Appendix 4-1

Wabash River Model Calibration

LimnoTech
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MEMORANDUM

FINAL FOR AGENCY REVIEW

DATE: October 30, 2008 (Draft submitted April 30, 2008)

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SUBJECT: Wabash River Model Calibration

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1. Summary

The City of Terre Haute is updating their collection system and river models as part of the improvements to their Combined Sewer Overflow (CSO) Long Term Control Plan (LTCP). The updated river model has been calibrated to monitoring data collected by the City in 2007 (described in LimnoTech, March 4, 2008 draft memorandum). The newly calibrated river model will provide a more accurate assessment of in-stream conditions during the evaluation of control alternatives for Terre Haute's CSO system than an earlier river model used in previous analyses.

The river model was calibrated and validated for the section of the Wabash River in Vigo County, Indiana from upstream of all Terre Haute CSOs at river mile (RM) 217.50 (between Highway 63 and US Route 40 bridges) to RM 200.0, 11.5 miles downstream of the City's wastewater treatment plant (WWTP), the City's most downstream source. The river model, which simulates flow and water quality, provides a causal linkage between the discharge of CSO pollutants and impacts on water quality. It provides a more complete assessment of water quality conditions than data alone by filling gaps between sampling locations and collection times and for simulating conditions under a "typical" or average year. The calibrated and validated river model will also provide the capability to forecast relative improvements in water quality conditions resulting from various CSO controls. This memorandum presents a description of the river model development, calibration and validation.

2. Model Description

The United States Geological Survey's (USGS) Branched Lagrangian Transport Model (BLTM) was selected as the model to simulate water quality in the Wabash River near Terre Haute. This model, developed in the 1980s, has been publicly available since the early 1990s. The version used in this project is Version 1.2 (November 4, 1996).

The BLTM was developed by the USGS to predict water quality in streams and estuaries. It is a fully dynamic model in that both flow and water quality conditions can vary with time and space. The USGS' stream hydraulic model, the Diffusion-Analogy Flow Model (DAFLOW), is used as a companion model to provide flow input to the BLTM model. BLTM uses a Lagrangian-based reference frame where the pollutant concentrations in parcels of in-stream water are tracked at computational nodes as they (the parcels) move with flow. Using a Lagrangian reference frame in water quality models is advantageous because it reduces numerical dispersion and is stable for any time step size.

BLTM is one dimensional in the longitudinal direction. It can simulate branched and distributary stream systems, although neither type are modeled in this project. Multiple pollutant source types, including CSOs, urban storm water, WWTP discharges and tributaries, can be specified at multiple points along the system. The model can simulate water quality under unsteady flow conditions, such as during a wet weather event.

The model is structured in branches, which are defined at their upstream and downstream boundaries by junctions. Branches are subdivided into grid sections that are defined by nodes. Nodes are also used as loading input locations. Multiple branches are allowed but each branch is limited to 100 grid sections. Grid sections within a branch can vary in size so that the nodes that define each grid section can more easily correspond to actual loading locations. The model structure developed for the Wabash River is described in the next section.

Channel geometry in BLTM is expressed as a function of flow and can vary by grid section to more accurately simulate the changing bathymetry found in a typical river system. The primary emphasis in defining the channel geometry is to accurately reproduce velocity and/or travel times with the flow portion of the model. Node geometry, kinetic rates, and flow and concentration inputs, which are used to simulate water quality can be customized for site-specific characteristics. This is described in more detail in Section 3.1.

3. Model Development

3.1. River Parameterization

The water quality model applied in this study was developed to simulate *E. coli* concentrations in the Wabash River. The model's spatial domain is the portion of the Wabash River within Vigo County extending from approximately 1.25 miles upstream of the US-40 bridge (and one mile upstream of the first CSO outlet), passing by the city and extending approximately 11 miles downstream of Terre Haute corporate limits. The model extends from RM 217.5 at the model's upstream boundary down to RM 200.0, the model's downstream boundary, as shown in Figure 3.1. This reach was chosen for several reasons:

- The model's upstream boundary is upstream of the City of Terre Haute's CSO sources, which will define the loads from upstream sources not originating from Terre Haute and permit a comparison of water quality in the area of the river receiving CSO discharge to water quality in the area of the river affected by upstream sources; and,
- The model domain extends eleven miles beyond the City's WWTP (at RM 211.50) and approximately fourteen miles beyond the last CSO outfall (at RM 214.25), permitting an assessment of the extent of downstream impacts of sources of *E. coli* within the model domain.

The model consists of one branch with 53 nodes. Nodes were selected to correspond with loading input and water quality sampling locations and to accurately represent the bathymetry of the Wabash River through geometry inputs based on the relationship between flow and area and flow and width for each grid section. Bathymetric data collected during the 2007 Sampling Program and data from the USGS were used to develop the geometry inputs to the model.

Also shown in Figure 3.1 are the locations where loadings from active CSOs are input into the model. Methods used to estimate flow and concentration inputs to the river model from these and other sources *of E. coli* are described in the following section. Table 3.1 presents location and loading information about each node in the model.

3.2 Model Inputs

The water quality model requires flow and concentration data for each source of *E. coli*. Upstream, CSO, WWTP, tributary (Sugar Creek) and other (e.g. wildlife, failing septics, etc.) sources are tracked separately in the model. The data and methods used to specify the model inputs are described in this section and are summarized in Table 3.2.

3.1.1. Upstream

The upstream boundary of the river model is 0.5 miles above the first monitoring station and approximately one mile above the most upstream CSO (CSO-010).

Hourly flows at the model boundary were obtained from a USGS gage (gage no 03341500) located near the US-40 Bridge and sampling location RS-2 (see Figure 3.1). Because the drainage area between the gage and the model upstream boundary is small, the flows measured at the gage were used directly in the model.

The water quality of the Wabash River at the model boundary is influenced by upstream sources of *E. coli.* The portion of the Wabash River upstream of the river model boundary is over 12,000 square miles. Therefore, to accurately simulate water quality within the model domain, the variability in loads from upstream sources need to be incorporated into concentration estimates at the model boundary. Measured data were used when available to specify the concentration at the upstream boundary. Linear interpolation was used to estimate upstream concentrations during the hours when measured data were not available. This method emulates the rising/falling upstream *E. coli* concentrations in the Wabash River during wet-weather events.

3.1.2. CSO

CSO flows were provided by Greeley and Hansen, who estimated the hourly flow discharging from each CSO using a calibrated model of the collection system. This model was applied by inputting hourly rainfall data during the monitored storm events to generate CSO flow inputs for the river model. Rainfall data were input into the collection system model and an hourly time series of flows from each CSO outfall simulated by the model were used directly in the Wabash river model.

E. coli loads from Terre Haute's CSOs were estimated by applying a representative concentration or event mean concentration (EMC) to the overflow volumes. Selection of EMCs (versus applying measured concentrations) facilitates credible use of the model for forecasting purposes. The EMCs for the CSOs were developed using the data collected during the Sampling Program for CSOs 004/011, 006, 007, and 009. The geometric mean concentration of all of the CSO data was 475,000 cfu/100 ml, which was used as the EMC for the CSOs in the river model and provided the best model-to-data fit to the in-stream data. Previous statistical analysis (see Sampling Program memorandum, March 2008) suggested that the concentrations in CSO-009 were much lower than the remaining sampled CSOs, indicating that a different EMC should be used for CSO-009. A sensitivity analysis using an EMC of 210,000 cfu/100 ml for CSO-009 and

675,000 cfu/100 ml for the remaining CSOs was performed but did not improve the calibration. This is described in Section 4.2.

3.1.3. WWTP

Daily effluent flows and *E. coli* concentration data were obtained from the Terre Haute WWTP for the period of interest and used as inputs to the model to represent loadings from the WWTP.

3.1.4. Other Nonpoint Sources (Tributary, Direct Drainage)

Tributaries

Sugar Creek is a tributary to the Wabash River draining approximately 100 square miles of rural land in western Indiana and eastern Illinois. Its average flow is much smaller than the Wabash River flow (approximately 0.44%). The confluence of Sugar Creek with the Wabash River occurs at RM 213.5, approximately two miles upstream of the Terre Haute WWTP. A USGS station located on Sugar Creek (gage ID 03341540) has a limited amount of flow data. Since a continuous set of flow data was not available for this tributary, flow data from the Wabash River flow gage (gage no 03341500) and a nearby tributary (Mill Creek) flow gage (gage no 03358000) were adjusted using a drainage area ratio to estimate the flow in Sugar Creek, A daily flow time series for the periods of interest in Sugar Creek were generated for use in the river model.

A number of dates from the Sugar Creek USGS data contained both measurements of flow and *E. coli* concentration. These data were used to establish a relationship between the flow and average *E. coli* concentration. *E. coli* concentrations were assigned for high-flow and low-flow conditions in Sugar Creek using the average *E. coli* concentration measured above and below the median flow. These *E. coli* concentrations were applied to the daily flow series calculated for Sugar Creek to estimate the *E. coli* concentration at the mouth of Sugar Creek.

Stormwater

The most downstream portion of the Sugar Creek watershed includes the very small communities of West Terre Haute and Taylorville (adjacent to the river). Storm water runoff from these areas is unlikely to be reflected in the daily time series of flow and concentration described above. Therefore, runoff from the Sugar Creek tributary area adjacent to the river (approximately 4.37 square miles) was estimated using the rational method, $Q = ciA$, where A = area of storm water drainage basin (acres), i = rainfall (in/hr), and c = runoff coefficient (unitless). The runoff coefficient was specifically developed for the Sugar Creek watershed, using spatial data on soil type and land cover in the basin. The *E. coli* event mean concentration from the stormwater data collected during the 2007 Sampling Program (5,000 cfu/100 ml) was applied to the estimated volume to develop a loading time series for the model.

Direct Drainage

The reach of the Wabash River used in the model included areas outside of the Terre Haute collection system and other neighborhoods, such as Taylorville, that utilize septic systems. Failing septic systems, particularly in Taylorville, which is adjacent to the river, may be a source of *E. coli* loading directly to the river. Wildlife also contribute *E. coli* directly to the river. A flow and *E. coli* load time series were estimated for these direct drainage sources using literature information on septic system failure rates.

Figure 3.1: Model boundaries and locations of loading inputs.

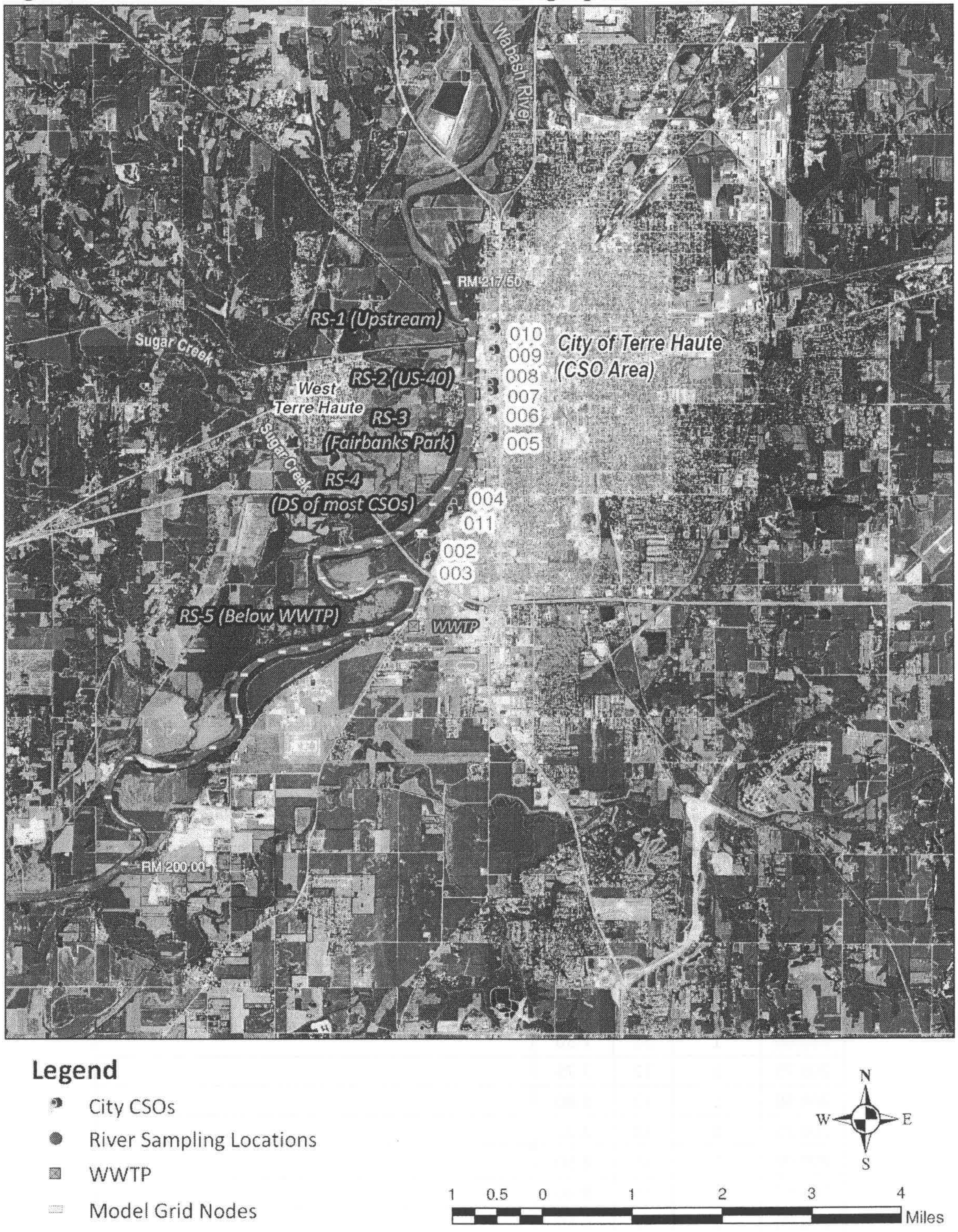

Table 3-1: Model Grid Node Descriptions, Including Sampling and Load Input Locations (Where Appropriate)

River Mile (RM)	Branch ID	Grid ID	Model R.M.	Description
217.50	1	1	0.00	Upstream model boundary
217.25	1	2	0.25	
217.00	1	3	0.50	River Station 1 (RS-1)
216.75	1	4	0.75	Location of CSO 010
216.50	1	5	1.00	Location of CSO 009
216.25	1	6	1.25	US-40 Bridge, River Station 2 (RS-2)
216.00	1	7	1.50	Locations of CSO 008 and CSO 007
215.75	1	8	1.75	Locations of CSO 006 and CSO 005
215.50	1	9	2.00	Fairbanks Park, River Station 3 (RS-3)
215.25	1	10	2.25	
215.00	1	11	2.50	
214.75	1	12	2.75	Locations of CSO 004 and CSO 011
214.50	1	13	3.00	River Station 4 (RS-4)
214.25	1	14	3.25	Location of CSO 002 and CSO 003
214.00	1	15	3.50	
213.75	1	16	3.75	
213.50	1	17	4.00	Sugar Creek confluence
213.25	1	18	4.25	
213.00	1	19	4.50	
212.75	1	20	4.75	
212.50	1	21	5.00	
212.25	1	22	5.25	
212.00	1	23	5.50	
211.75	1	24	5.75	
211.50	1	25	6.00	Location of WWTP
211.25	1	26	6.25	River Station 5 (RS-5)
211.00	1	27	6.50	
210.75	1	28	6.75	
210.50	1	29	7.00	
210.25	1	30	7.25	
210.00	1	31	7.50	
209.75	1	32	7.75	
209.50	1	33	8.00	
209.25	1	34	8.25	
209.00	1	35	8.50	
208.50	1	36	9.00	
208.00	1	37	9.50	
207.50	1	38	10.00	

River Mile (RM)	Branch ID	Grid ID	Model R.M.	Description
207.00	1	39	10.50	
206.50	1	40	11.00	
206.00	1	41	11.50	
205.50	1	42	12.00	
205.00	1	43	12.50	
204.50	1	44	13.00	
204.00	1	45	13.50	
203.50	1	46	14.00	
203.00	1	47	14.50	
202.50	1	48	15.00	
202.00	1	49	15.50	
201.50	1	50	16.00	
201.00	1	51	16.50	
200.50	1	52	17.00	
200.00	1	53	17.50	Downstream Model Boundary

Table 3-2: Data and Methods used to specify model inputs.

Pollutant Source Type	Methodology for Flow Time Series	Methodology for *E. coli* Concentration Time Series
Upstream	USGS gage @ US-40 bridge (RM 216.25) (Gage ID = 03341500)	Measured data from 2007 Sampling Program when available. Linear interpolation between measured data.
Terre Haute CSOs	SWMM Model Simulation	Event mean concentrations (EMC) based on geometric mean concentration from 2007 Sampling Program
Terre Haute WWTP	Daily average effluent flow data	Daily effluent data
Sugar Creek	Applied drainage area ratio to flows from Wabash River and Mill Creek USGS gages, then used average of calculated flows in model.	Sugar Creek data-derived representative high-flow and low flow *E. coli* concentrations.
Surface Water Runoff	Rational Method	EMC equal to median concentration of 5,000 cfu/100 ml from 2007 Sampling Program
Direct Drainage	0.01 cfs (dry weather) 0.10 cfs (wet weather)	1,000,000 cfu/100 ml (from literature)

4. Model Calibration

LimnoTech conducted a wet weather Sampling Program in the Summer and Fall of 2007. Over the duration of wet weather sampling (August 2007 through October 2007), LimnoTech sampled in-stream water quality conditions during three storms of varying magnitude (August 20, September 25, and October 17, 2007). LimnoTech also sampled in-stream water quality conditions in a dry period (August 9, 2007). Thus, the monitoring period data were collected over a range of environmental conditions and represent a robust dataset to compare with *E. coli* concentrations simulated by the river model.

The river model was applied over the three month period comprising the 2007 Sampling Program (August-October 2007). *E. coli* data from the September 25 storm were used to calibrate the model because this event was a mid-range storm in terms of rainfall volume and duration (the August 20 event was a light scattered-rain and the October 17 storm was a very heavy and long-lasting rain event). The data from the entire monitoring period were used to validate the model. However, the validation focused on reproducing the data from the October 17 storms since these data were collected when all the City's CSOs were active and the data from the August 20 storm. Event characteristics for each of the storms are summarized in Table 4.1. Rainfall depth ranged from 0.30 to 2.22 inches while stream flow ranged from 1,750 cubic feet per second (cfs) to more than 8,500 cfs (the 95th percentile flow). Calibrating and validating the model to this range of conditions increases confidence in the use of the model for CSO control alternative analysis by demonstrating its ability to reasonably represent the range of conditions that will be evaluated for each alternative.

The objectives of the river model calibration and validation were:

1 The model reasonably estimates peak concentrations observed in the data at each sampling location;

2 The model reasonably estimates the timing of the river response to bacteria CSO loads observed in the data; and,

3 The model reasonably estimates the range of observed concentrations over the duration of the Sampling Program period (August - October 2007).

Determining when the model was adequately calibrated was based on visual inspection of temporal and spatial comparisons of model output and data at the monitoring locations and on the model's ability to meet statistical goals. The model results for the September 25 event were statistically adequate and model outputs for the other monitored storms were also comparable to the data. Calibration results and sensitivity analyses are discussed in more detail in this section.

Table 4-1: Event Characteristics of Sampling Events.

Event ID	1	2	3	4
Dates (2007)	9-Aug	20-Aug	25-Sep	17-Oct
Start Time	-	15:00	17:00	15:00
Total Rainfall (in.)	-	0.3	0.5	2.22
Maximum Intensity (in/hr)	-	0.05	0.07	0.14
Duration (hrs)	-	6	7	16

Event ID		1	2	3	4
Flow Range during sampling period (cfs)		2,100 - 2,510	2,090 – 8,520	2,070 - 2,130	2,200 – 4,230
E. coli Concentration Range (cfu/100 ml)	Upstream Boundary	5	2 – 58	12 – 126	62 - 2,419
	Highway 40 Bridge	2	2 – 29	5 - 2,419	210 - 816,400
	Fairbanks Park	6	5 – 387	3 – 770	461 - 30,760
	Near Hulman St. CSO	1	12 - 58	2 - 2,419	613 - 38,730
	Downstream Boundary	10	6 - 35	3 - 2,419	649 - 57,940

4.1. Volumes and Loads to the River

The inputs to the model over the simulation period were developed as described in Section 3.2. As noted in Section 3.2.2, the CSO volumes used in the river model calibration were the simulation results from the collection system model. The rain data used as input to the collection system model were collected at several different locations and used for the CSO simulation.

Table 4.2 displays a summary of the volume and *E. coli* load inputs by individual source for the September 25 calibration event. The period of calculation spanned the rising limb of the river hydrograph (usually when the rain started) to 24 hours later (after confirming that the river hydrograph was near base flow conditions). CSOs from the City contribute only a small fraction of the volume (less than 1% total) but can contribute a much larger portion of the load during and immediately after a storm event. The loads are illustrated graphically in Figure 4.1 by source category. These tables and figures indicate that the most significant source of *E. coli* during the modeled wet weather periods are Terre Haute's CSOs (98% of the total *E. coli* load to the river). Upstream sources contribute 1.4% of the total load while the combined load from storm water, tributaries, direct drainage and the City's WWTP contribute less than 1% of the total load delivered to the river during this period.

Table 4-2: Summary of the Volume and *E. coli* Load Inputs by Individual Source Type for the September 25 Calibration Event.

Category	Volume (MG)	% of Total Volume	*E. coli* Load (cfu)	% of Total Load
Upstream	1,369	97.6%	2.06E+12	1.36%
Tributary	7	0.5%	4.62E+10	0.03%
CSO	8	0.6%	1.48E+14	97.74%
SWO	6	0.5%	1.22E+12	0.81%
WWTP	12	0.9%	8.76E+10	0.06%
Total	**1,403**	**100%**	**1.513E+14**	**100%**

Note: Maximum CSO overflow duration simulated with the collection system model was 10 hours (CSO-009).

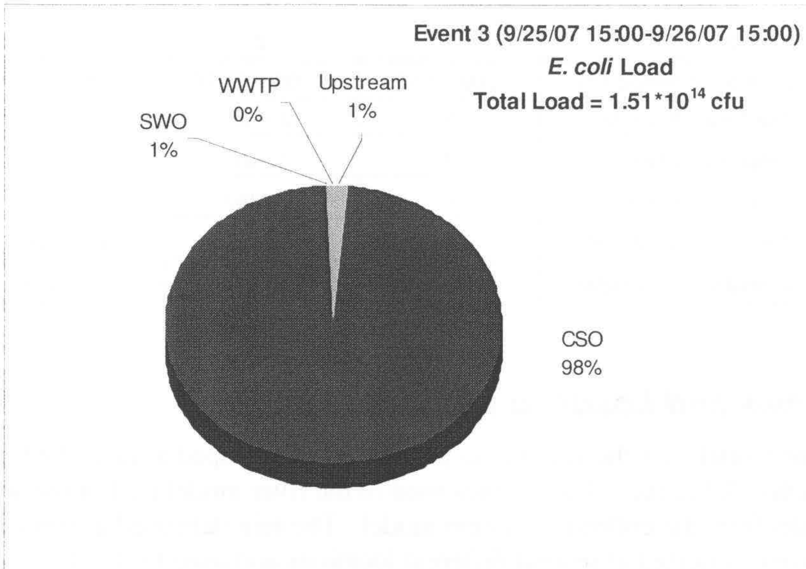

Figure 4-1: ***E. coli*** **Loads from September 25, 2007 Event.**

Volumes and *E. coli* loads by individual source are summarized in Table 4.3 for the August 20, 2007 event, Table 4.4 for the October 17, 2007 event and in Table 4.5 for the entire simulation period. Table 4.6 presents a summary of volume, load and duration of overflow for each CSO for each event. Figure 4.2 shows the *E. coli* load distribution for the August 20 event by source type. Figure 4.3 shows the same information for the October 20 event. Although the total *E. coli* load varies, the distribution of load by source type for the October 20 wet weather event is similar to the calibration event, with approximately 93% of the load to the river originating in Terre Haute's CSOs and most of the remaining load originating from upstream sources. A small rainfall event, such as the August 20 event (0.3 inches), caused fewer CSOs to activate (only three of the City's ten CSOs overflowed). The relative magnitude of CSO *E. coli* load comprised only 64% of the total load for this event, which is much less than larger storm events when more CSOs are active.

Table 4-3: Summary of the Volume and *E. coli* Load Inputs by Individual Source Type for the August 20 Event.

Category	Volume (MG)	% of Total Volume	*E. coli* Load (cfu)	% of Total Load
Upstream	1,406	98.5%	1.07E+12	20%
Tributary	6	0.4%	4.30E+10	0.80%
CSO	0	0.0%	3.43E+12	64%
SWO	4	0.3%	7.33E+11	14%
WWTP	12	0.8%	8.38E+10	1.56%
Total	**1,428**	**100%**	**5.358E+12**	**100%**

Note: Maximum CSO overflow duration simulated with the collection system model was 7 hours (CSO-009).

Table 4-4: Summary of the Volume and E. coli Load Inputs by Individual Source Type for the October 17 Event.

Category	Volume (MG)	% of Total Volume	*E. coli* Load (cfu)	% of Total Load
Upstream	3,059	95.5%	8.03E+13	6.23%
Tributary	22	0.7%	1.58E+11	0.01%
CSO	67	2.1%	1.20E+15	93%
SWO	29	0.9%	5.43E+12	0.42%
WWTP	26	0.8%	2.78E+11	0.02%
Total	**3,202**	**100%**	**1.290E+15**	**100%**

Note: Maximum CSO overflow duration simulated with the collection system model was 24 hours (CSO-009).

Table 4-5: Summary of the Volume and E. coli Load Inputs by Individual Source Type For All Events.

Category	Volume (MG)	% of Total Volume	*E. coli* Load (cfu)	% of Total Load
Upstream	5,834	96.7%	8.35E+13	5.77%
Tributary	34	0.6%	2.47E+11	0.02%
CSO	75	1.2%	1.35E+15	94%
SWO	39	0.6%	7.38E+12	0.51%
WWTP	50	0.8%	4.49E+11	0.03%
Total	**6,033**	**100%**	**1.446E+15**	**100%**

Table 4-6 Summary of the Volume and *E. coli* Load Inputs by Individual CSO For All Monitored Wet Weather Events.

	Event 2, 8/20/2007			Event 3, 9/25/2007			Event 4, 10/17/2007		
Source	Volume (MG)	Hours of Overflow	Percent of Total *E. coli* Load	Volume (MG)	Hours of Overflow	Percent of Total *E. coli* Load	Volume (MG)	Hours of Overflow	Percent of Total *E. coli* Load
CSO 002	0.000	0	0.0%	0.000	0	0.0%	0.000	0	0.0%
CSO 003	0.000	0	0.0%	0.060	3	0.7%	1.986	10	2.8%
CSO 004	0.007	2	2.4%	4.144	5	49.2%	20.106	15	28.0%
CSO 005	0.000	0	0.0%	0.106	3	1.3%	1.676	12	2.3%
CSO 006	0.000	0	0.0%	0.020	2	0.2%	0.985	7	1.4%
CSO 007	0.000	0	0.0%	0.893	4	10.6%	12.213	13	17.0%
CSO 008	0.079	2	26.4%	0.084	2	1.0%	1.461	8	2.0%
CSO 009	0.105	7	35.2%	0.769	10	9.1%	7.648	24	10.7%
CSO 010	0.000	0	0.0%	0.195	2	2.3%	7.992	10	11.1%
CSO 011	0.000	0	0.0%	1.956	4	23.2%	12.864	13	17.9%
	1,428	**7**	**100%**	**1,403**	**10**	**100%**	**3,202**	**24**	**100%**

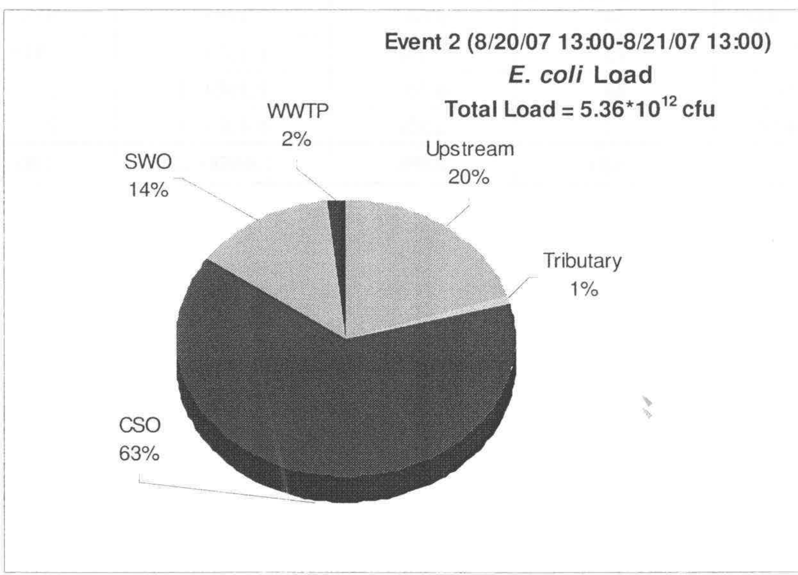

Figure 4-2: *E. coli* Loads from August 20, 2007 Event.

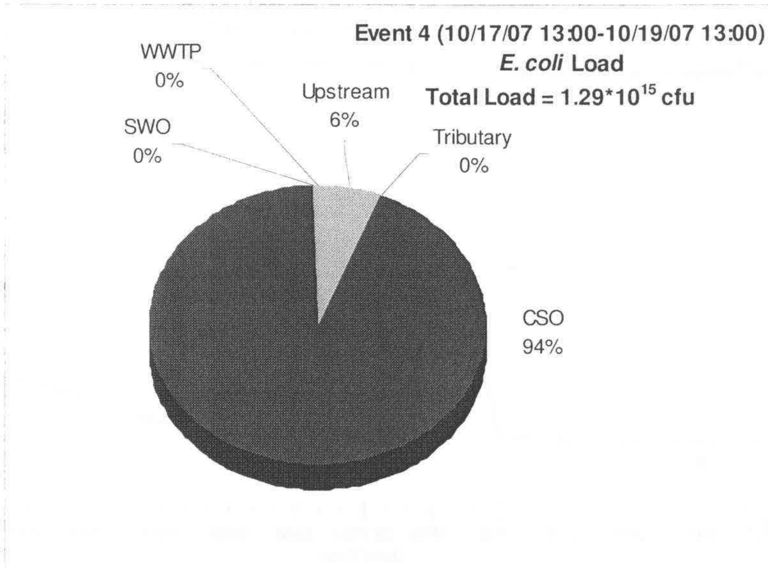

Figure 4-3: ***E. coli*** **Loads from October 17, 2007 Event.**

4.2. Comparison of Model Output to Data

4.2.1. Comparison for Calibration Event

Model simulated concentrations for the calibration event were compared to the data several ways to evaluate how well the model results met the objectives described above. Evaluation methods included temporal profiles at sampling locations, scatter plots, statistical summaries and animations of spatial profiles over the duration of the event. Results were evaluated at four locations:

1 Highway 40 Bridge (RM 216.30), which is downstream of two CSO outfalls (CSO 010 and CSO 009) and also corresponds to the location of the USGS gage (gage no 03341500);

2 Near the boat docks at Fairbanks Park (RM 215.5), which defines the impacts of the CSOs at Fairbanks Park and represents a potential area of recreational use;

3 ¼ mile downstream of the Hulman Street CSO outfall, which reflects the influence of CSOs 004 and 011 and also captures the impact of ~90% of the total CSO volume; and,

4 ½ mile downstream of the WWTP, which is downstream of all of the City's CSO sources and also shows the effect of the Sugar Creek tributary loading.

Comparisons at the most upstream sampling location (RM 217.00) were not included because these data were used to derive the boundary conditions that were input to the model. As the following discussion indicates, the model calibration to the September 25 event is well constrained.

Figures 4.4 through 4.7 are temporal plots of measured and simulated concentrations at each sampling location during the September 25 storm event. The model reproduces the temporal profile observed with the data during the event at each sampling location.

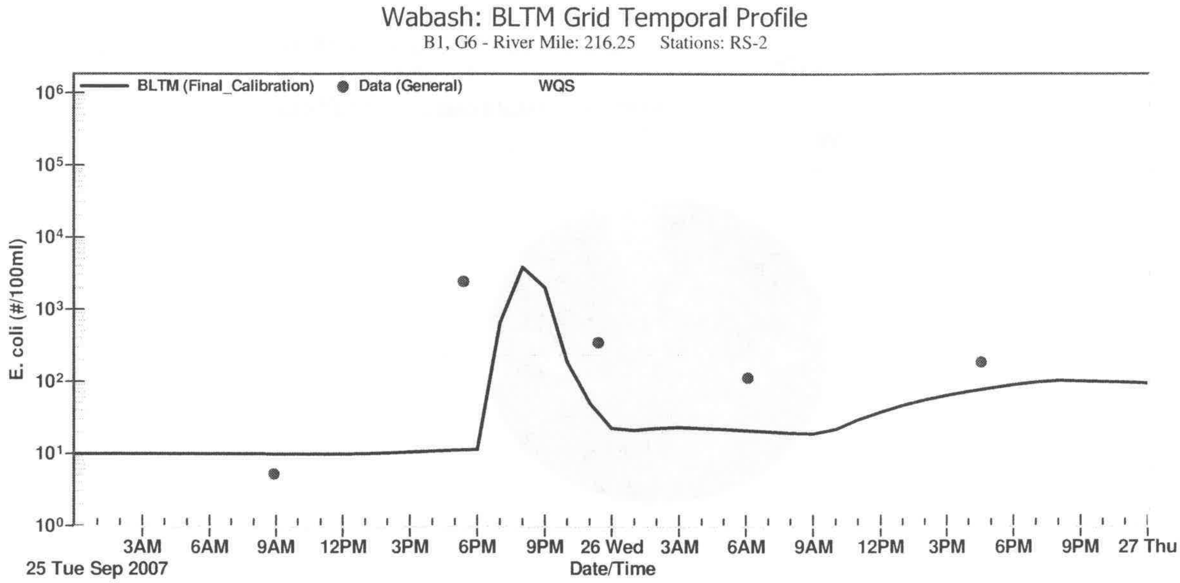

Figure 4-4: Temporal Profile of Observed and Simulated *E. coli* Concentrations at Highway 40 Bridge (RS-2) During the September 25, 2007 Event.

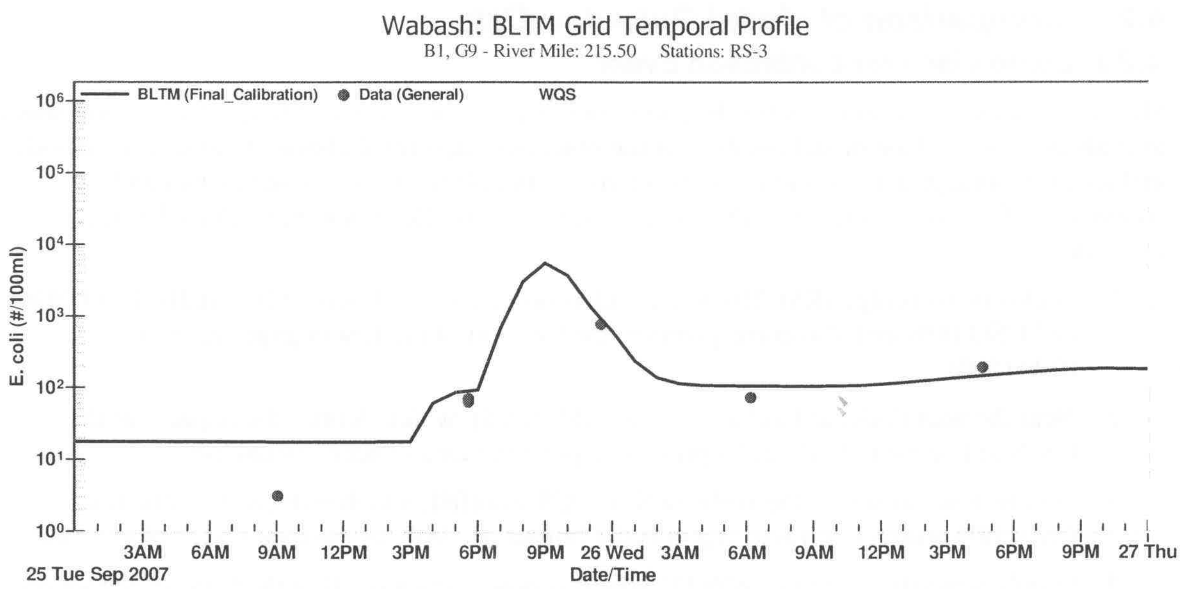

Figure 4-5: Temporal Profile of Observed and Simulated *E. coli* Concentrations Near Fairbanks Park (RS-3) During the September 25, 2007 Event.

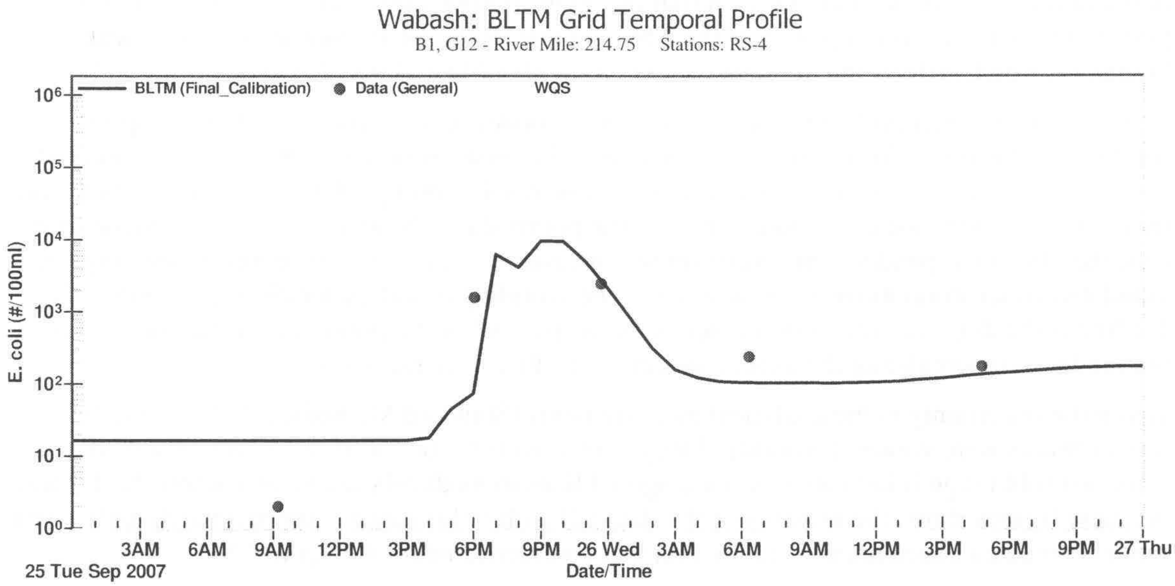

Figure 4-6: Temporal Profile of Observed and Simulated *E. coli* Concentrations ½ Mile Downstream of Hulman St. CSO (RS-4) During the September 25, 2007 Event.

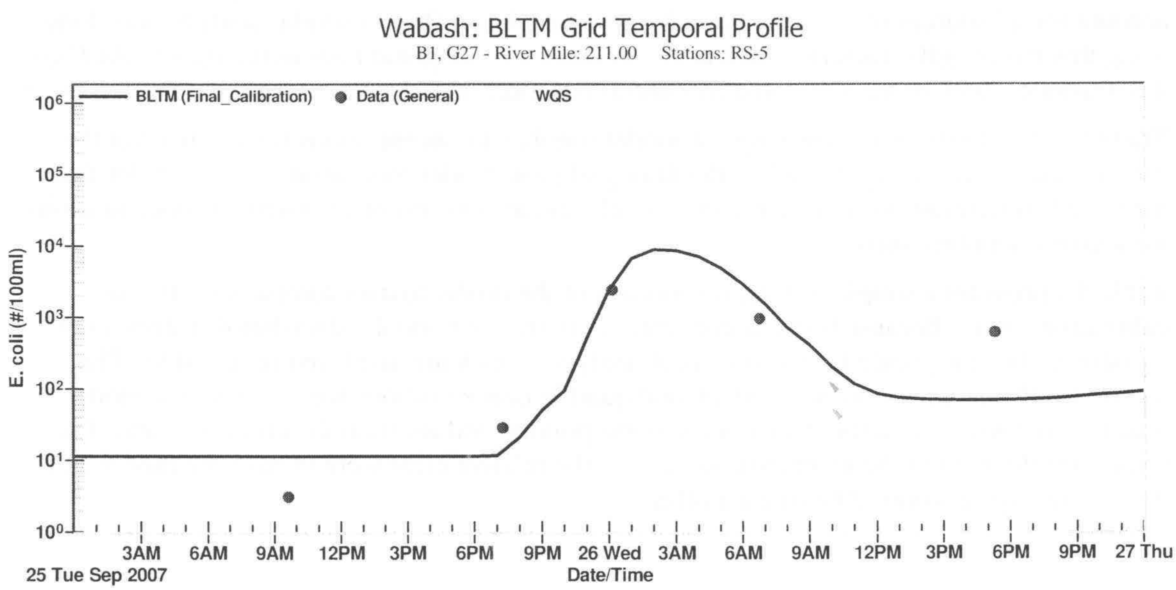

Figure 4-7: Temporal Profile of Observed and Simulated *E. coli* Concentrations Downstream of CSO Outfalls and WWTP (RS-5) During the September 25, 2007 Event.

These figures show that the model generally reproduces the timing and magnitude of the observed data at each location, although the model comparison to data at the US 40 bridge was not as good as other locations. Attempts to adjust EMCs to reflect the concentration at US 40 bridge compromised the overall model-to-data fit. However, the model reproduces the maximum *E. coli* concentration for each of the other locations and performs very well in the portion of the river receiving 90% of the CSO volume (RM 214.75) and at the downstream boundary, which reflects the ultimate impacts from all CSO outfalls (211.00).

Figure 4.8 is a scatter plot showing a regression of model versus data at all of the sampling locations. This figure further illustrates how well the model reproduces the range of observed concentrations, including peak concentrations. Figures 4.9 through 4.12 are scatter plots for the individual sampling locations noted above. The points show the model result at the same date-time that the corresponding concentration was measured. The whiskers represent the range in simulated concentrations over the duration of the sampling round, generally $\pm$ 2-3 hours. The 1:1 line is the diagonal line in the center of the graph. All of the points would fall on this line if the model were simulating the exact concentrations that were measured.

Given the uncertainty in the analytical measurements (Standard Methods, 20th Edition), the model results were viewed favorably if they agreed within a factor of two of the observed data. This two-fold range is indicated by the diagonal lines immediately above and below the 1:1 line. As these figures show, the majority of the data fall within this range. Approximately 65% of the model simulated concentrations fall within this confidence interval (Figure 4.8).

In addition to uncertainty associated with the analytical procedures, other factors, such as in-stream variability and sample collection and handling, also contribute to uncertainty in the observed data. A less rigorous calibration objective was to have the model-simulated concentrations be within an order of magnitude of the observed data. This target was intended to account for all sources of uncertainty in the observed data. Thus, a similar analysis was done using this target ($\pm$10x factor), which is the second set of diagonal lines in the figure. As Figure 4.8 illustrates, 95% of the simulated concentrations meet this objective for the calibration event.

These figures illustrate that the range of model simulated concentrations usually bracket the measured data, indicating that while the timing of peak model concentrations may differ from measured concentrations, in general, the model simulates the range of observed concentrations for a given sampling survey.

Table 4.7 provides a simple statistical summary of the model to data comparisons for the calibration event. Because bacteria concentrations are not normally distributed, values were transformed to a log scale for the statistical analysis, which are displayed in the table. The targets for the geometric mean, median, and quartile concentrations were to have the model results agree within a factor of two of the corresponding values from the observed data. The targets for the ratio of the geometric means and the relative error were to have the model and data results agree within 20% of each other.

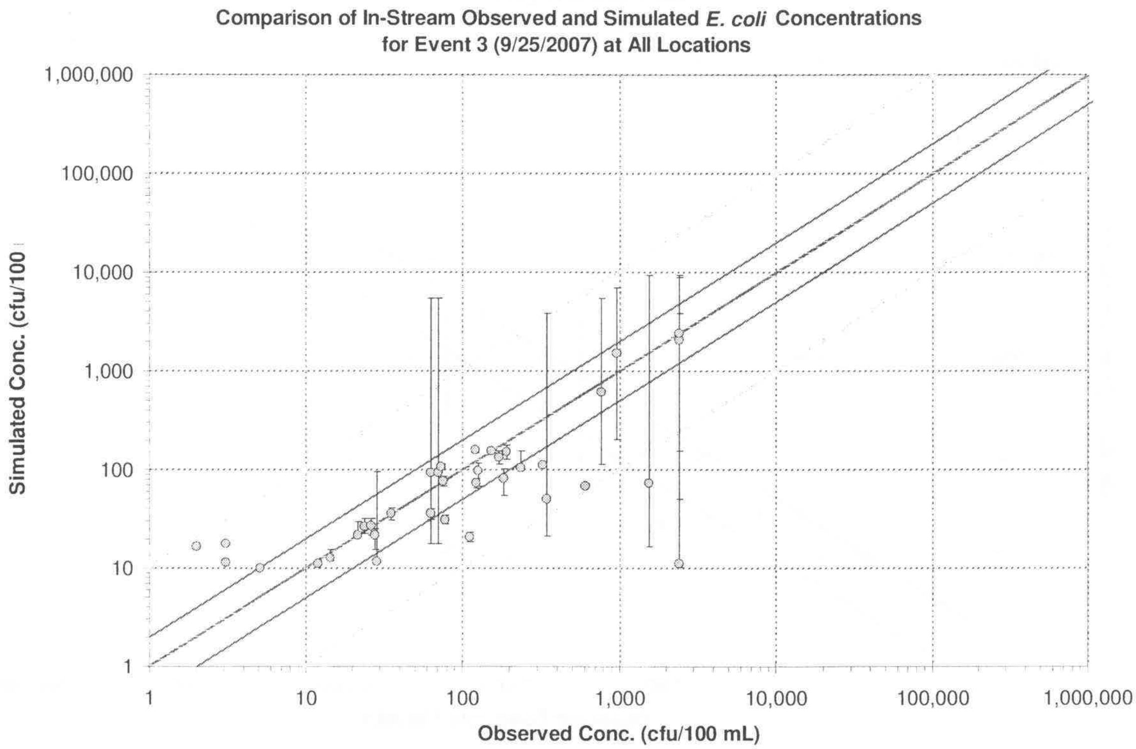

Figure 4-8: Comparison of In-Stream Observed and Simulated *E. coli* Concentrations During the September 25, 2007 Event at All Locations.

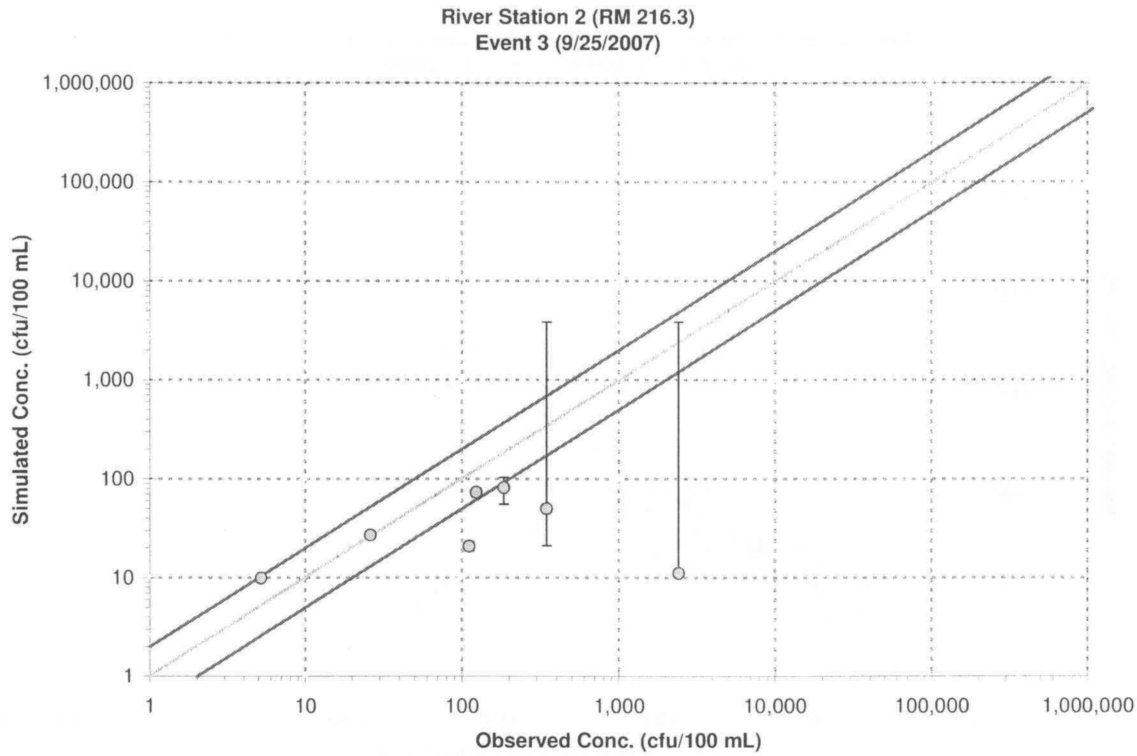

Figure 4-9: Comparison of In-Stream Observed and Simulated *E. coli* Concentrations at Highway 40 Bridge (RS-2) During the September 25, 2007 Event.

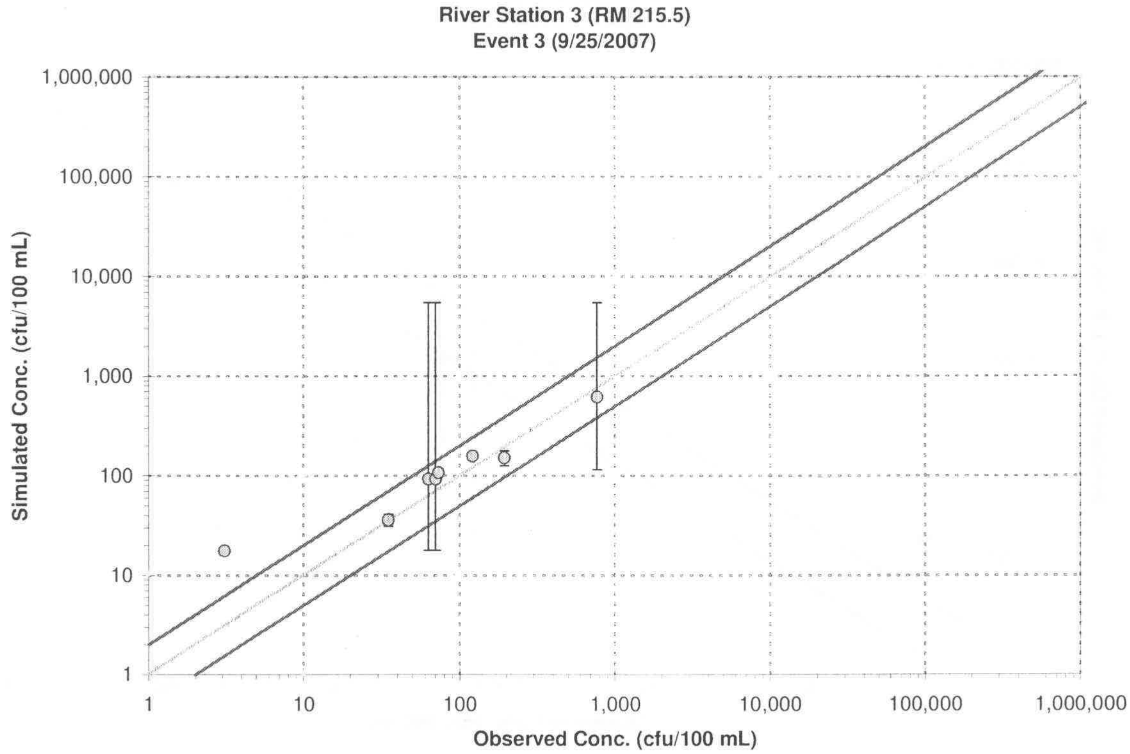

Figure 4-10: Comparison of In-Stream Observed and Simulated *E. coli* Concentrations Near Fairbanks Park (RS-3) During the September 25, 2007 Event.

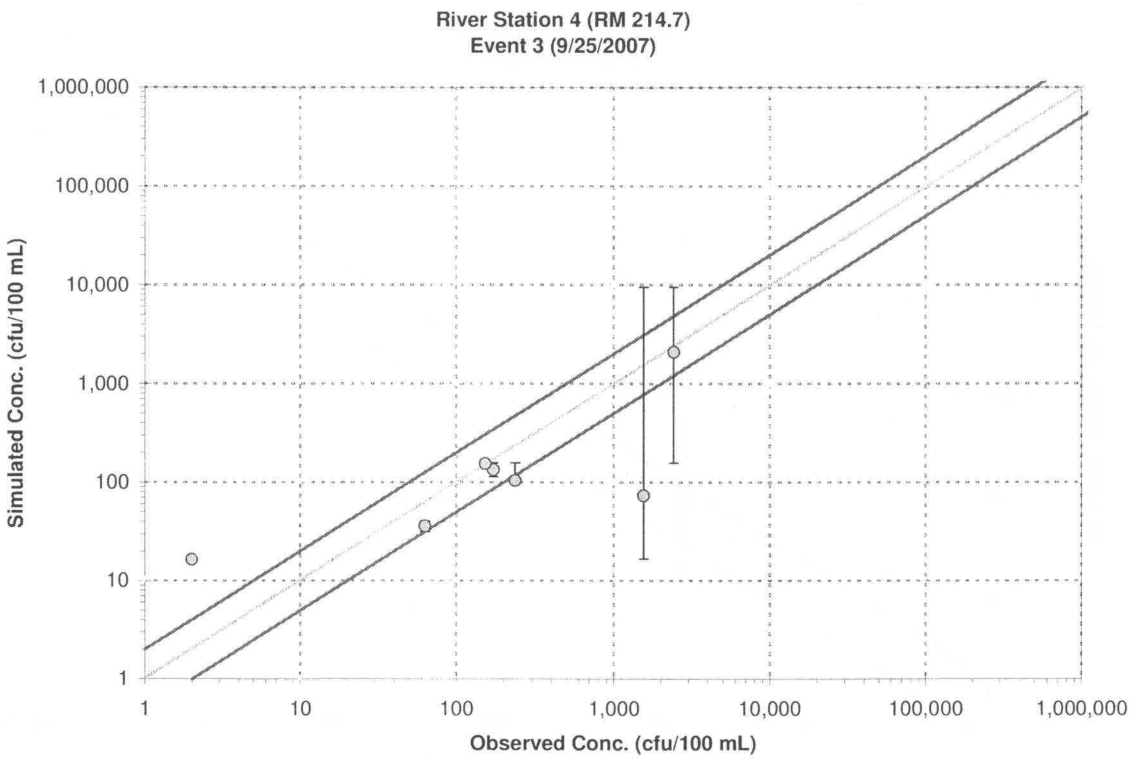

Figure 4-11: Comparison of In-Stream Observed and Simulated *E. coli* Concentrations ½ mile Downstream of Hulman St. CSO (RS-4) During the September 25, 2007 Event.

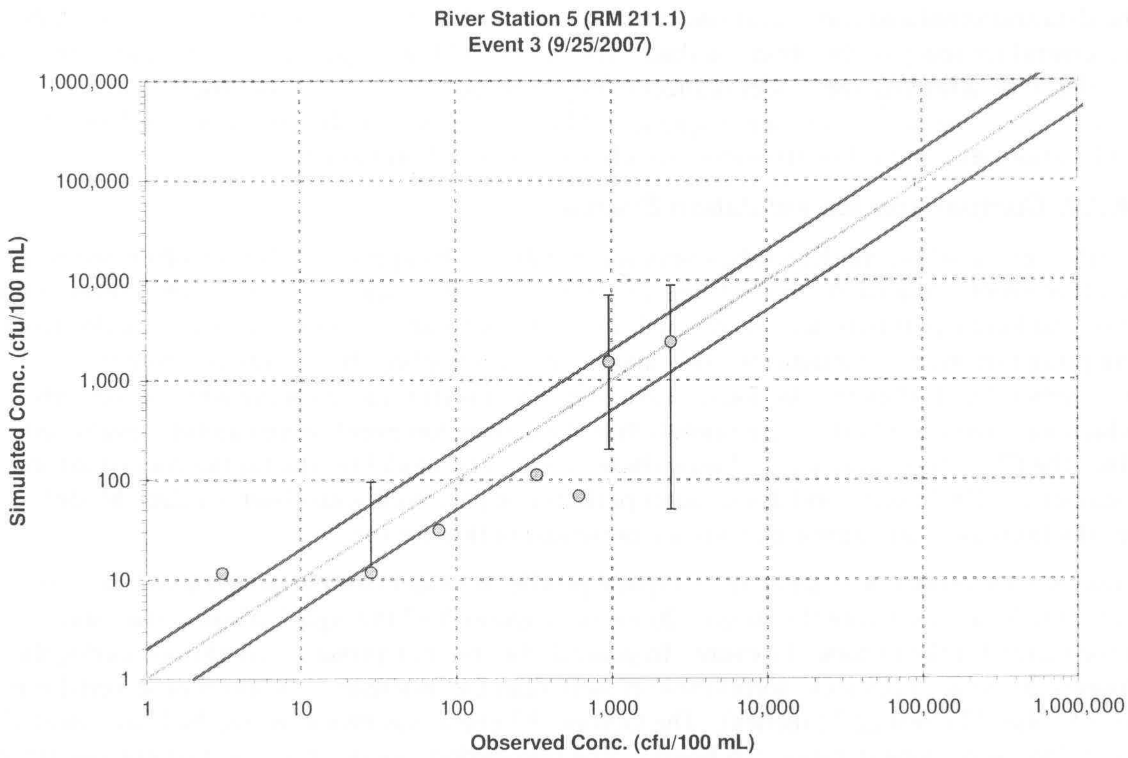

Figure 4-12: Comparison of In-Stream Observed and Simulated *E. coli* Concentrations Downstream of CSO Outfalls and WWTP (RS-5) During the September 25, 2007 Event.

Since river mile 217.00 is where the upstream boundary is specified and was not influenced by the City, the statistics at this location are not very useful for evaluating model performance. It was included in the table for completeness since it was one of the routinely monitored locations. Table 4.7 also includes an assessment of the model performance that does not include this location.

Table 4-7: Statistical summary of the model to data comparisons for the calibration event.

River Mile	Count	Data Geometric Mean	Model Geometric Mean	Data Median	Model Median	Data 25th Percentile	Model 25th Percentile	Data 75th Percentile	Model 75th Percentile	Mean Data/Model Ratio	Relative Error
217	21	3.41	3.33	3.18	3.08	2.67	2.55	4.33	4.33	1.03	-2.56%
216.25	21	4.76	3.38	4.81	3.30	3.27	2.41	5.84	4.29	1.41	-28.98%
215.50	24	4.26	4.59	4.27	4.61	4.00	4.30	4.91	5.03	0.93	7.70%
214.75	24	5.10	4.73	5.15	4.77	4.81	4.12	5.93	4.94	1.08	-7.24%
211.00	21	5.10	4.63	5.79	4.23	3.35	2.46	6.87	7.32	1.10	-9.20%
All	111	4.53	4.16	4.71	4.29	3.33	3.07	5.46	4.72	1.09	-8.27%
All-217	90	4.80	4.35	4.92	4.35	4.14	3.30	5.84	4.90	1.10	-9.22%

Nearly all of the statistical comparisons met the targets. The geometric mean concentration of the data and simulated concentrations compare very well indicating that the model is reproducing the central tendency of the observed data. The upper and lower quartile concentrations are also similar, indicating that the model is successfully reproducing the range of observed concentrations at the appropriate frequency. The relative percent difference is less than 10% for all locations except the US 40 bridge, which was discussed previously.

4.2.2. Comparison for Validation Events

Further testing of the model's robustness was conducted by applying it for the other two wet weather events, August 20 and October 17, 2007, using the same kinetic rates and updating the flow and load inputs to reflect event conditions. A dry weather period was also included from sampling performed on August 9, 2007 and pre-event sampling that occurred before the September 25, 2007 event. As noted above, the model performance for the other two events, which had significantly different rainfall than the calibration event, were carefully evaluated since the CSOs were also active during these events. The model results for the August 20 and October 17, 2007 events and dry weather periods compare well with observed data. Model results from these simulation periods are presented in this section.

Figures 4.13 through 4.16 show the temporal profile of model concentrations and data at the sampling locations during the August 20 event. Figures 4.17 through 4.20 show the same information for the October 17 event. In general, the model reproduces conditions during the August 20 event (a 0.3 inch storm) more closely than the in-stream conditions observed during the October 17 event (2.22 inches). The October 17 event was characterized by heavy rainfall over a relatively long duration (16 hours). The rain during this storm was not continuous (there was a 5 hour period of no rain midway through the event) and the river results reflect the difficulty in reproducing the collection system volumes under these rainfall conditions in which CSOs discharged for up to 24 hours. In comparison, the August 20 event had very light, scattered rainfall and only three CSOs discharged for short periods of time. The smaller volume and shorter time-frame for discharge allowed for a more precise prediction of the river conditions.

Figure 4.21 is a scatter plot of observed concentrations and corresponding data at each sampling location for all three wet-weather events. As this figure shows, the majority of the model results are within a factor of two of the data. The figure also suggests that the model tends to overpredict concentrations when in-stream concentrations are low (e.g. less than 10 cfu/100 ml). Concentrations measured at these low levels have more analytical uncertainty than higher concentrations. At higher concentrations, the model performance is much better but the tendency is to underpredict concentrations when in-stream concentrations are high (e.g. greater than 1,000 cfu/100 ml). Statistical comparison of all simulated and observed concentrations is shown in Table 4.8. The statistical comparison of the 25th percentile shows that the simulated (model) concentration is lower than the corresponding percentile calculated from the observed data. The reverse occurs with the 75th percentile comparison. However, the model and data values agree within a factor of two of each other, suggesting that the model is predicting concentrations within the range of uncertainty associated with the data. Further, the median concentrations and relative percent differences at each location compare very well.

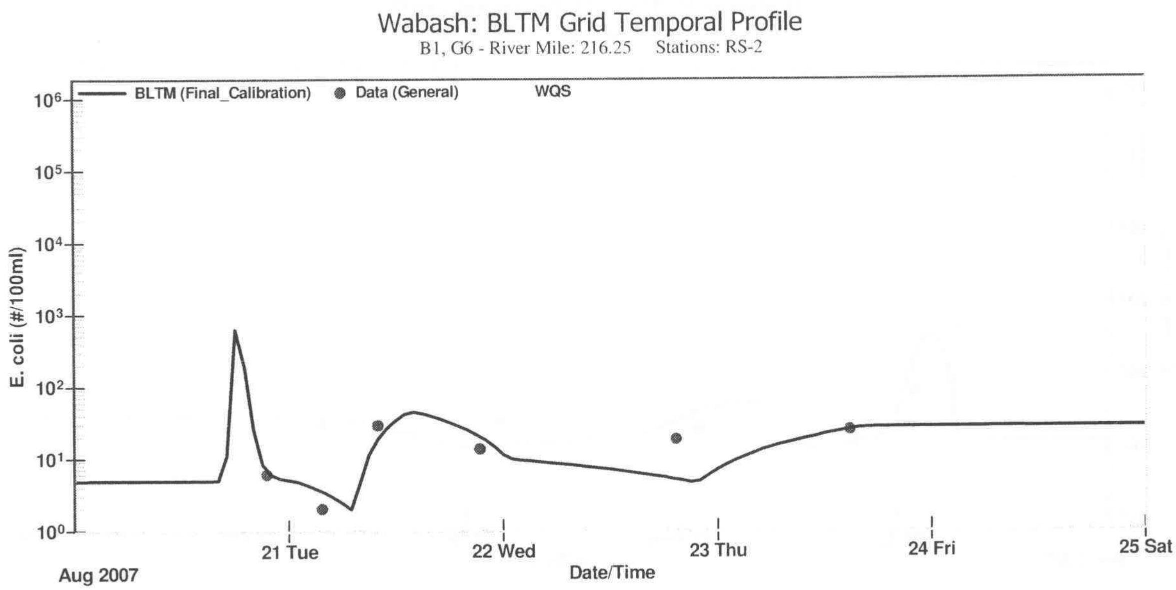

Figure 4-13: Temporal Profile of Observed and Simulated *E. coli* Concentrations at Highway 40 Bridge (RS-2) During the August 20, 2007 Event.

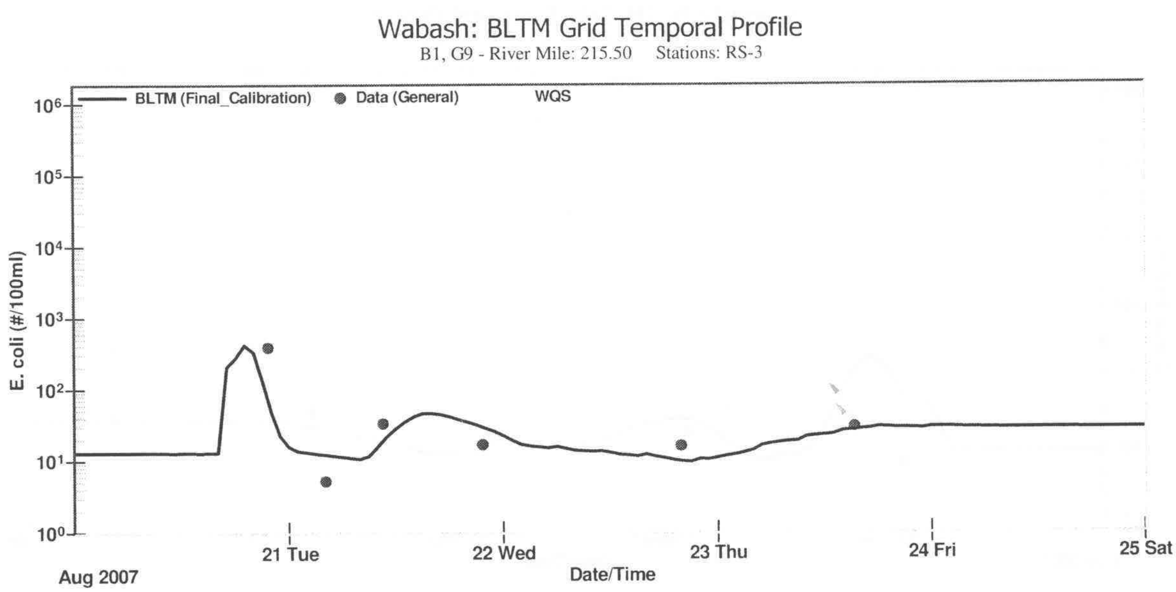

Figure 4-14: Temporal Profile of Observed and Simulated *E. coli* Concentrations Near Fairbanks Park (RS-3) During the August 20, 2007 Event.

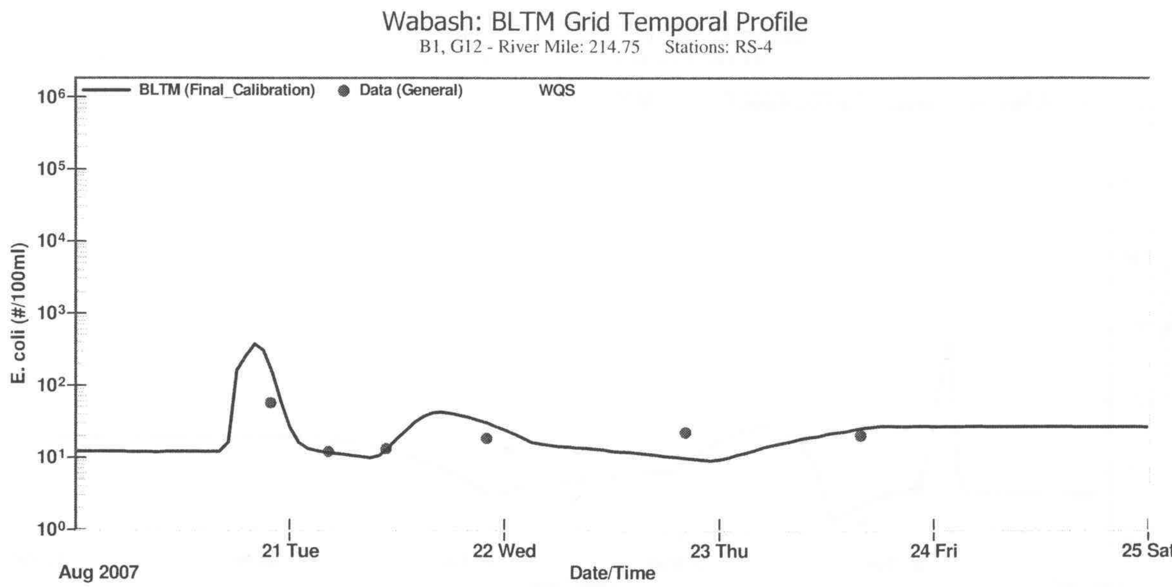

Figure 4-15: Temporal Profile of Observed and Simulated *E. coli* Concentrations ½ Mile Downstream of Hulman St. CSO (RS-4) During the August 20, 2007 Event.

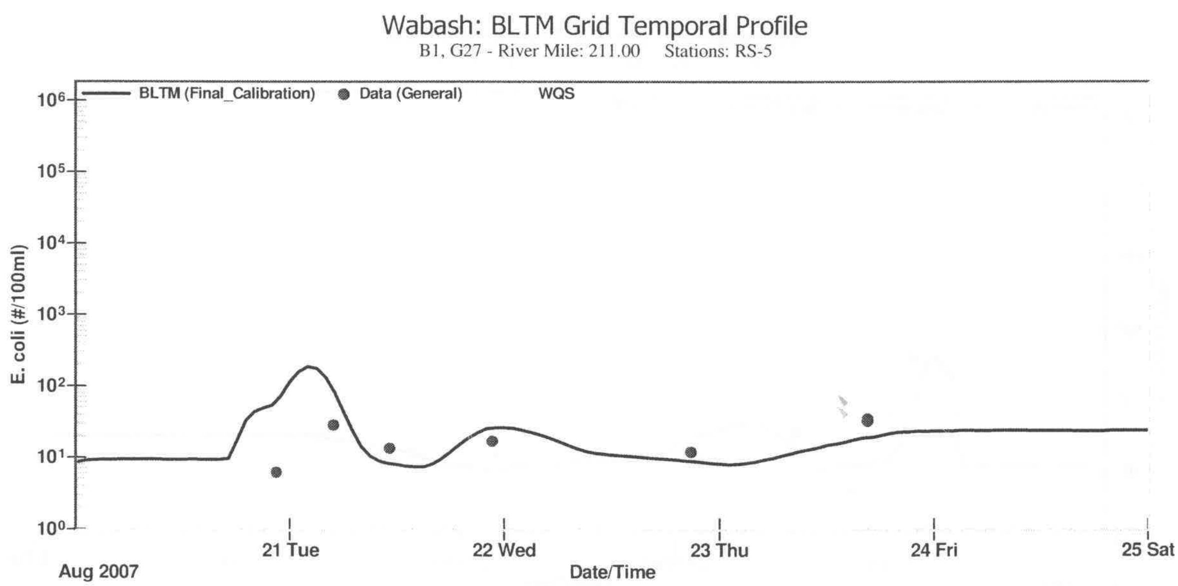

Figure 4-16: Temporal Profile of Observed and Simulated *E. coli* Concentrations Downstream of CSO Outfalls and WWTP (RS-5) During the August 20, 2007 Event.

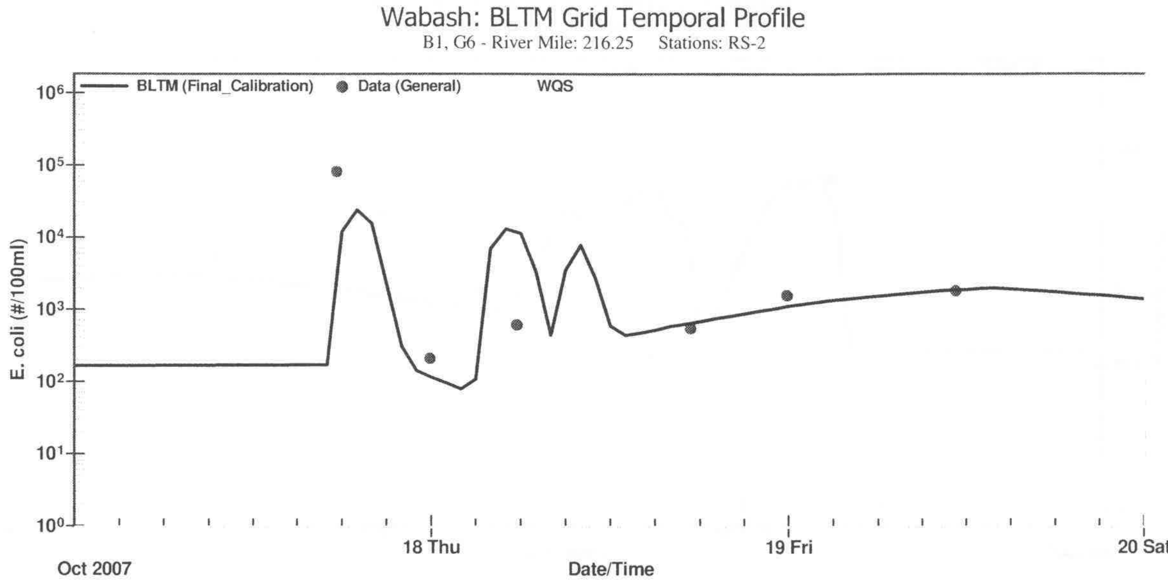

Figure 4-17: Temporal Profile of Observed and Simulated *E. coli* Concentrations at Highway 40 Bridge (RS-2) During the October 17, 2007 Event.

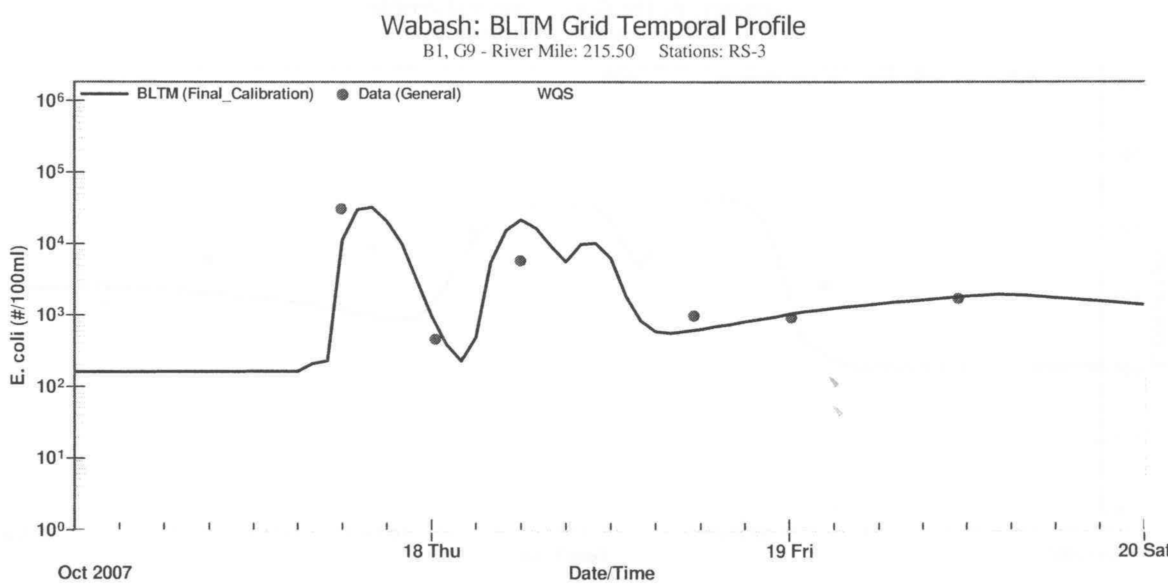

Figure 4-18: Temporal Profile of Observed and Simulated *E. coli* Concentrations Near Fairbanks Park (RS-3) During the October 17, 2007 Event.

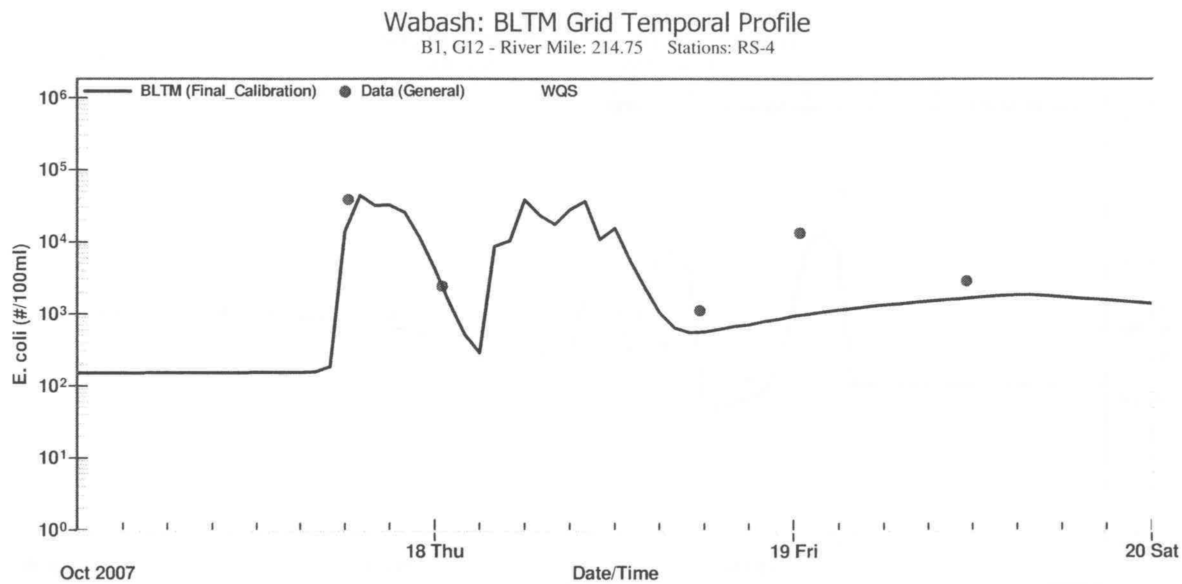

Figure 4-19: Temporal Profile of Observed and Simulated *E. coli* Concentrations ½ Mile Downstream of Hulman St. CSO (RS-4) During the October 17, 2007 Event.

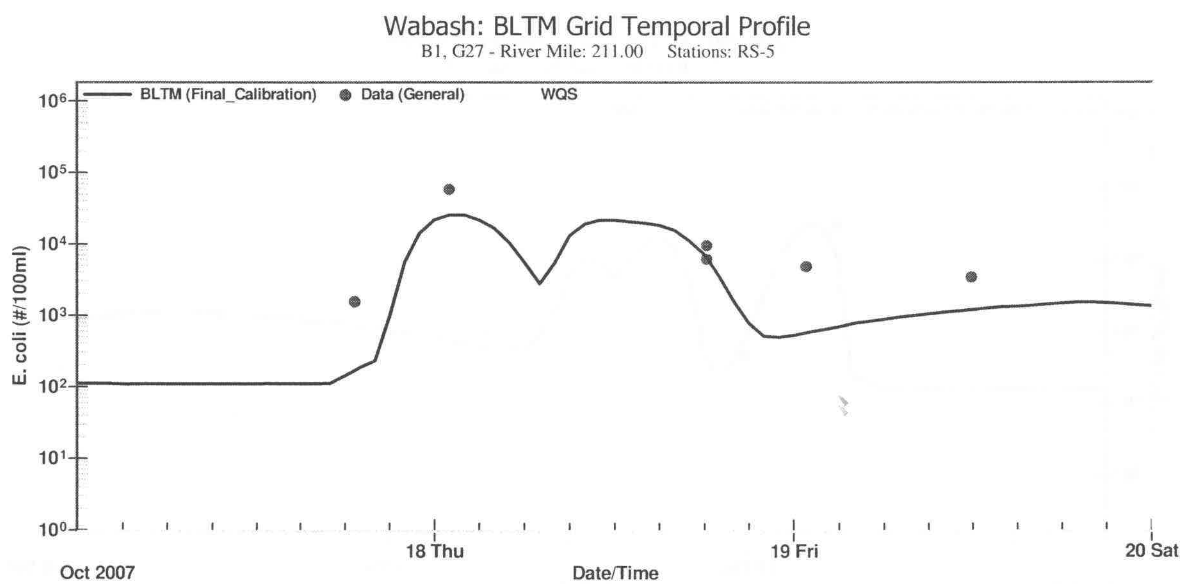

Figure 4-20: Temporal Profile of Observed and Simulated *E. coli* Concentrations Downstream of CSO Outfalls and WWTP (RS-5) During the October 17, 2007 Event.

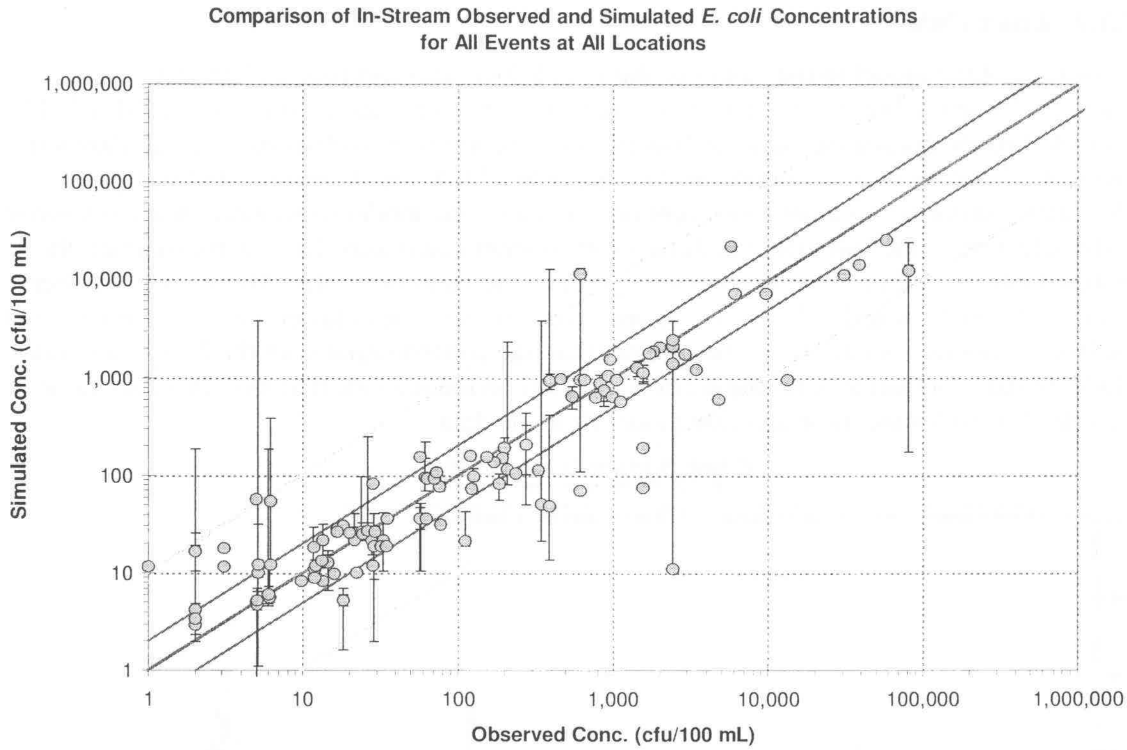

Figure 4-21: Comparison of In-Stream Observed and Simulated *E. coli* Concentrations For All Events at All Locations.

Table 4-8: Statistical Summary of the Model to Data Comparison for All Events.

River Mile	Count	Data Geometric Mean	Model Geometric Mean	Data Median	Model Median	Data 25th Percentile	Model 25th Percentile	Data 75th Percentile	Model 75th Percentile	Data Std. Dev.	Mean Data/ Model Ratio	Relative Error
217.00	69	4.12	4.06	4.04	3.58	2.48	2.55	5.62	5.32	2.03	1.01	-1.34%
216.25	63	4.70	4.30	4.81	3.30	2.91	2.41	6.31	6.45	2.61	1.09	-8.61%
215.50	66	4.96	5.07	4.55	4.61	3.38	3.28	6.83	6.84	2.34	0.98	2.09%
214.75	63	5.15	4.93	5.15	4.90	3.00	3.23	7.35	6.85	2.75	1.04	-4.25%
211.00	66	5.33	4.99	5.07	4.31	2.82	2.93	7.79	7.10	2.78	1.07	-6.43%
All	327	4.85	4.67	4.35	4.30	2.91	2.93	6.83	6.77	2.53	1.04	-3.71%
All-217	258	5.04	4.83	4.92	4.40	3.13	2.93	6.42	6.84	2.62	1.04	-4.23%

4.3 Sensitivity Analyses

4.3.1 Loss Rate

Sensitivity of the model to the values of the *E. coli* loss rate (specified as 1.00 day^{-1}) was evaluated by rerunning the simulations using two other decay rates: 0 day^{-1} and 2.0 day^{-1}. Model simulated concentrations using these loss rates were compared to observed data, as shown in Figure 4.22, for the most downstream station at RM 211.00 for all events. As this figure illustrates, during dry weather (pre-event on August 9), the model concentration is more sensitive to the selection of the loss rate than during wet weather conditions. During dry weather, the standard rate of 1.00 day^{-1} most accurately predicts the measured value. During wet weather, when in-stream flow and velocity are increased and travel time is faster, the concentration with the 0 day^{-1} loss rate is only two times greater than the concentration with the 2 day^{-1} loss rate. Model to data comparisons for the entire validation period indicate that the calibrated value of 1.00 day^{-1} provides the most accurate model fit to the data.

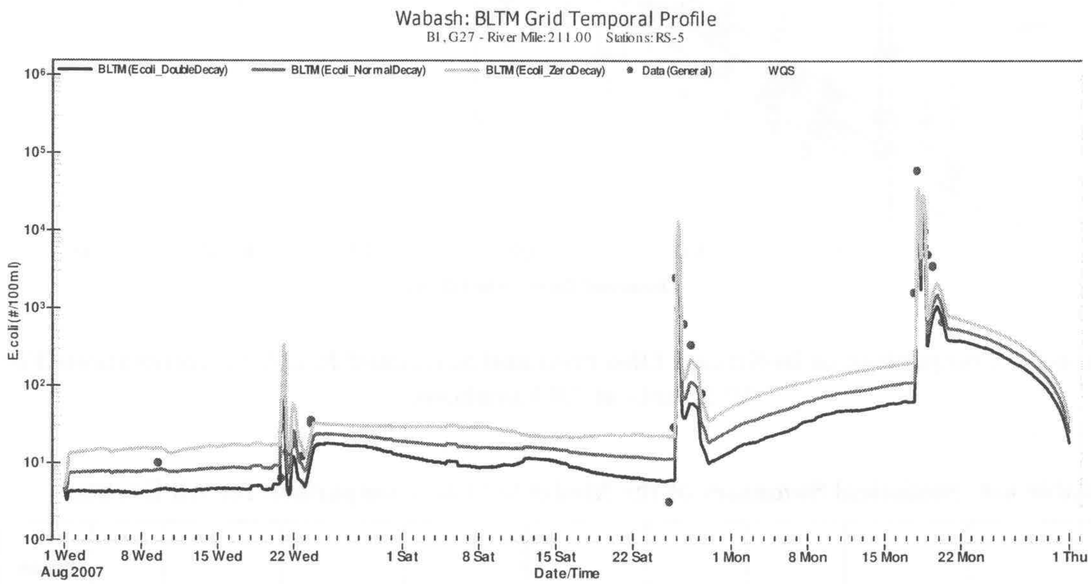

Figure 4-22: Model Simulated Concentrations Using Different *E. coli* Loss Rates For the Most Downstream Station at RM 211.00.

4.3.2 CSO Concentration

Model sensitivity to the values of the *E. coli* EMC in the CSOs was also evaluated to determine the importance of the lower *E. coli* EMC for CSO 009. Detailed statistical analysis of the *E. coli* concentration data in the CSO discharges suggested the EMC of CSO 009 was significantly less than the concentrations from the other sampled CSOs. The model was applied using the distinct EMC measured from CSO 009 (210,000 cfu/100 ml) and an average EMC for the remaining CSOs (675,000 cfu/100 ml). A separate model run was completed using the EMC determined for all CSOs (475,000 cfu/100 ml). The model results for both runs were very similar but the model to data comparisons indicated that a separate EMC for CSO 009 did not improve the model's performance.

5. Conclusions

The calibration and validation of the river model indicates that it is capable of reproducing the timing and magnitude of most of the observed data. The model performs well for a variety of conditions, from dry weather to storms ranging from 0.2 inches up to 2.2 inches. It is suitable for evaluating in-stream impacts from Terre Haute and watershed sources under a range of environmental conditions and control scenarios, and therefore should be sufficient for evaluating different CSO control alternatives.

6. References

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