series of equations.

Convective transport in shallow overland flow can be adequately approximated by the kinematic wave analogy. The kinematic wave analogy is a mass balance that takes into account pollutant movement in runoff, run-on, rainfall deposition, and flux from the land surface as well as accumulation of pollutant in the overland flow. Mathematically this takes the form:

$$\frac{\partial (Ch)}{\partial T} + \frac{\partial (CQ)}{\partial X} + \frac{\partial P}{\partial T} = C_R I \tag{10}$$

Where C is the concentration of the pollutant in runoff, C_R is the concentration in rainfall, Q is the overland flow rate, h is the depth of runoff, P is the mass of pollutant on the surface of the land, and I is the intensity of rainfall (Akan, 1987). The first term is the change in mass flux of the pollutant in the runoff overtime. The second term is the net flux of pollutant in the runon and runoff. The third term is the change in mass of pollutant per area of land surface over time. The term on the right hand side is the mass of pollutant falling on the land surface in rainfall.

The transport relationship is solved for the pollutant concentration at each time step in each cell of the watershed grid through the following:

$$
\begin{aligned}
0 &= \frac{C(x,y,t)h(x,y,t) - C(x,y,t-1)h(x,y,t-1)}{\Delta T} \\
&+ \frac{\sum Qin(x,y,t-1)C(x,y,t-1) - \sum Qout(x,y,t-1)C(x,y,t-1)}{\Delta X} \\
&- Zh(x,y,t)P(x,y,t-1)
\end{aligned}
\tag{11}
$$

Where Q_{in} is the runoff discharge entering a grid cell from the adjacent cell and Q_{out} is the discharge leaving the cell. Further details on the implementation of this solution are given in the Methods section.

5. Methods

The basic setup of the project is illustrated in Figure 3. The water quality management system is comprised of hydrologic modeling using RADAR rainfall input and pollutant loading and buildup using SELECT which are used to model pollutant washoff and transport. Each of these water quality processes is calculated for each grid cell in the watershed model for simulation of pollutant concentration in runoff at each time-step of the modeled rainfall event.

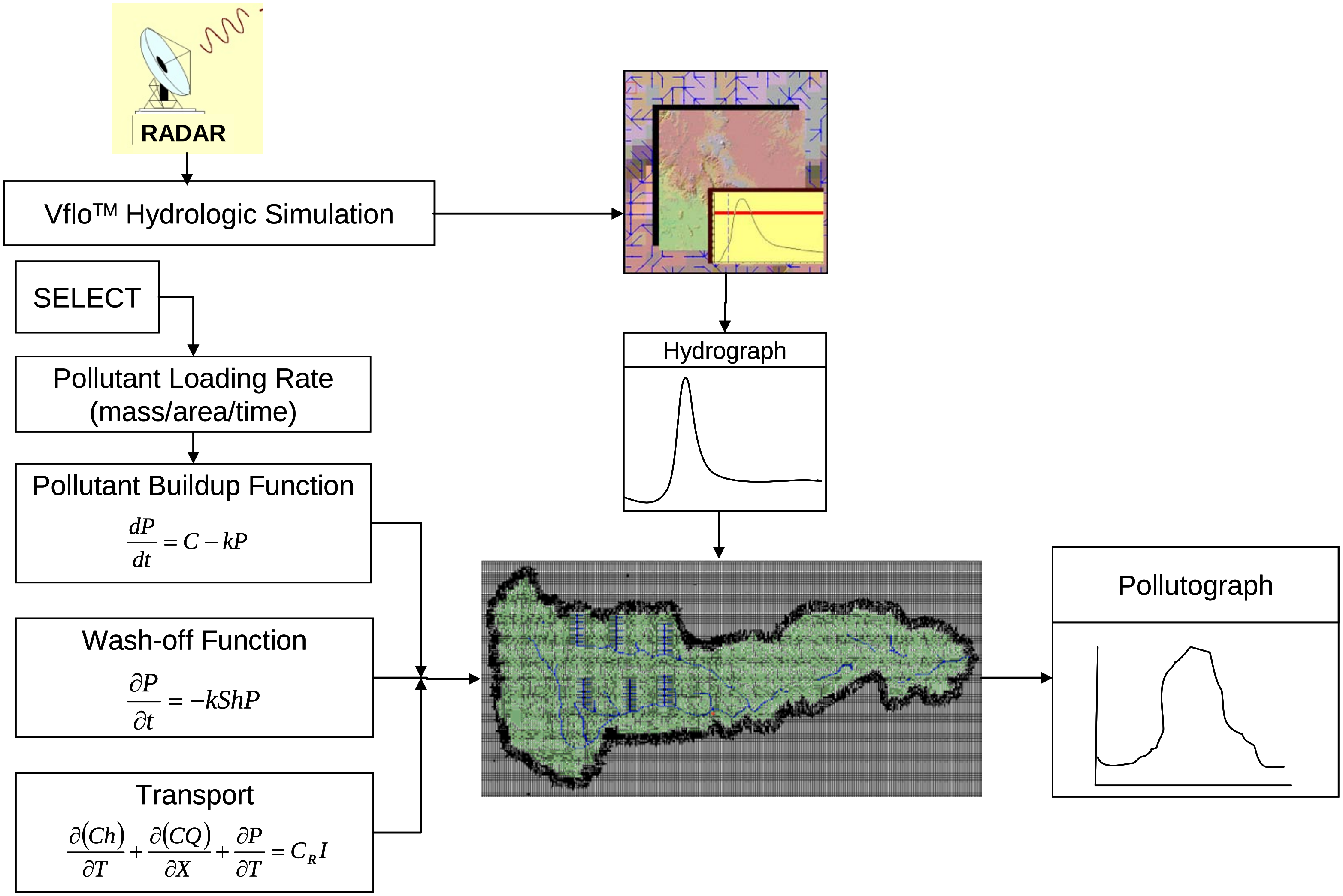

Figure 3. Flowchart of *Vflo*$^{\text{TM}}$ Water Quality Application

5.1 Hydrologic Model

A *Vflo*^{TM} model developed by Zimmer (2007) was created in order to assess flooding in Little Cypress Creek, a sub-watershed of Cypress Creek (Fang et al., 2009). Geospatial inputs to the model include slope and flow accumulation grids that were derived from Lidar data gathered by the Tropical Storm Allison Recovery Project (TSARP) in 2006. Soil roughness and conductivity were taken from values associated with the soil types present according to the STATSGO soil survey. Channel cross sections were inserted for each of the 71 sub-watersheds of Cypress Creek. The channel cross sections were taken from HEC-RAS model developed as a part of TSARP. Model inputs and data sources are shown in Table 1.

Table 1. Cypress Creek Vflo Model Data Sources

Data Type	**Source**	**Data Processed**
Elevation Data	Lidar -TSARP	Slope Flow Direction Flow Accumulation
Soils Data	Statsgo	Infiltration Hydraulic Conductivity Wetting Front Soil Depth Initial Saturation Impervious
Land Use Data	TSARP	Roughness
HEC RAS Cross Sections	TSARP	Channel Geometry
TWDB Lake Evaporation	TWDB	Evapotranspiration
Baseflow	H-GAC Permitted Outfalls, WWTP	

A grid consisting of 22 acre cells (or 300 meter on a side) was used to spatially represent the watershed (See Figure 4). The 308 mi^2 watershed is represented by a total of 25,070 cells. A digital elevation model (DEM) created from Lidar topographic data was processed in ArcView using the Spatial Analyst Toolbox to create a slope grid and

ArcHydro (Maidment, 2006) to create a flow direction grid. Land use data collected through the TSARP project (2006) was used to determine the Manning's overland roughness, *n*. In addition, each land use category was assumed to have a percent impervious value.

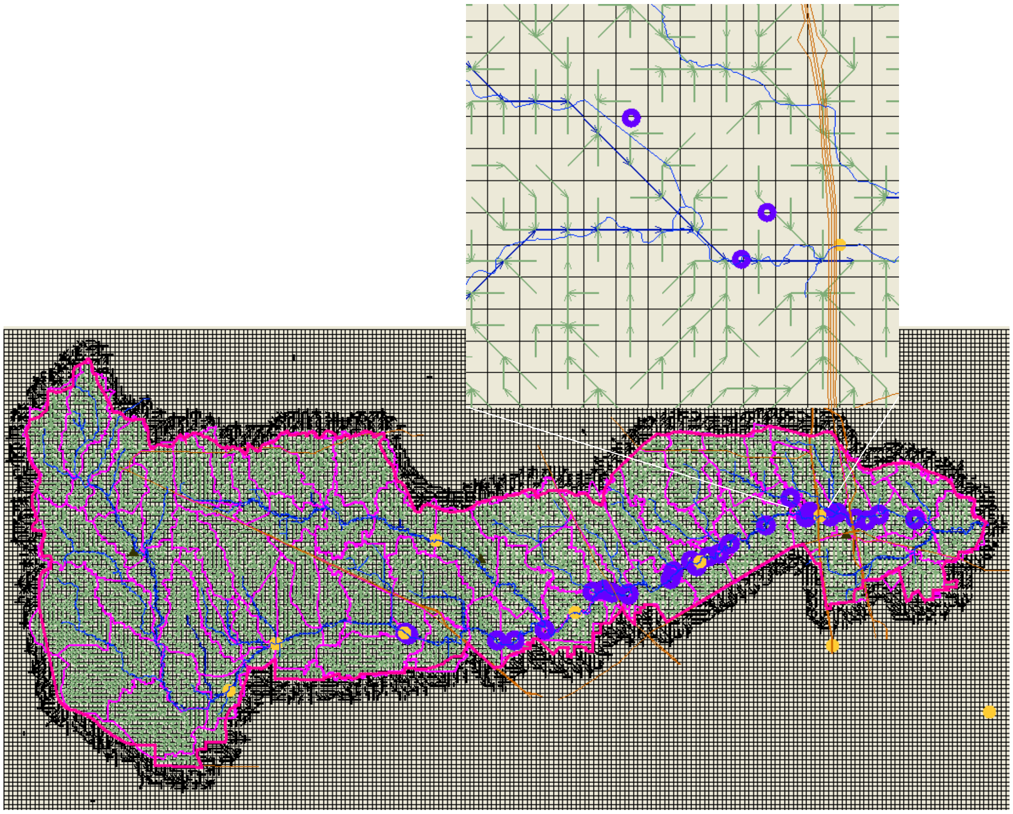

Figure 4. *Vflo*^{TM} Grid and Grid Details of Cypress Creek

The rainfall runoff model, *Vflo*$^{\text{TM}}$, was run with NEXRAD rainfall data, delivered by Vieux and Associates in 10 minute intervals at a 1km resolution. The RADAR data was collected from the National Weather Service RADAR at Dickinson, Texas and calibrated by Vieux and Associates to the 12 rain-gauges within and around the watershed.

5.2 Pollutant Loading

Average daily pollutant loading was estimated using SELECT (Spatially Explicit Load Enrichment Calculation Tool). The identified *E. coli* sources within Cypress Creek are waste water treatment plants (WWTP), pet waste, urban runoff, septic system failure, wildlife, and agricultural animals. The population estimates for cattle and sheep were taken from the 2002 U.S. Department of Agriculture Census (USDA-NASS, 2002). The population estimates for feral hogs and dogs were derived from literature values as outlined in Teague et al. (2009). The population estimates are in Table 2.

Table. 2 Cypress Creek Population Estimates

Populations	Description	Estimate
Beef Cattle	2002 USDA NASS	11,610
Dairy Cattle	2002 USDA NASS	153
Sheep	2002 USDA NASS	265
Feral Hogs	5/km^2 distributed to Riparian Cooridor	3,156
Pets	0.8 dogs/ Household	123,680

Nutrients, including total phosphorus and total nitrogen have associated sources including waste water treatment plants, agricultural fertilizer, urban fertilizer application, and agricultural, pet, and wildlife wastes. The potential loading of nutrients has been estimated based upon the EPA suggested pollutant loading rates for different land uses.

5.3 Water Quality Modeling of Pollutant Washoff and Transport

The mass of pollutant in the runoff leaving each grid cell is calculated by the kinematic wave equation for the selected pollutant in each grid cell at each time step. This mass balance approach accounts for the washoff, deposition, and pollutant runon from other cells, so that the pollutant discharge from each cell can be calculated (See Figure 5).

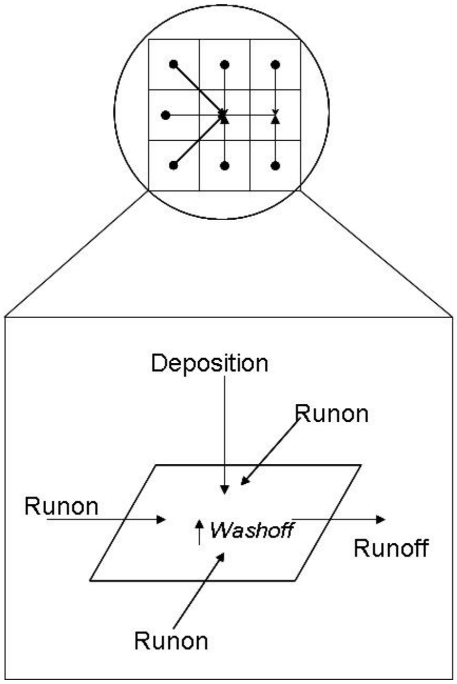

Figure 5. Schematic Representation of Pollutant Runoff in Grid-based Finite Element Model Solutions

The algorithm to accomplish this is conceptualized within the following steps for overland flow:

1. Calculate the mass of pollutant washed from the surface for every grid cell at the initial time step.
2. Calculate the mass of pollutant in the runoff leaving each grid cell.
3. Assign the runoff from each grid cell as the runon to the receiving grid cell.
4. Use conservation of mass and momentum (kinematic wave equation) to calculate the mass of pollutant in each grid cell.
5. Repeat for the next time step.

5.4 Washoff Calculation

The mass of pollutant washed off the land surface is calculated for each time step using the depth of the flow, washoff coefficient, and the mass of pollutant from the previous time step. Because the mass of pollutant washed off the land surface is independent of the concentration of the pollutant concentration in the overland flow, the pollutant washoff can be calculated independently of the transport, thus simplifying the calculation. The results of the *Vflo*^{TM} simulation, distributed discharge, can be used in ArcGIS to calculate the washoff, using Spatial Analysis: Raster Calculator as:

$$\frac{P(x,y,t)-P(x,y,t-1)}{\Delta t}=-kSh_i(x,y,t)P(x,y,t-1) \qquad (12)$$

The calculation requires slope *S*, the washoff factor *k*, depth of flow, *h*, from the *Vflo*^{TM} model output, and *P*, the mass of pollutant per cell from the previous timestep. The *P(x,y,0)* is taken from the loading and buildup calculation.

5.5 Simulation of Transport

The transport of the pollutant using kinematic wave equation (see equations 10 and 11) then requires calculation of concentration of pollutant in the runoff from each grid cell (See Figure 6) with

$$
\begin{aligned}
0 = {} & \frac{C(x,y,t)h(x,y,t) - C(x,y,t-1)h(x,y,t-1)}{\Delta T} \\
& \begin{bmatrix} Qin(x-1,y-1,t-1)C(x-1,y-1,t-1) + Qin(x,y-1,t-1)C(x,y-1,t-1) \\ + Qin(x+1,y-1,t-1)C(x+1,y-1,t-1) + Qin(x-1,y,t-1)C(x-1,y,t-1) \\ + Qin(x+1,y,t-1)C(x+1,y,t-1) + Qin(x-1,y+1,t-1)C(x-1,y+1,t-1) \\ + Qin(x,y+1,t-1)C(x,y+1,t-1) + Qin(x+1,y+1,t-1)C(x+1,y+1,t-1) \end{bmatrix} - \\
+ {} & \frac{\begin{bmatrix} Qout(x-1,y-1,t-1)C(x-1,y-1,t-1) + Qout(x,y-1,t-1)C(x,y-1,t-1) \\ + Qout(x+1,y-1,t-1)C(x+1,y-1,t-1) + Qout(x-1,y,t-1)C(x-1,y,t-1) \\ + Qout(x+1,y,t-1)C(x+1,y,t-1) + Qout(x-1,y+1,t-1)C(x-1,y+1,t-1) \\ + Qout(x,y+1,t-1)C(x,y+1,t-1) + Qout(x+1,y+1,t-1)C(x+1,y+1,t-1) \end{bmatrix}}{\Delta X} \\
- {} & ZY_i(x,y,t)P(x,y,t-1) +
\end{aligned}
\tag{13}
$$

Where Q_{in} is the discharge from one cell into the target cell and Q_{out} is the discharge leaving the target grid cell and entering the other cells. It should be noted that most of these cells will have a Q_{in} or Q_{out} of zero. This simulation will require exporting to matrix solver software that can support the large number of grid cells required by the simulation. In this project, this was accomplished using ArcObjects programming in ArcGIS.

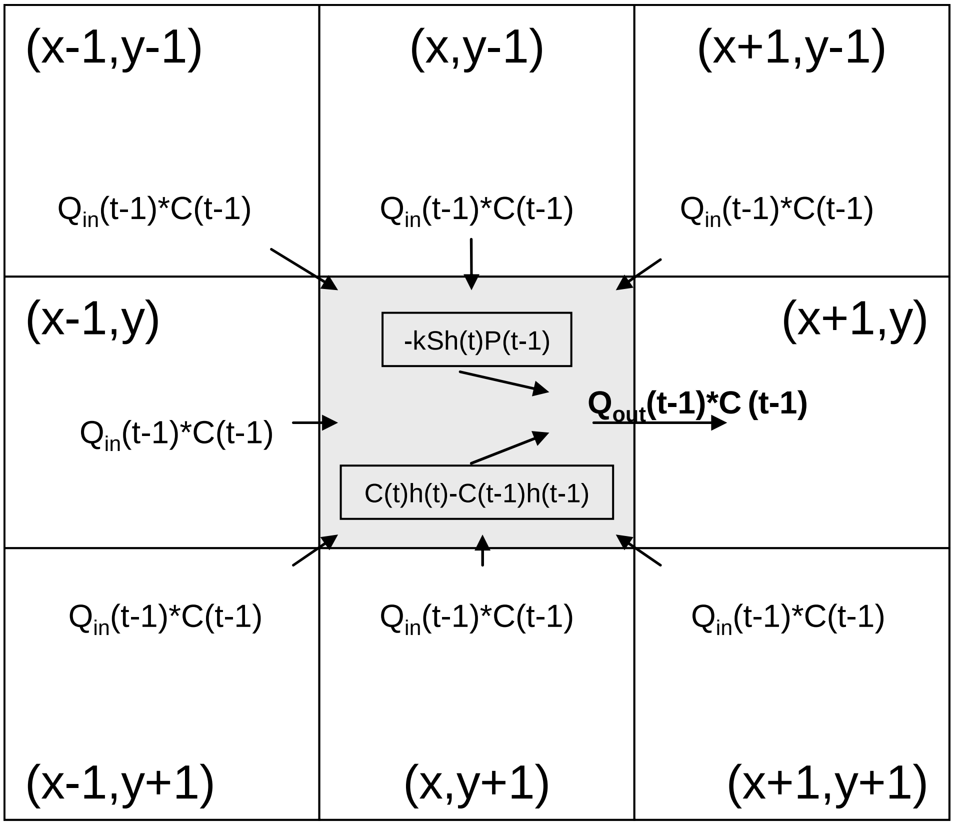

Figure 6. Grid Based Calculation of Pollutant Transport

6. Results

The proposed water quality management system is currently in development. Thus far the system is in the process of application for two rainfall events for which corresponding water quality data has been collected at the water quality monitoring station at IH45. The *Vflo*^{TM} hydrologic model was applied for July7, 2009 and September 22, 2009 rainfall events using delivered RADAR rainfall. The modeled versus observed discharge at the IH45 from the hydrologic model are shown in Figure 7 for July 7, 2009 and Figure 8 for September 22, 2009. Distributed discharge, or the modeled runoff for each grid cell of the watershed model, from a sample of time-steps, are shown in Figures in Appendix A.

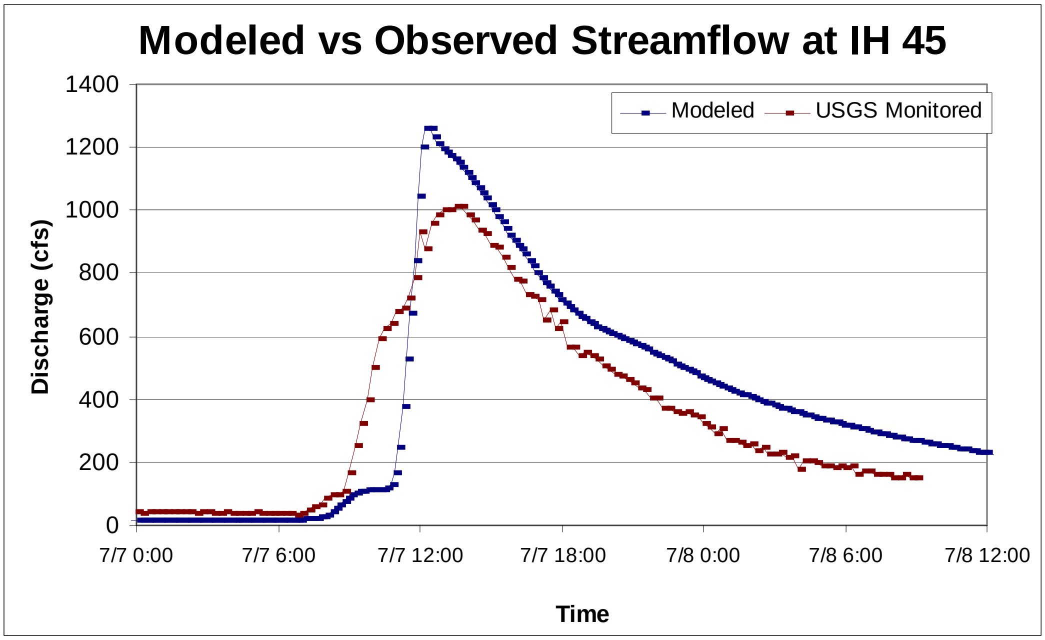

Figure 7. *Vflo*^{TM} Simulation of July 7, 2009 Storm

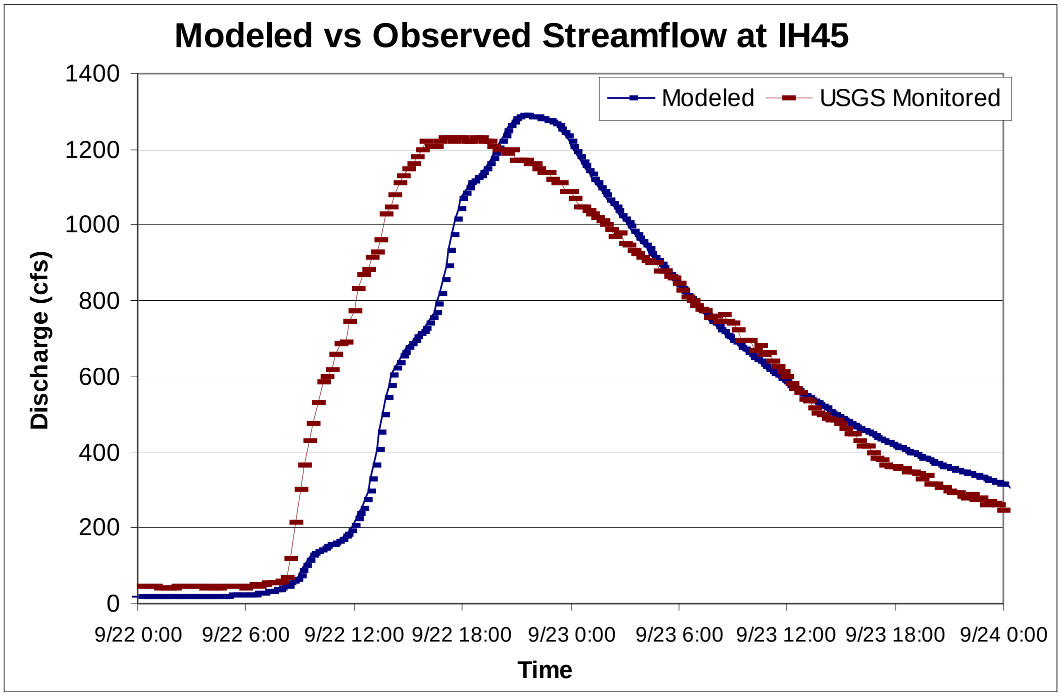

Figure 8. *Vflo*^{TM} Simulation of September 22, 2009 Storm

The previously discussed storms have been sampled to assess storm water quality of Cypress Creek at IH-45. The timing of the water quality observations are shown in Figures 9 and 10 with associated water quality data in Tables 3 and 4.

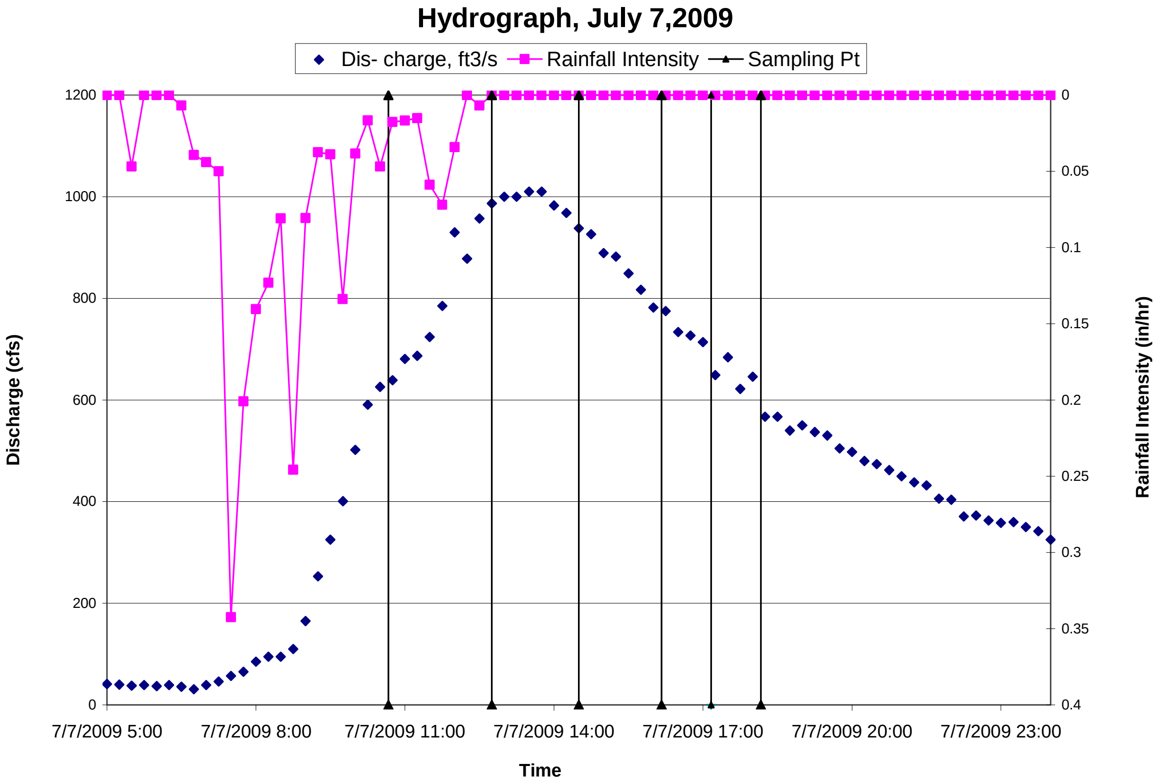

Figure 9 . Storm Water Quality Sampling from July 7, 2009

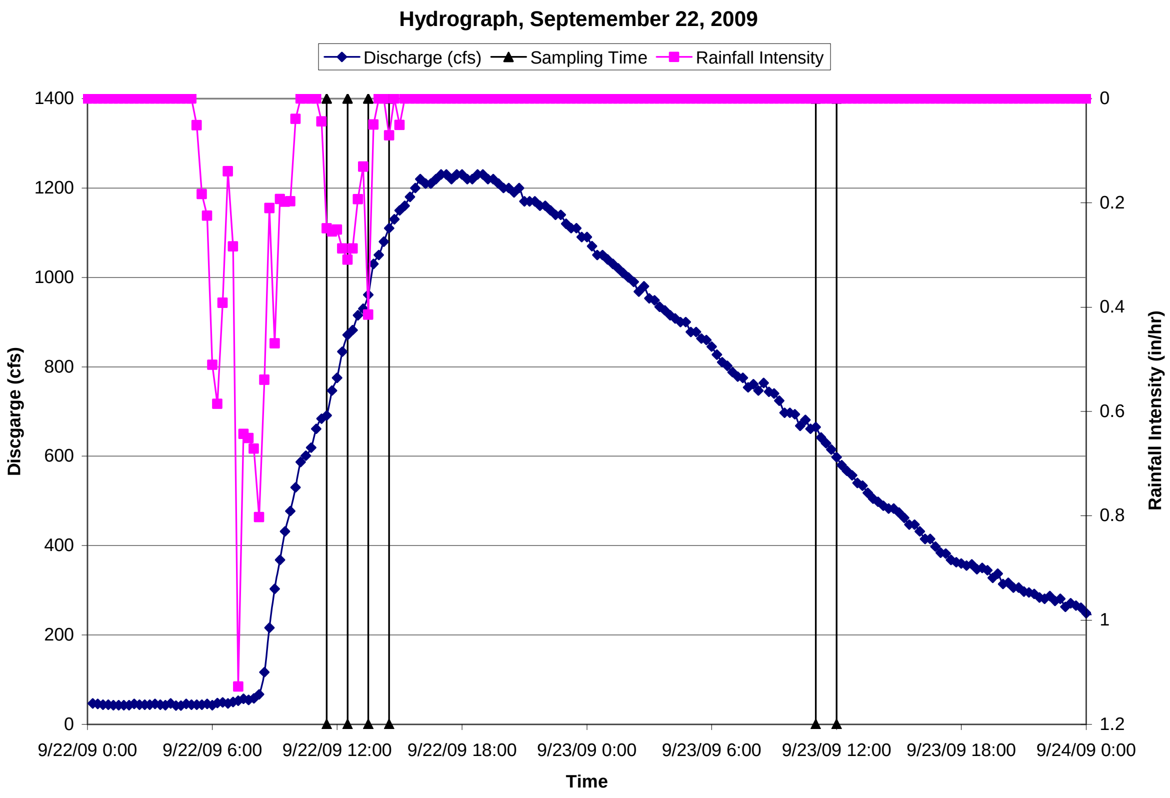

Figure 10 . Storm Water Quality Sampling from September 22, 2009

Table 3. Water Quality Data for July 7, 2009 Storm

Time	Streamflow (cfs)	*E.coli* (MPN/dL)	Nitrite (mg/L)	Nitrate (mg/L)	TP (mg/L)	OP (mg/L)	NH3 (mg/L)	TSS (mg/L)
7/7/2009 10:40	626	10,265	0.11	5.44	1.82	1.59	0.716	107
7/7/2009 12:45	987	49,657	0.048	2.68	1.31	0.968	0.911	213
7/7/2009 14:30	938	60,480	0.06	2.7	0.99	0.99	0.826	192
7/7/2009 16:10	782	49,657	0.064	2.34	0.904	0.904	0.862	155
7/7/2009 17:10	714	60,492	0.067	2.36	0.929	0.929	0.765	149
7/7/2009 18:10	646	60,492	0.061	2.09	0.841	0.841	0.777	125
Min	626	10,265	0.05	2.09	0.84	0.84	0.72	107.00
Max	987	60,492	0.11	5.44	1.82	1.59	0.91	213.00
Median	748	55,069	0.06	2.52	0.96	0.95	0.80	152.00
Std Dev	151	19,472	0.02	1.25	0.37	0.28	0.07	39.88
EMC		*49,706*	*0.07*	*2.87*	*1.12*	*1.02*	*0.82*	*163.15*

Table 4. Storm Sampling from Sept. 22, 2009

Time	Streamflow (cfs)	*E.coli* (MPN/dL)	Nitrite (mg/L)	Nitrate (mg/L)	TP (mg/L)	OP (mg/L)	NH3 (mg/L)	TSS (mg/L)
9/22/09 11:30	629	12,210	0.041	4.672	1.414	1.344	0.411	107
9/22/09 12:30	871	38,827	0.028	3.192	1.128	1.003	0.484	134
9/22/09 13:30	961	27,996	0.044	4.811	1.411	1.358	0.436	157
9/22/09 14:30	1,110	43,322	0.037	4.479	1.4	1.281	0.508	173
9/23/09 11:00	665	14,485	0.035	1.246	0.935	0.681	0.883	99
9/23/09 12:00	598	14,485	0.036	1.155	0.885	0.691	0.92	88
Min	598	12,210	0.03	1.16	0.89	0.68	0.41	88.00
Max	1,110	43,322	0.04	4.81	1.41	1.36	0.92	173.00
Median	768	21,241	0.04	3.84	1.26	1.14	0.50	120.50
Std Dev	207	13,567	0.01	1.70	0.25	0.32	0.23	33.96
EMC		*27,883*	*0.04*	*3.48*	*1.23*	*1.10*	*0.58*	*133.51*

7. Discussion

The hydrologic modeling results for the two storms shown in Figures 7 and 8 show that the *Vflo*^{TM} rainfall runoff model performs adequately on average with varying performance for each rainfall event. The spatially distributed results of hydrologic modeling of the July 7, 2009 rainfall event shown in Appendix A, show the format of the *Vflo*^{TM} hydrologic modeling. The hydrologic results, in the form of modeled runoff from each grid cell at each time step can be used in the modeling of pollutant washoff and transport. Examination of the hydrographs at IH45 (Figures 7 and 8) show that at the beginning of rising streamflow, the modeled flow is less than the observed streamflow. Near the peak in streamflow, the modeled flow is greater than the observed flow. Despite this, the modeled results are considered within an acceptable range. Further modeling of additional storms, including further calibration efforts, will improve the model performance.

The July 7, 2009 storm followed after 51 days of dry weather, where as the September 22, 2009 storm followed after 9 days of dry weather. Corresponding to a longer period of buildup, the median and Event Mean Concentration (EMC) (See Tables 3 and 4) of *E.*

coli and total suspended solids are larger for the July 7 storm. In contrast, the median and EMC for nitrate, total phosphorus, and orthophosphorus were higher for the September 22nd storm than the July 7th storm. For the July 7, 2009 storm, concentrations of nitrate and total phosphorus at the beginning of the rising limb of the hydrograph are higher than the observed concentrations at the end of the falling limb of the hydrograph. This indicates the presence of a first flush phenomenon. In contrast, *E. coli* observations were higher at the falling limb of the hydrograph. This could possibly be attributed to greater buildup on areas of the watershed that contribute to streamflow at this time or to overflows at the wastewater treatment plants. The September 22nd storm also exhibited higher concentrations of nitrate and total phosphors in the rising limb of the hydrograph, displaying first flush phenomenon. The observations of *E. coli* start low and increase with the rising limb of the hydrograph, with a decrease on the falling limb. This displays a lack of first flush phenomenon. This data will be used to calibrate the water quality model with future storms used for further calibration and validation.

Future efforts needed to further develop the proposed water quality management system include :

1) Estimation of Pollutant Loading using SELECT
2) Simulate the selected storms using *Vflo*™ with RADAR Rainfall input
3) Calculate pollutant washoff at each time step
4) Calculate pollutant discharge at each time step
5) Process the simulation results to produce pollutographs at the Cypress Creek at IH-45 gauge.

6) Calibrate the model based upon comparison of simulated results with measured pollutant loads.

8. Conclusion

The proposed project to develop a water quality prediction system was composed of three primary components including hydrologic modeling, pollutant buildup, washoff, and transport modeling, and water quality data collection. The hydrologic model *Vflo*^{TM} has been calibrated for use of RADAR rainfall input. Currently the rainfall-runoff modeling results are being used for development of the pollutant washoff and transport modeling. Water quality data have been collected for two rainfall events and the data used for development and calibration of the pollutant washoff and transport model.

Future efforts will include continuation of water quality data collection during selected rainfall events with the goal of capturing information on bacterial and nutrient loads during the rising and falling limb of the hydrograph. Further development of the water quality prediction model will include the estimation of pollutant buildup with SELECT, and automated calculation of pollutant washoff and transport.

This project is the basis for building a continuous, real time alert system for on-demand prediction of influent pollutant loading to Lake Houston. The intent is for this study to be the first phase of a wider project encompassing the Lake Houston Basin. Overall, the expected outcome of the proposed project is an advance in water quality modeling capabilities. It will extend current models by producing a fully distributed water quality model simulating pollutant buildup, washoff, and transport. Specifically it will provide valuable management information to the City of Houston Northeast Water Purification Plant Operations Manager for improved efficiency of water quality treatment.

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Appendix A: Spatially Distributed Results of Rainfall-Runoff Modeling

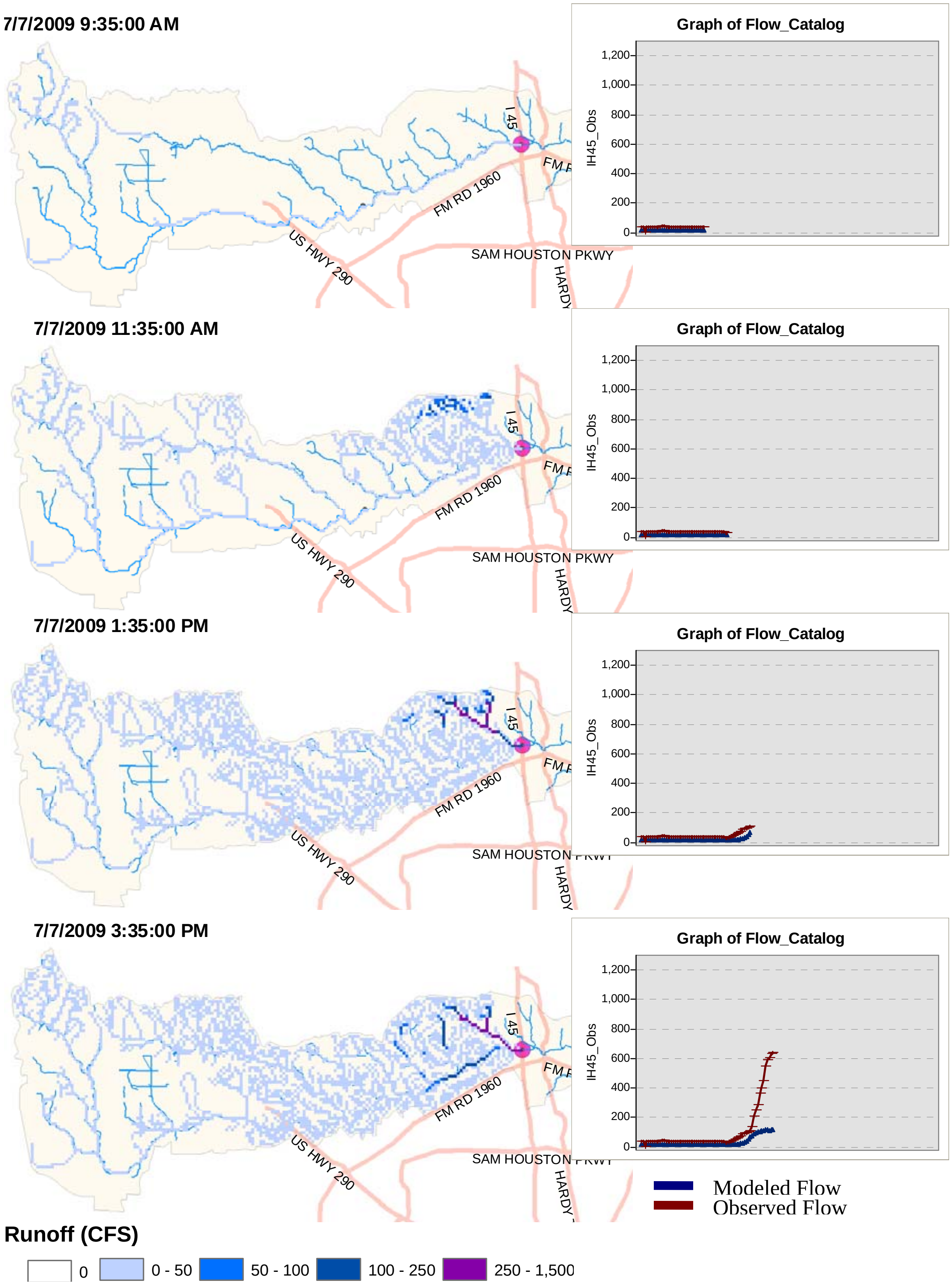

Figure A-1. Spatially Distributed Results of Rainfall-Runoff Modeling of July 7, 2009 Rainfall Event

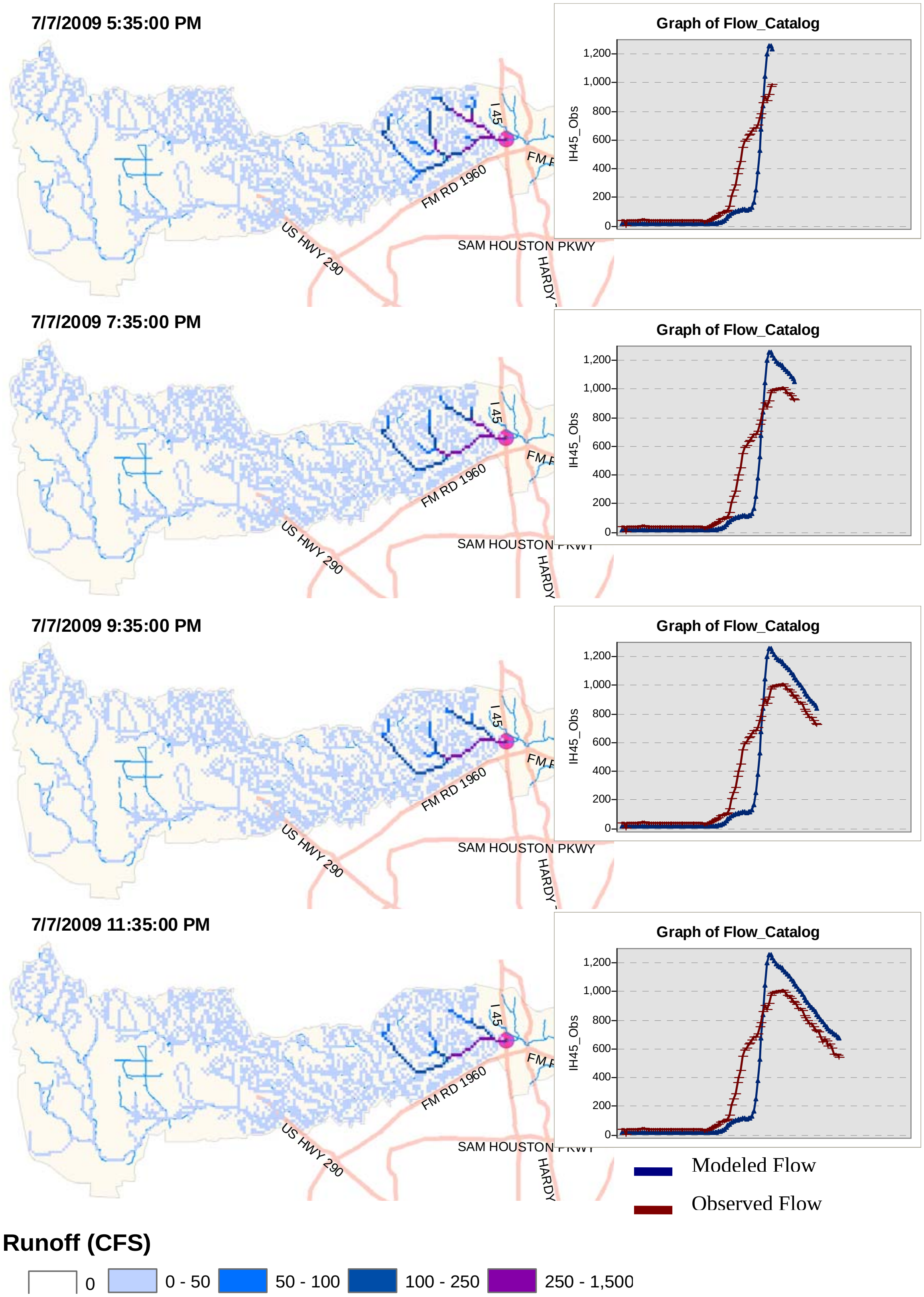

Figure A-2. Spatially Distributed Results of Rainfall-Runoff Modeling of July 7, 2009 Rainfall Event

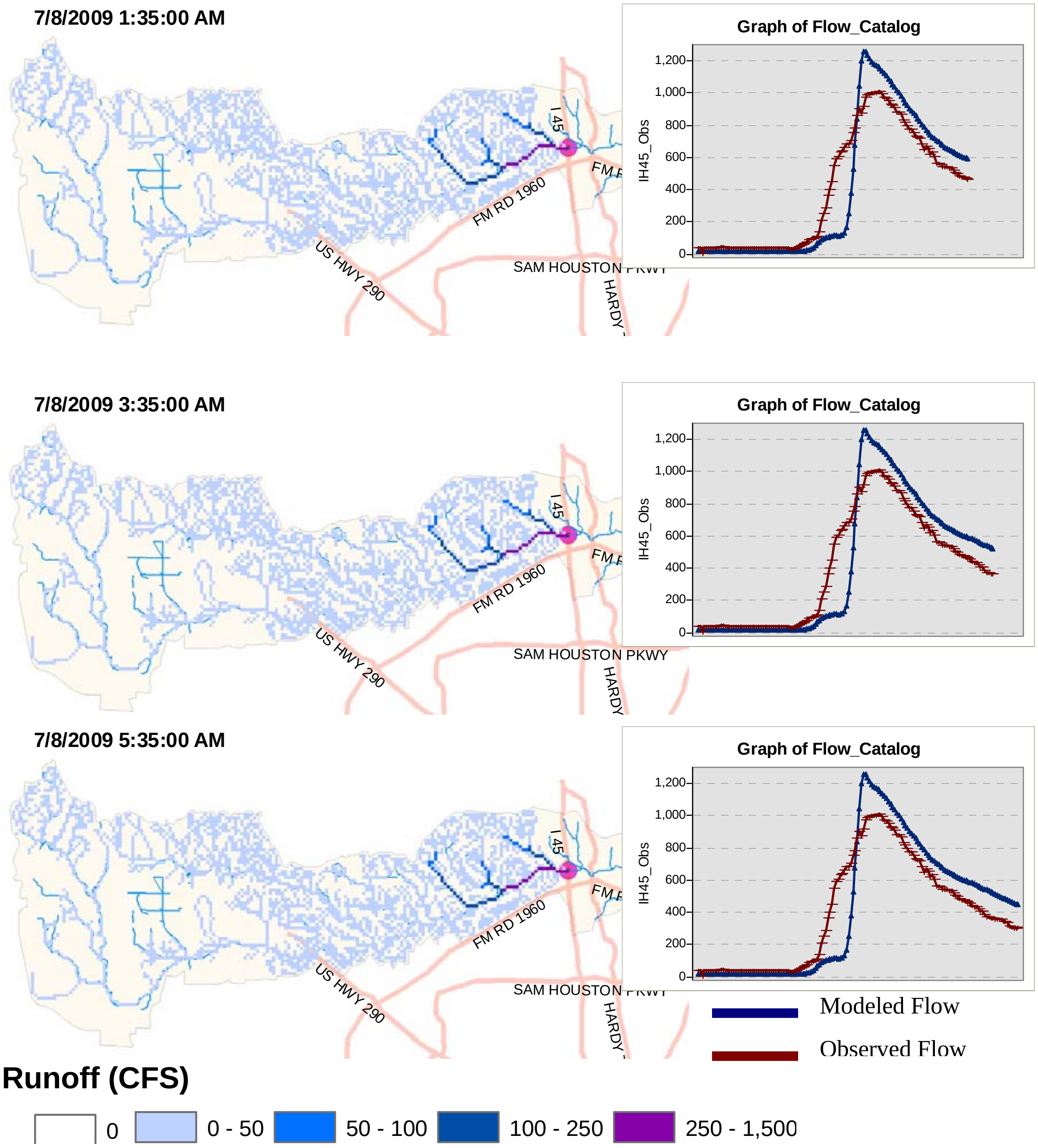

Figure A-3. Spatially Distributed Results of Rainfall-Runoff Modeling of July 7, 2009 Rainfall Event