

Section 6 - Hydrological Modeling and Hydraulics (*Scope of Services 1.d*)

The charge under the Scope of Services was to create a yearly phosphorus, nitrogen and hydrologic water budget. We have used the EPA Storm Water Management Model (SWMM) for our hydrological modeling and to support the development of nutrient budgets. SWMM is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality. The runoff component of SWMM operates on a collection of subcatchment areas that receive precipitation and generate runoff and pollutant loads. The routing portion of SWMM transports this runoff through a system of conduits, pipes, channels, storage/treatment devices, pumps, and regulators. SWMM tracks the quantity and quality of runoff generated within each subcatchment, and the flow rate, depth, and quality of water in conduit during a simulation period comprised of multiple time steps (James et al. 2005).

SWMM accounts for various hydrologic processes that produce runoff, including rainfall, evaporation of standing surface water, rainfall interception from depression storage, infiltration of rainfall into unsaturated soil layers, percolation of infiltrated water into groundwater layers and interflow between groundwater and the drainage system. Spatial variability in all of these processes is achieved by dividing a study area into a collection of smaller, homogeneous subcatchment areas, each containing its own fraction of pervious and impervious sub-areas. Overland flow can be routed between sub-areas, between subcatchments, or between entry points of a drainage system.

In order to both assess the quantity and dynamics of water flow through the Martins Pond watershed, hydrological and hydraulic modeling using SWMM and PCSWMM were used in this study. The objectives in conducting this modeling were threefold:

- (1) get a better understanding of water flow through the different subwatersheds in the Martins Pond watershed
- (2) Develop the model via calibration and validation so that gauge-discharge relationships could be used for future studies
- (3) To assist in the development of nutrient budgeting for the entire Martins Pond watershed

6.1 - SWMM 5.0.009 Modeling Parameters

The Martins Pond watershed was divided up into 29 separate catchments based on the 10 subwatersheds outlined earlier (Section 2.6 and Figure 5). Figure 33 shows the 29 catchments used in the SWMM modeling. A large number of subcatchments were used to better capture the complexity of water and nutrient (N and P) movement through the watershed and to include the detailed transect and conduit data gathered as part of the study.

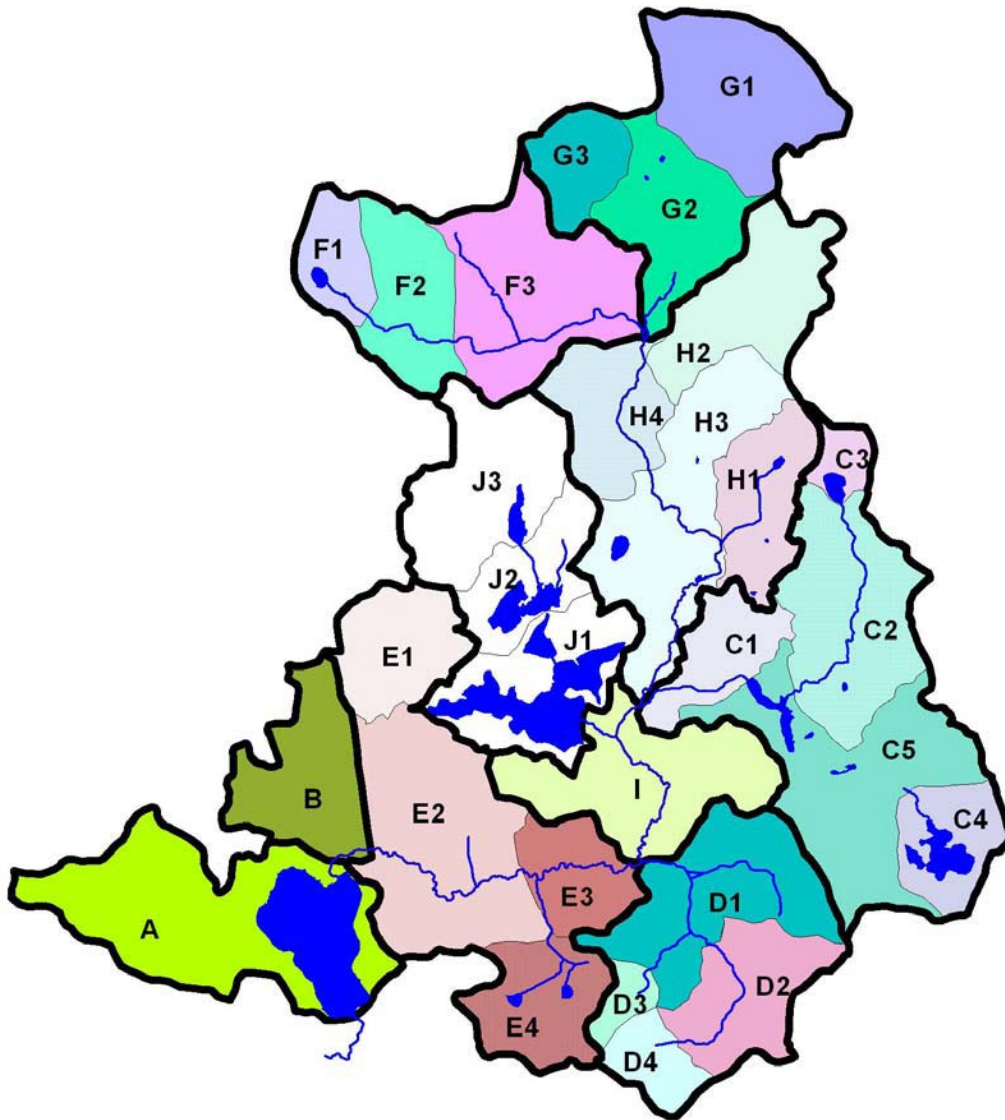


Figure 33. A summary of the 29 catchments used for the SWMM modeling. The ten major watersheds (A-J) were subdivided in some cases to obtain more detail and to more effectively model hydrology and nutrient dynamics in this complex watershed.

Table 28 summarizes some of the SWMM model input for the 29 catchments. Much of this information was calculated utilizing MassGIS datalayers and DEP data using ArcView and ArcGIS.

Table 28. A summary of information for the 29 catchments used in SWMM for this project. The ID column provides the ID codes for each catchment.

Catchment Input Information for SWMM						
ID	Acres	Percent of Total Watershed	Flow Path (m)	Width	Percent Impervious Surface	Percent Slope
A	401.5	8.15	316	5144	24.0	5.7
B	164.7	3.34	251	2658	11.9	6.9
C1	100.7	2.05	232	1755	4.9	4.9
C2	240.7	4.89	477	2044	4.9	11.7
C3	37.1	0.75	113	1325	14.1	8.5
C4	104.7	2.13	193	2193	8.6	8.6
C5	293.6	5.96	465	2558	7.9	7.9
D1	228.2	4.63	850	1084	3.9	5.4
D2	148.8	3.02	980	614	4.2	5.3
D3	31.0	0.63	205	611	3.8	8.1
D4	60.2	1.22	330	738	4.0	8.4
E1	129.7	2.63	186	2826	9.5	11.7
E2	315.6	6.41	427	2988	9.8	6.3
E3	102.0	2.07	316	1306	14.2	2.8
E4	132.9	2.70	200	2692	4.9	6.8
F1	74.2	1.51	135	2218	4.5	4.9
F2	138.3	2.81	198	2829	3.8	6.7
F3	266.8	5.42	449	2406	4.8	8.7
G1	219.3	4.45	1775	500	2.5	10.2
G2	172.7	3.51	377	1853	4.9	8.8
G3	85.0	1.73	149	2314	3.7	13.5
H1	128.7	2.61	750	695	3.0	12.1
H2	176.3	3.58	1085	658	2.5	10.3
H3	279.2	5.67	2150	526	2.6	10.8
H4	137.0	2.78	960	578	3.6	9.7
I	243.7	4.95	418	2359	6.4	6.4
J1	186.2	3.78	891	845	39.9	8.7
J2	115.4	2.34	447	1045	15.3	12.4
J3	210.7	4.28	592	1440	3.9	13.1

6.2 - SWMM Modeling Parameters

Starting in 2005, Merrimack College in collaboration with Larry Soucie, used the Storm Water Management Model (SWMM 5.0.009) with PCSWMM (version 1.092) to model the hydraulics, hydrology and nutrient fluxes through the Martins Pond watershed. PCSWMM provides a group decision support system for the EPA SWMM model (James et al. 2005). The following conditions were used in the SWMM and PCSWMM modeling:

- 29 individual catchments and aquifers within the Martins Pond watershed
- 103 Junction Nodes
- 35 Storage Unit Nodes
- 141 Conduit Links
- 71 Channel and Road-Crossing Transects
- 1 Outfall (Benevento Culvert)
- 1 Rain Gauge - data from a station located within the watershed with rainfall at 0:15 minute intervals (used as the model hyetograph)
- Horton Infiltration Model
- Dynamic Wave Flow Routing with Dampened Inertial Terms
- 15 Minute Time Step

Spatial Data

Subcatchments boundaries and outfall locations were delineated from USGS quad maps aided by contour, topography, hydrography, soil, wetland and land-use GIS data. These data were obtained from a variety of sources including local municipalities, the Massachusetts Geographic Information System (MassGIS) office of the Massachusetts Executive Office of Environmental Affairs, and the Massachusetts Department of Environmental Protection (wetland coverages). Soils data were obtained both from MassGIS (southern Essex County) and the NRCS 1:25,000-scale digital SSURGO (Soils Survey Geographic) data for Middlesex County. MassGIS land use layers were adjusted based on the newer DEP wetland delineations so as to avoid overlap in layer coverages.

Mapping of the surface water conveyance system as well as stream channel transects was used using a composite of all the GIS layers available for the study area. All spatial information was entered into ArcView/ArcGIS as digital data layers. Transect information was gleaned from

topographical data (and verified in the field), available engineering drawings or field measurements. In addition, detailed transect data from the 2004 North Reading FEMA study (FEMA 2004) were also entered into the model. Field verification of all culverts sizes and configurations appearing on GIS data layers (and subsequently SWMM model inputs) was also conducted in 2005.

Time Series Data

Precipitation data were collected using a Davis® Vantage Pro weather station located at 4 Allston Road in North Reading, MA. This location is within 800 feet of Martins Pond and within the Martins Pond watershed. The weather station recorded precipitation at 15 minute intervals. Supplemental rainfall data were used from the Lawrence Municipal Airport Station (94723) during the period of 20 May to 7 June 2005 when the Davis weather station located in North Reading was inoperable.

Flow monitoring assessment for model calibration purposes was conducted by Severn Trent Pipeline Services (Manchester, NH). They installed continuous flow monitoring equipment at the Skug River crossing with Route 28 at the Andover-North Reading town line. This site corresponds to water quality sampling site WW-6. Data were collected at the site from 11 April 2005 to 1 July 2005. The monitoring equipment recorded flow depth, velocity, and flow rate in 15 minute increments over that time period. During the final visit to the site, the Severn Trent field crew took a measurement to correlate the flow meter depth reading to the river staff gauge reading located at the site. Severn Trent reported a flow meter reading of 33.5 inches equaled a river staff gauge reading of 62.25 inches.

Total monthly evaporation factors were derived from Farnsworth et al. (1982) by calculating the mean monthly pan evaporation values based on the measurements at the Worcester and Boston stations. Those monthly evapotranspiration values (in units of in day^{-1}) are presented below:

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
.0482	.0588	.0868	.1407	.1890	.2070	.2124	.1890	.1408	.1071	.0688	.0500

SWMM Runoff Block - In SWMM, the runoff block simulates the hydrographs for each subcatchment, according to a hyetograph of entrance and the physical characteristics of the subcatchment, including area, width, average slope, grade of impermeability, resistance factor for the surface runoff, infiltration parameters and surface storage. The hyetograph for the period of work in the current study is shown in Figure 34.

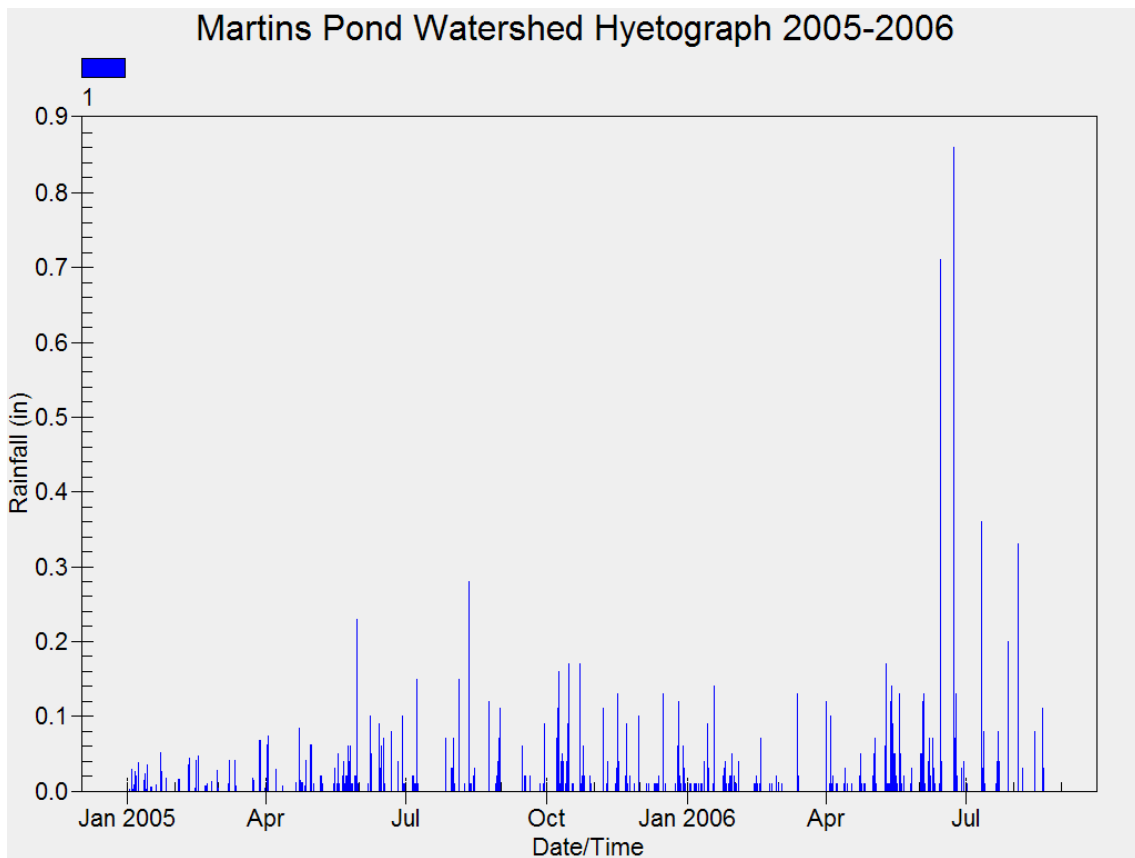


Figure 34. Hyetograph used in the hydrological modeling over the 2005-2006 study period. Rainfall in inches is shown.

Groundwater Flow and Watershed Partitioning

Groundwater flow is a very important parameter in modeling surface water flow in the Martins Pond watershed. To establish a base flow condition, both the Severn Trent results and the gauge-discharge relationships were used to estimate base flow conditions along the Skug River.

Based on this value, the amount of groundwater flow in each of the 29 catchments was calculated by multiplying base flow by the proportion of area made up by each of the 29 subcatchments. These values were then entered into the SWMM input file as flows in a fixed monthly time series.

Because of a beaver dam breach at site WW-1 in Andover in mid-May 2005, the observed hydrograph exhibited a peak on 16 May 2005. Because this was not modeled and involved no precipitation inputs, in the calibration procedure, the observed flow data from 14 May to 20 May were not used to avoid distorting the calibration. This range of dates was chosen because the observed hydrograph showed base flow conditions on those dates, before and after the breach. Despite the beaver dam breaching incident, the model calibration was still successful.

6.3 - Model Calibration

The calibration was conducted by means of an iterative process of trial and error, by adjusting the infiltration, groundwater and aquifer parameters, and comparing (numerically and graphically) the hydrograph obtained in each simulation with the measured hydrograph, until a good fit was obtained. Width of watersheds was also adjusted. Subcatchment width (W) initially was calculated as the average distance between the subcatchment boundaries perpendicular to its drainage channel. During calibration, the widths were calibrated to obtain the best fit between the simulated and observed storm-peak discharge and time of peak.

A ‘hot-start’ simulation was used, which is a process by which some SWMM variables are initialized using previous simulation results. The values of the internal modeling variables represent the final state that the model reached at the end of the simulation period and some of these values are written into the output file. The so-called hot-start takes the available values and initializes the corresponding variable initial values at the start of the next simulation period.

Model Fit

Model fit is a measure of how well the simulated discharge and runoff volumes match the observed values at the Route 28 crossing (Conduit C652 in the SWMM model). Various measures of model fit can be used for calibration including absolute measures of model error, relative measures of fit, and coefficient of determination (r^2). Absolute error is reported as the standard error of estimate (SE) and the RMSE, which were calculated.

The results of the calibration plot between observed and modeled values at the Route 28 crossing (WW-6) is shown in Figure 35. The % difference between observed and simulated at flows > 6 MGD was 8.82% (SE 0.15); the model was not as good at predicting very low flows with a mean difference of 42.4% (SE + 2.0) between observed and modeled values at flows < 6 MGD. Thus, the SWMM model developed may not be as well suited for drought periods.

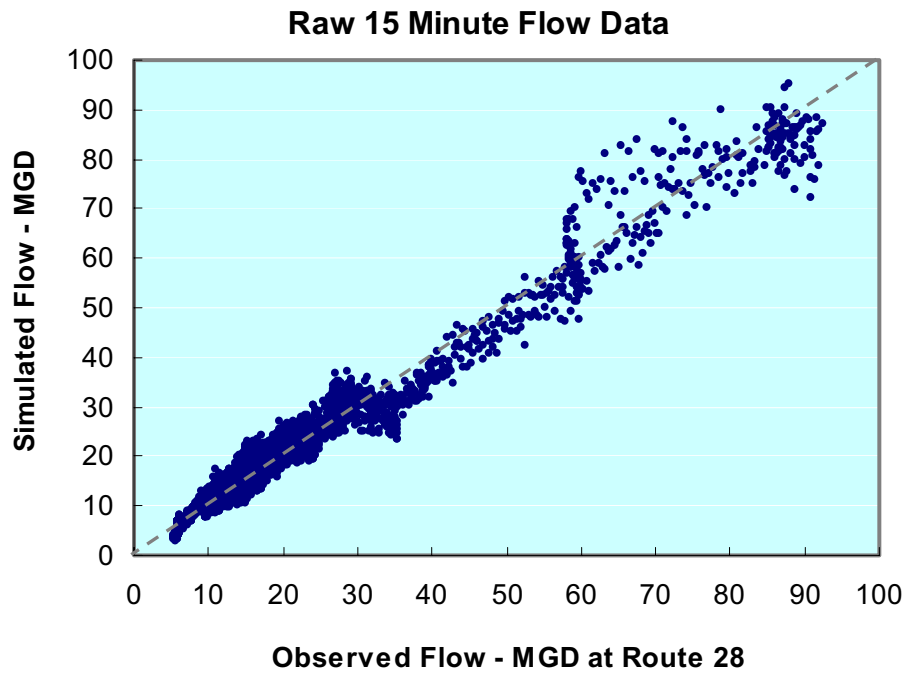


Figure 35. Plot of observed versus simulated flow at the Route 28 – Skug River crossing. A line of equality is also shown (dashed). The results are based on flow from 11 April to 1 July 2005 and plot raw 15 minute data at the observed site (WW-6). Linear regression based on the plot (not shown) was highly significant ($P < .001$) and explained some 96.93% of the variation.

The calibration regression was both highly significant ($P < .001$) and had a coefficient of determination (r^2) of 0.969. The standard error (MGD) was 2.9 and the root mean square error was 11.1%. Very similar results were presented by Zarriello and Ries (200) in their development of a precipitation-runoff mode for the entire Ipswich River Basin.

6.4 - Model Validation

The model was verified using gauge data and hand flow measurements conducted in the field both prior to the calibration period (January through March 2005) and after the calibration period (July 2005 to March 2006). Field flow measurements were made based on detailed cross-section maps and transect data using Marsh-McBirney Flo-Mate Model 2000 portable flow meters. The modeling goal was to make sure that all predicted/calculated model flows were within 10% of all field flow measures. Model validation also involved use of stream gauge and stream gauge-discharge relationships developed during the study period.

Gauge Information

Since 2003, gauges have been set up at three locations within or near the current study area: (1) at the Route 28 crossing of the Skug River in Andover (site WW6); (2) at the Martins Pond outlet at Burroughs Road in North Reading (MP3); and (3) at the Route 62 crossing of Martins Brook in North Reading. The results of gauge height monitoring at these three sites is presented in Figure 36.

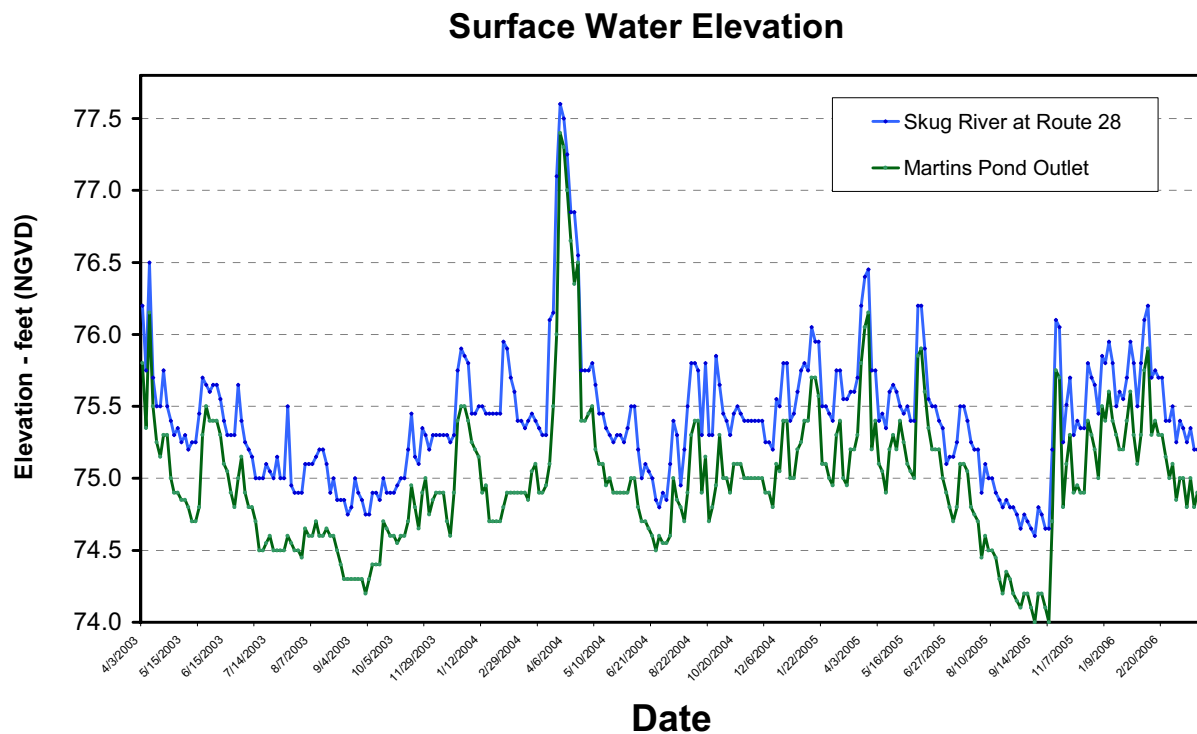


Figure 36. A comparison of gauge height over time at three gauged sites: Skug River at Route 28 and the Martins Pond outlet at Burroughs Road.

Stage – Discharge Relationship for the Skug River at Route 28

A stage-discharge relationship was ascertained from the flow monitoring equipment provided by Severn Trent for the Skug River crossing at Route 28 in North Reading (WW-6). Flow and water elevation data were collected at the site from 11 April 2005 to 1 July 2005. Flows ranged from some 3.6 to 81.4 MGD over that period. The ln-ln plot of gauge height and flow data are presented in Figure 37. Both the flow and gauge data were confirmed by hand-held flow monitoring results and gauge observations on several dates during the entire study period (March 2005-March 2006). Thus, the stage-discharge relationship shown in Figure 37 can be applied to other seasons and flow conditions, including those in summer, fall and winter.

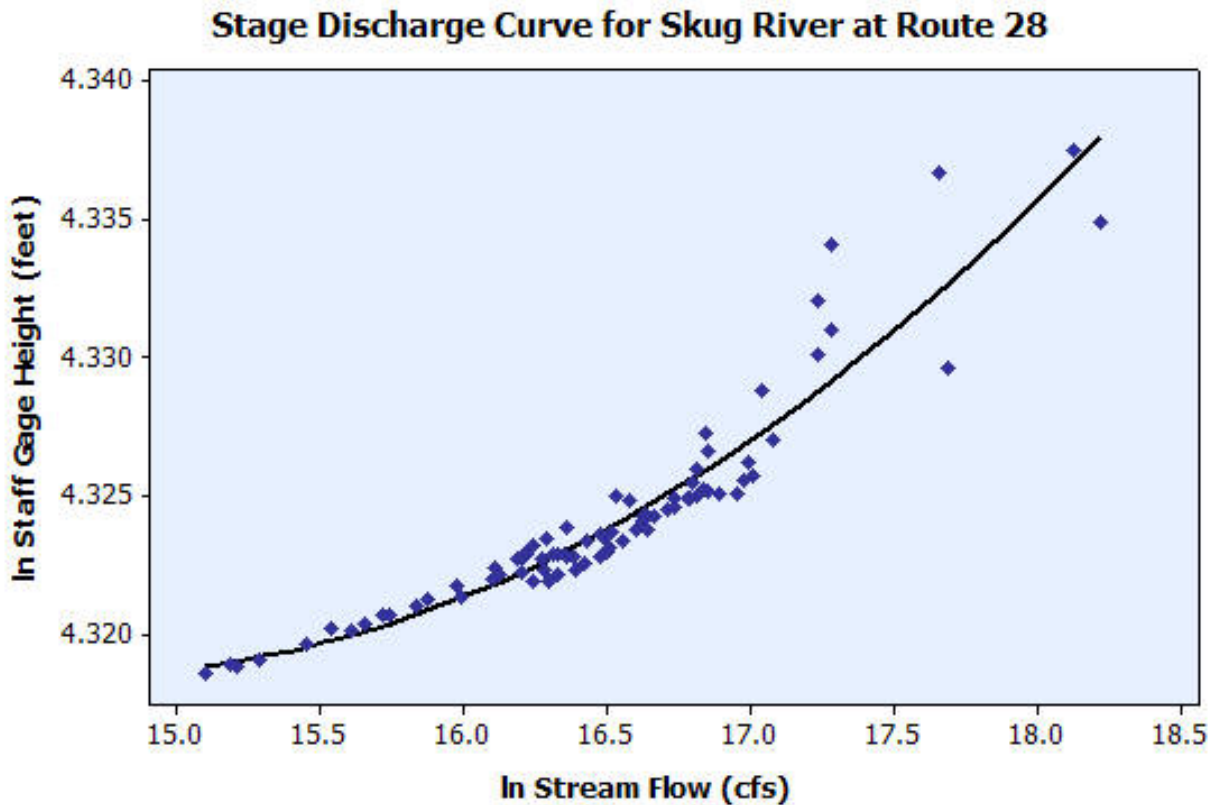


Figure 37. A stage-discharge plot of ln stream flow (cfs) versus ln gauge height for the Skug River at Route 28 in North Reading. Sample points are based on data collected from 4/11/05 to 7/1/2005. Means for each sample day are plotted (a total of 81 days representing 81 points on the Figure). A significant quadratic regression line is shown ($R^2 = 93.0\%$). While the relationship is weaker at extremely high flows (>40 million gallons per day), the relationship shows much lower variability at lower flow levels. The regression equation of the best fit line was:

$$\text{ln Gauge} = 4.645 - 0.04458 \text{ ln Flow} + 0.001523 \text{ ln Flow}^2 - R^2 (\text{adj}) = 93.0\%; P < 0.001$$

Stage – Discharge Relationship for the Skug River at Harold Parker Road

A stage-discharge relationship was ascertained from periodically monitoring flow at this site (WW-3) and correlating it with a gage established by the USGS (USGS site 01101380). Flow monitoring was conducted over the entire study period under different flow conditions to develop a stage-discharge relationship across a wide range of flows.

Field Flow Validation

Table 29 summarizes the results of the field flow measurements compared to the SWMM model predictions. Some 63.4% of all field samples were within 10% of the SWMM prediction.

Table 29. A summary of flow monitoring results conducted over the study period. Field monitoring results are presented with SWMM modeling predictions of flow immediately beneath them. All SWMM modeling predictions within 10% margin of all field determined flow samples are highlighted in yellow. 63.4% of SWMM flow predictions were within 10% of field flows; the remainder were within 15%.

		MP3	WW6	WW5	WW4	WW3	WW1	WW-NA	WW-NB	WW-NC	WW-ND	WW-NE
Time	Date	A	B	E&I	J	H	G	I	H	C	E	D
Flow – cubic feet per second (cfs)												
10:30	3/7/05	11.26	17.25	10.97	1.04	5.68	1.85	0.61	0.32	0.35	0.41	1.07
SWMM Prediction		13.60	16.49	12.47	1.09	5.89	2.17	0.61	0.28	0.39	0.45	1.18
07:30	4/14/05	23.28	28.99	22.35	1.33	9.25	5.19	0.59	0.34	0.36	0.57	1.18
SWMM Prediction		22.40	27.92	20.61	1.53	10.69	5.06	0.63	0.28	0.49	0.57	1.20
18:00	5/10/05	17.02	22.09	15.65	1.34	7.80	ND	0.82	0.32	0.58	0.49	1.25
SWMM Prediction		16.65	20.02	15.20	1.40	7.65	-	0.74	0.28	0.62	0.56	1.21
12:00	6/2/05	29.68	37.93	32.25	2.24	15.99	ND	1.41	0.19	1.35	1.00	1.35
SWMM Prediction		32.54	40.86	28.50	2.50	15.28	-	1.33	0.20	1.31	0.88	1.63
14:30	6/24/05	6.23	9.35	6.59	0.30	3.25	ND	0.25	ND	0.97	1.18	0.56
SWMM Prediction		7.58	9.71	7.08	0.48	3.63	-	0.32	-	1.18	1.21	0.62
15:30	6/28/05	7.13	8.16	6.13	0.41	2.89	ND	0.36	ND	ND	ND	0.57
SWMM Prediction		6.46	8.23	6.01	0.46	3.12	-	0.32	0.15	-	-	0.61
07:30	7/13/05	14.25	15.64	11.88	1.37	5.86	2.54	0.37	ND	0.63	ND	0.66
SWMM Prediction		15.09	17.97	13.69	1.38	6.16	2.16	0.42	-	0.44	-	0.64
15:00	7/26/05	3.98	6.71	4.79	0.27	2.80	1.02	0.19	0.09	ND	0.15	0.38
SWMM Prediction		5.05	6.93	4.67	0.35	2.50	0.98	0.24	0.11	-	0.16	0.48
15:30	8/9/05	4.08	5.25	3.48	0.28	2.13	0.69	0.23	0.06	0.11	0.13	0.51
SWMM Prediction		4.11	5.26	3.80	0.34	1.95	0.69	0.24	0.11	0.13	0.15	0.48
06:30	8/19/05	3.31	5.01	2.97	0.36	1.81	ND	0.23	ND	ND	0.11	0.35
SWMM Prediction		3.91	4.41	3.63	0.34	1.81	-	0.24	-	-	0.15	0.47
15:00	9/14/05	3.11	4.38	3.70	0.36	1.54	NF	NF	NF	ND	NF	NF
SWMM Prediction		3.95	4.47	3.65	0.35	1.76	-	0.26	-	-	-	-
17:30	9/28/05	3.15	4.38	2.98	0.45	1.53	NF	NF	NF	ND	NF	NF
SWMM Prediction		3.97	4.50	3.66	0.36	1.75	-	0.27	-	-	-	-
14:30	10/18/05	ND	ND	ND	ND	26.50	ND	1.71	ND	ND	ND	ND
SWMM Prediction		61.77	95.18	51.25	5.07	27.24	-	1.66	-	-	-	-
11:30	11/4/05	15.36	18.5	12.79	4.35	6.89	ND	0.42	0.09	0.25	0.32	0.56
SWMM Prediction		15.05	19.10	13.93	1.07	7.58	-	0.36	0.17	0.27	0.31	0.75
12:00	12/22/06	16.21	19.65	12.86	1.02	5.26	ND	0.42	0.12	ND	ND	ND
SWMM Prediction		14.82	19.42	13.44	1.18	6.30	-	0.35	0.14	-	-	-
13:30	2/8/06	17.35	19.83	13.53	1.33	7.52	ND	ND	ND	ND	ND	ND
SWMM Prediction		16.67	22.04	15.10	1.40	7.80	-	-	-	-	-	-
12:30	3/21/06	9.25	12.00	9.67	0.74	4.29	1.44	0.62	ND	0.29	0.62	1.17
SWMM Prediction		10.61	12.45	9.71	0.95	4.58	1.51	0.60	-	0.35	0.41	1.18
13:30	5/15/06	ND	ND	ND	ND	ND	52.31	21.23	ND	ND	11.06	13.85
SWMM Prediction		336.46	339.89	310.02	24.37	137.69	48.86	19.21	-	-	10.81	14.39
07:30	6/12/06	41.66	63.25	34.18	3.74	22.30	8.03	1.22	0.22	0.85	1.33	1.37
SWMM Prediction		42.15	59.85	37.97	3.78	20.57	8.47	1.25	0.15	0.96	1.20	1.40
14:30	7/18/06	12.25	19.65	12.60	1.00	5.66	3.35	0.29	0.13	ND	ND	ND
SWMM Prediction		13.96	18.00	12.72	1.05	5.87	2.35	0.31	0.11	-	-	-

NF = minimal or no flow; ND = no flow data collected

The waters reaching Martins Pond are influenced by rainfall, evapotranspiration, surface run-off, wetland storage-discharge characteristics, conveyance systems, groundwater infiltration of rainfall and municipal wells. Based on the SWMM results, the fate of precipitation during the study was determined to be as follows:

Precipitation Total (3/1/05 to 2/28/06)	43.78 inches	100%
Evapotranspiration	16.77 inches	38.33%
Surface Runoff	1.65 inches	3.77%
Groundwater Inflow	25.36 inches	57.90%

Over the course of the study period (March 2005 – February 2006) the mean inflow into Martins Pond was some 15.2 MGD while the mean outflow was 16.7 MGD. Given that the volume of Martins Pond is calculated to be some 168 million gallons, that corresponds to a mean hydraulic residence time of 10.1 days or the pond is flushed some 36 times per year.