Barton Creek Watershed Model Study

City of Austin
Watershed Protection and Development Review Department
Environmental Resources Management Division

October1997

BARTON CREEK WATERSHED MODEL STUDY

Prepared by
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Watershed Protection and Development Review Department
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Prepared For
The Austin City Council, Environmental Board, and Austin Community

Acknowledgements

This report was prepared in the Environmental Resources Management Division of the City of Austin's Watershed Protection and Development Review Department under the general supervision of Joe Pantalion, Department Director, and Nancy L. McClintock, Division Manager

The project team appreciates the assistance in technical support given to them by a number of other City employees. The authors also thank the many agencies, organizations and individuals who have provided valuable input into the development of the Barton Creek Watershed Model Study. Contributors and agencies include:

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Texas Natural Resources Information Systems
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United Stated Geological Survey

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BARTON CREEK WATERSHED MODEL REPORT

EXECUTIVE SUMMARY

Several modeling tools have been proposed for investigating the effects of land use changes on water quality, and this report describes the efforts towards application of a predictive model for water quantity and quality in Barton Creek. The general purpose of the modeling effort was to develop a tool capable of explicit representation of the physical processes governing water quantity and quality in the Barton Creek watershed. The focus of this modeling effort was the application of the industry standard public domain Stormwater Management Model (SWMM) to the Barton Creek watershed. Due to SWMM ground water routine limitations, only the portion of the watershed above the Recharge Zone was simulated.

Ideally, the results from the surface water quality model were to be used as simulation input to the ground water model in order to predict the impact to Barton Springs discharge water quality under a variety of land use scenarios. Due to the complexity of the system modeled and the limitations of the available model formulations, water quality was not predicted well although a statistical formulation allowed simulation of historical conditions. However, water quantity may be simulated well enough by SWMM to provide a basis for input scenarios to the ground water model using land use based mean concentrations from the City of Austin Storm Water Monitoring Program (COA, 1986 and 1996d). This use of the model is under investigation in association with the Drainage Utility City-Wide Masterplan

Data Analysis Supporting Surface Water Quality Modeling Efforts

One of the major contributions of the Surface Water Model Study was the analysis of data from both the USGS stations located in the watershed and that provided by the City of Austin Storm Water Monitoring Program (Plate 6). A significant amount of information was provided on hydrology and water quality in Barton Creek from the summary of these data.

In the analysis of USGS discharge gaging station data, flows in Barton Creek were separated into baseflow volumes and direct runoff volumes. Above the Recharge Zone, more than three-quarters of the flow volume is baseflow (Loomis, 1995). This fraction decreases over the Recharge Zone as flows contribute to aquifer recharge. On the basis of baseflow volume differences between the Lost Creek and Loop 360 gaging stations, it is estimated that for Lost Creek flows of less than 20 to 30 cfs, all of the flow is lost to recharge. The recharge rate remains constant at about 30 cfs for channel discharges ranging from 30 to 130 cfs. For channel flows at Lost Creek in excess of 130 cfs, the recharge rate is about 23 percent of the Lost Creek discharge. All of these estimates include only the recharge occurring between these two stations.

Stormwater quality from individual rainfall events is quite variable from storm to storm, through time for a given event, from one constituent to another, and from one site to another. The USGS/City of Austin joint monitoring program provides data for evaluating water quality along the mainstem of Barton Creek. In general, water quality is good. Available water quality data for three stations along Barton Creek were analyzed and are presented in summary form in Table ES-1. Mean values for most of the constituents are higher during storm flow conditions than for baseflow conditions. Total suspended solids (TSS), which is the most widely considered indicator of stormwater quality, has an average concentration which is an order of magnitude larger under storm flow conditions when compared with baseflow conditions. Both the storm flow mean TSS concentration and its variability increase for downstream stations along the Creek. The storm flow mean TSS concentration at Loop 360 is more than double that at Highway 71 and

Lost Creek stations, possibly reflecting the impacts of land use changes in the lower portions of the watershed.

Stormflow and baseflow data from the USGS stations was evaluated prior to use in model calibrations. Of the water quality constituents which are correlated with discharge rate in stormflow data, all except total lead (TPb) have average concentrations which are greater at Loop 360 than at the other monitoring stations. One explanation of these increases is the greater amount of impervious cover at the lower end of the Barton Creek watershed. In addition, BOD5, TOC, FCOL, FSTR, and total nitrogen have average concentrations which are one to two orders of magnitude larger during direct runoff conditions. Further, the mean TOC concentration at Loop 360 more than doubles that at Highway 71 and Lost Creek under storm flow conditions. The average TDS concentration is larger for baseflow than for storm flow conditions at all three stations, with greatest concentrations at the Lost Creek station. Correlation analysis shows that TSS, BOD5, TOC, TKN, FCOL, FSTR, TP and TPB all increase with runoff, while only NO2+NO3 is inversely related to flowrate in storm flow conditions. The other water quality parameters are insignificantly correlated to the runoff magnitude. In baseflow data, only NO2+NO3 - N was correlated inversely to flowrate. Details of the data analyses used in support of the surface water model effort are presented in a separate document (City of Austin, 1997).

Table ES-1
Barton Creek Water Quality Summary

Constituent	Baseflow Conditions						Storm Flow Conditions					
	Hwy 71		Lost Creek		Loop 360		Hwy 71		Lost Creek		Loop 360	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Flow (cfs)	53	132	101	194	89	90	1735	2805	1735	2790	2410	3322
TSS	3	4	4	3	5	5	203	309	225	321	563	637
TDS	254	26	409	266	253	30	216	63	307	142	189	62
BOD5	0.43	0.28	0.48	0.34	0.45	0.34	2.76	3.37	3.23	4.02	3.76	3.10
TOC	2.16	1.71	1.85	0.34	2.18	1.54	10.01	11.35	10.88	11.40	21.18	27.70
FCOL(x1000)	0.09	0.29	0.07	0.08	0.03	0.03	9.18	14.76	7.67	8.77	20.53	21.42
FSTR(x1000)	0.63	1.41	0.15	0.20	0.10	0.15	21.85	32.42	17.63	22.23	27.76	26.59
TP	0.02	0.03	0.04	0.10	0.01	0.00	0.07	0.08	0.09	0.13	0.15	0.18
NO2+NO3	0.08	0.06	0.15	0.12	0.15	0.13	0.19	0.22	0.22	0.16	0.32	0.23
NH3	0.02	0.02	0.02	0.02	0.02	0.02	0.04	0.05	0.05	0.04	0.06	0.08
TKN	0.25	0.17	0.24	0.08	0.26	0.14	0.60	0.59	0.54	0.49	1.43	1.72
Dis. CU (ug/L)							0.86	0.69	1.00	0.00	2.35	3.43
Dis. FE (ug/L)	6.71	8.62	4.64	2.42	5.50	9.34	19.58	20.82	12.33	9.63	23.33	25.23
Dis. PB (ug/L)							2.17	1.60	1.00	0.00	2.12	2.43
Dis. ZN (ug/L)	3.71	1.42	5.64	7.47	3.69	1.93	9.45	15.35	12.11	17.47	9.32	11.21
Tot. PB (ug/L)	3.74	10.27	1.23	0.83	1.14	0.38	11.15	24.65	5.58	6.22	6.88	7.14

All units mg/L except as noted

SWMM Model Application

The U. S. Environmental Protection Agency's Stormwater Management Model (SWMM) was identified as having the greatest flexibility and potential for application as a stormwater quantity and quality simulation tool for the large and complex Barton Creek watershed. In the application of the SWMM model to the Barton Creek watershed, only four of the simulation model blocks are utilized: the runoff, transport, statistics, and rain blocks. The Green and Ampt infiltration model is used, though it is found that the overall performance of the model is not very sensitive to this choice. The subsurface flow system is modeled as a linear reservoir, with flow rate from the saturated ground water zone to the stream channel being based on the head difference between the aquifer and channel bottom.

The Hydrolog Software package which was developed as part of this project is a system for hydrologic and stormwater quality analyses. This package simplifies the many analyses which are required to calibrate watershed models such as SWMM, and provides a set of tools for analysis of stormwater runoff data.

Extensive rainfall and streamflow data are available through the City of Austin and the USGS monitoring programs. These data cover single land use watersheds and the Barton Creek watershed at three stations. Because rainfall is not uniform over large areas, there is always uncertainty as to how the recorded rainfall reflects watershed average values. Correlation analysis suggests that available records are adequate for most conditions, even over the upper reaches of the Barton Creek watershed for most of the year. Summer months may not calibrate as well due to typically localized rainfall patterns. This limits the available time periods for long term validation using SWMM or any other watershed simulation. Rainfall distribution and quality of rainfall data from FEWS stations remains a major calibration problem with large scale watershed modeling of Barton Creek.

Variables and parameters used for modeling flow in the Barton Creek watershed are primarily physically based. Most parameters are estimated before the calibration process begins through physical equations and measured parameters. In some respects, this simplifies calibration because there are fewer model parameters to adjust in order to obtain a better fit to the observed data. The only parameters which were modified for the Barton Creek calibrations were the effective watershed width and the baseflow intensity parameter. In addition, these were modified for all watersheds uniformly, so that their values were not changed for each subcatchment independently. The single land use watersheds do not have a subsurface flow component, so many of the flow parameters in the single land use watershed model are not used. Fewer subcatchments and parameters to consider are also present in the single land use watershed model, and the effective watershed width remains a sensitive variable.

Applications show that the SWMM model can be adequately calibrated for representation of the hydrology of a single land use site and for the Barton Creek watershed (above the Recharge Zone). Both single event and long-term periods can be simulated. The existing SWMM formulation is not able to simulate water loss from the Creek over the Recharge Zone, so the model cannot be used to simulate flow quantity at the Loop 360 station.

The task of simulating stormwater quality has proven to be more difficult than that of simulating stormwater quantity. The buildup model used in SWMM does not lead to results which are consistent with observed data. In addition, no other public domain model has been identified which could adequately replace those available within SWMM. This means that the model, if applied to a single land use watershed, or any more complex watershed, will not be able to represent the available constituent load (buildup) at the beginning of a runoff event. Thus the washoff load and concentrations will also remain uncertain. However, if the buildup could be predicted, the washoff model based on total storm runoff appears to adequately represent the monitoring data.

For large storm events, much of the sediment load in Barton Creek was determined to be derived from erosion of the channel, rather than from watershed surface stormwater runoff. The potential load from erosion increases for locations further down the watershed.

The overall conclusion from the investigation of the single land use data is that there does not exist a model which is able to adequately predict the accumulated stormwater load on a watershed at the beginning of a runoff event, nor the initial constituent concentration. The model does do a better job of representing the washoff processes. Thus, SWMM may be a useful model for simulating single storm events, but our understanding of the various processes which control the quality of urban runoff does not allow us to model a continuous series of events with SWMM or any other available model. Also, the difficulty in calibration may have resulted from application of an urban runoff model in a low impervious cover watershed which is still operating within its natural buffering capacity.

Adequate calibration of the water quality model could not be achieved and may have been confounded by unstable response of the watershed to pollutant loads due to its low impervious cover.

Given the simplification in channel hydraulics necessary to model the mainstem of Barton Creek, no direct correlation can be made between model prediction and the data obtained for perennial mainstem pools or small spring-fed canyons (Sections 3.2 and 3.3). In addition, spatial scales of evaluation are much different between the localized pools/canyons studies and the whole-watershed SWMM model. In addition, the intermittent frequency of data obtained from both canyon and pool studies is not compatible with the intensive, consecutive, runoff quality data required to calibrate the SWMM model. However, comparison of the pool and canyon data with simulations may be possible with a revised sampling program which includes automated canyon sampling stations.

Statistical Model Application

Statistical regression analysis provides empirical models for prediction of water quality in Barton Creek as a function of location, season, time period (construction), existing flow conditions, and antecedent flow conditions. Compared to the baseflow model, the models for storm flow conditions have greater predictive power.

Application of the statistical regression water quality model with a measured or simulated discharge hydrograph will provide useful estimates for Barton Creek water quality at the three monitoring stations, but it is difficult to extrapolate the model form to address questions associated with impacts of land use changes on water quality. For the most part, baseflow water quality concentrations were not found to be impacted by construction activities in the Austin area during the period of 1983 - 1986. On the other hand, during storm flow conditions, the water quality concentrations in Austin area creeks showed an increase during this period of active construction. In particular, the average TSS concentration increased by 550 mg/L.

A substantial amount of variability remains in the storm and baseflow water quality data after statistically accounting for flow rate, site, season changes, and prior flow rates. Additional research might provide further insight into the source of this variability.

CONCLUSIONS

The following conclusions are provided in summary of the Surface Water Modeling project:

- From literature review and recent applications, SWMM and HSPF are the most generally applicable detailed public domain models for simulation of stormwater quantity and quality for single and multiple events.
- Application of SWMM to single land use watersheds was successful for estimation of both quantity and stormwater quality loads for single event simulations.
- Single land use water quality data appears to follow the theoretical washoff process (used by most NPS water quality models) for certain constituents including TSS. However, prediction of initial concentrations through a constituent buildup process is not supported by the empirical data. Further, for certain constituents, their concentrations are generally greater on the rising limb of the hydrograph

than on the falling limb, and a functional relationship between flow and concentration is not applicable. It is thus concluded that simulation of multiple events on single land use watersheds cannot be performed.

- Deterministic models such as the buildup/washoff relationships lack the capability of predicting multiple-event (consecutive) pollutographs in the single land use data set developed by the COA Storm Water Monitoring Program.
- Prediction of total annual loads using buildup and washoff with calibration may be possible. However, equivalent methods are available for planning levels of analysis which are less labor intensive than application of SWMM modeling. The planning level loading model will allow prediction of cumulative loads from developed areas as a function of land use and impervious cover changes.
- The COA/USGS stormwater monitoring program is one of the most intensive in the country in terms of the number of locations monitored and samples taken. For events on single land use watersheds, there are a large number of events with sufficient data to adequately characterize the pollutograph for calibration purposes. However, despite the extensive database contributed to this study, the stormwater monitoring program on Barton Creek has provided only a small number of storms with sufficient data for characterization of the consecutive pollutographs for model calibration purposes.
- The SWMM model was developed with sufficient flexibility to represent many important features in the hydrologic cycle. However, channel losses such as occur over the Recharge Zone of the Edwards aquifer are not represented in a realistic fashion.
- For the Barton Creek watershed above the Recharge Zone, the SWMM model was adequately calibrated to simulate observed creek flows over periods of short duration and partially calibrated to general simulations over periods of long duration. Significant anomalies exist in the flow gage data to make long duration calibrations problematic.
- Stormwater quality is often evaluated through measured TSS concentrations. Given the single land use monitoring data, one can estimate the watershed derived load from each subcatchment of the Barton Creek watershed, and thus estimate the expected load at the monitoring stations along the Creek. However, the observed TSS loads greatly exceed the estimated loads because of channel derived TSS.
- While there are few records with sufficient data to characterize the stormwater quality pollutograph for Barton Creek for SWMM calibration, there are sufficient data to apply statistical regression techniques to develop a statistical model for simulating historical stormwater quality. Therefore, a statistical model was developed with some limited predictive capabilities for stormwater quality in Barton Creek under existing land use conditions.
- Pollutographs from single land use stormwater quality monitoring were analyzed in terms of buildup and washoff models. Washoff data were used to develop predictive models for the washoff pollutograph for certain constituents including TSS. This model met with limited success when compared with empirical data because the initial concentrations remained uncertain.
- From the data provided by the COA stormwater quality monitoring program, stormwater pollutant loads are more sensitive to changes in stormwater quantity than concentration. Thus, land use changes that increase stormwater quantity (runoff) are especially significant in increasing constituent loads.
- Given the uncertainty in prediction of existing stormwater quality for the Barton Creek watershed, and the uncertainty on how the predictive parameters which control water quality vary with land use changes, it does not appear that detailed stormwater quality models can be used to accurately predict the affects of development on water quality in Barton Creek. For this reason, future efforts using more simplified methods are concluded to provide the best focus for Drainage Utility efforts.

RECOMMENDATIONS

The following recommendations are provided in summary from the Barton Creek Surface Water Model Study in the areas of model applications, regulatory and development review, data collection, and further research:

Model Applications

Using the developed model framework, the Barton Creek SWMM Model can accurately predict flow quantities above the Recharge Zone. Therefore, the calibrated model can be used to develop flow inputs to the Barton Springs/Edwards Aquifer ground water model developed under a contract between the City of Austin and The University of Texas Center for Research in Water Resources. The calibrated SWMM model can be used to predict changes in baseflow and direct runoff quantities in Barton Creek resulting from changes in impervious cover for various development and regulatory scenarios. This will allow the prediction of the effects of urban development on water levels in the aquifer and discharge rates at Barton Springs.

Analysis of water quality data during the course of the study demonstrated the relative importance of channel derived load. Much of the concern about the viability of the Barton Springs salamander is centered on the effects of increased suspended solids loads in the Creek and Springs. Approximately 50 percent of the suspended solids load in the lower segments of the Creek is estimated to originate from bank erosion. The Barton Creek Model could be used to predict the changes in flow rates which will accompany increased urban development in the watershed. The model can, with some modifications, be used to assess the effects of various BMP's on flow rates during runoff events.

Through this modeling effort the city staff has developed a familiarity with the operation, capabilities and limitations of SWMM. Because all of the available models have unique limitations and capabilities, it is recommended that the City support the use of SWMM in the Barton Creek watershed due to its familiarity and flexibility. The recommended uses of SWMM include the evaluation of various BMP's using the storage/treatment block in addition to the four blocks used in this study. The storage/treatment block simulates the effect upon flow quantity and quality of capture and residence processes occurring in structural water quality or quantity control devices. SWMM should also be used to provide guidance in site selection and planning for single land use flow monitoring.

Regulatory and Development Review

City of Austin flood control regulations should be reviewed in light of the importance of Barton Creek channel scour to pollutant load documented in this study. Current regulations, which are based on limiting the peak discharge from a site to predevelopment conditions, may have unintended consequences on flow rates in creeks downstream of discharge points. Depending on the relative position of the site and other factors, stormwater detention facilities constructed to City standards may increase storm flow rates in the main creek channel downstream of the site compared to developed conditions with no controls in place. The Barton Creek Model should be used to evaluate the effectiveness of current regulations and predict the impacts of proposed changes to these rules.

Infiltration practices should be promoted as an effective water quality BMP based on the following conclusions:

- Analysis of data from single land use watersheds indicate that the amount of impervious cover has a greater impact on stormwater loads than land use classification.
- Peak flows and sustained velocities have a dominant impact on water quality due to channel scour and bank erosion.
- The recreational uses of Barton Creek are dependent on the maintenance of a healthy baseflow.

- Promoting baseflow in Barton Creek will help maintain the quality of water recharged to the Barton Springs portion of the Edwards aquifer.
- Therefore, promoting infiltration practices through the City's water quality control standards is recommended to reduce runoff entering the channel, decrease channel scour and water quality impacts, and assure that baseflow quantity will not be reduced.

Data Collection

It is recommended that the City address the potential problems associated with channel derived suspended solids by developing a monitoring program to document current rates of bank erosion and channel scouring. Additional empirical data including critical stream velocity which produces erosion will be necessary for the design of stormwater controls system.

The accuracy of the Barton Creek Model is limited by a lack of accurate knowledge of rainfall distribution and evaporation rates. Continuously recording rain gages should be installed upstream of Highway 71 near the border of the City's ETJ to better document rainfall rates and volumes. It is recommended that the City install a pan evaporation monitoring site to provide a backup source of data to the National Weather Service which has proved to be inconsistent in the past.

A continuous flow gage should be installed just upstream of Barton Springs Pool. This gage can be designed to enable greater accuracy in measurement of recharge volumes including ground water discharge from the Edwards aquifer to Barton Creek during periods of high water levels in the aquifer. In addition, the gage can provide a station for water quality measurements downstream of all development. Data from this site will be needed for model calibration if SWMM is modified to include channel losses and ground water recharge as suggested in the recommendations for "Additional Research."

To better understand the processes controlling water quality in Barton Creek, the frequency of sampling should be increased during storm events. In addition, the duration of sampling should be sufficient to define the transition from direct runoff to baseflow water quality. An automated station similar to that used in the City of Austin Storm Water Monitoring Program should be maintained in Barton Creek to obtain this high resolution data at the least cost to the City. Additionally, the Flood Early Warning gages in the watershed with depth monitoring capabilities should be converted to flow rate monitoring by developing accurate rating curves. This will allow the transition to baseflow to be characterized in greater detail.

The monitoring of rainfall water quality as currently performed by the City of Austin should be expanded to document the possible differences between urban and rural rainfall quality. This monitoring will help establish a relationship between rainfall and runoff water quality.

Additional Research

A study should be initiated to evaluate channel stability and sediment transport in Barton Creek. The study should be supported by the ongoing City-wide Master Plan because it will complement the planned needs assessment for erosion control scheduled for Non-Urban watersheds within the next several years.

Beginning with SWMM version 4.26, the model has been modified to simulate channel losses. The newer versions should be investigated with the additional data provided by the recommended monitoring gage above Barton springs to evaluate channel losses over the Recharge Zone.

The SWMM model should be modified to incorporate the predictive model for the stormwater washoff pollutograph with variable RCOEF and combined with a stochastic generator for selection of initial concentrations to provide a tool for generating realistic multiple event stormwater loads for design and evaluation of BMP's. Such a representation would still be adequate for simulation of yearly loads, and could provide a more realistic representation for the input loads to BMP's.

A statistical cluster analysis should be performed using all 48 water quality constituents which are currently measured. This analysis will lead to a grouping of constituents which show similar water quality behavior. From these groups, one may select representative indicator constituents for monitoring, thereby reducing the number of analyses which must be performed on a routine basis.

It has been suggested that the inability of the model to simulate water quality in single land use watersheds was related to the absence of flow and rainfall data between storm events. Once such data is obtained the model should be revisited to determine the validity of the buildup algorithm.

1.0 INTRODUCTION

Barton Creek drains more than 120 square miles of mostly undeveloped Texas Hill Country terrain. Meandering approximately 48.5 miles from its headwaters in northern Hays County, the creek extends eastward toward its confluence with the Colorado River (Town Lake) near downtown Austin, Texas. Along the final 7.0 miles of its approach to Town Lake, the creek traverses an outcrop of porous Edwards Limestone. Creek flows over this reach are subject to loss rates of up to 300 cubic feet/second (cfs) or more into the Barton Springs segment of the Edwards aquifer. A few hundred feet upstream of its confluence with the Colorado River, Barton Creek is dammed to capture the waters of Barton Springs located in the bed of Barton Creek. The captured springflow creates a popular public swimming facility known as Barton Springs Pool.

In recent years, existing and proposed development in the Barton Creek watershed engendered significant public interest in assuring that water quality in Barton Creek and Barton Springs be maintained at its current high level. In October 1987, the Austin City Council passed a resolution directing city staff to evaluate nonpoint source (NPS) pollution control strategies for the Barton Creek watershed and requesting the city's Environmental Board to review the analysis and provide recommendations to Council. The Council's resolution led to the development of the Barton Creek Policy Definition Report in March (BCPDR) of 1988. The BCPDR included three Action Groups, which were identified as the Barton Creek Watershed Study. These Action Groups included development of baseline data on biological and physical resources, development of a wastewater service management strategy, and the development of a water quality model from data to be supplied by an expanded water quality monitoring program.

Non-degradation was identified as the goal for water quality in Barton Creek and Barton Springs, and a multi-year study was recommended to address the technical limitations of existing NPS information related to this goal. In September 1988, as part of ongoing data collection and technical analyses, the City Council passed a resolution directing the city's Department of Environmental Protection (now the Drainage Utility Department) to further enhance data collection and analysis and to develop a predictive watershed model for the Barton Creek basin. The Environmental Board proposed a multi-year work plan for the study in January 1989. In January 1990, a local engineering firm (Espey, Huston & Associates) was selected by the city to serve as consultant for development of a watershed model to evaluate the effects of development in the Barton Creek watershed. The consultant’s scope of work included technical review and verification of the model to be developed by city staff. The consultant contract expired prior to calibration and verification of the selected model system; however, significant support for further work was provided by Dr. Randall Charbeneau and Dr. Michael Barrett of the University of Texas Center for Research in Water Resources (CRWR).

At the heart of the Barton Creek watershed study was the development of a watershed model capable of representing the basin's hydrologic and water quality processes for a variety of hypothetical development scenarios. The purpose of this work was to predict the specific impacts of varying levels and types of development in the Barton Creek watershed. Specific tasks of the watershed study included:

- Review and compilation of available data
- Subdivision of the hydrologic system to properly represent the watershed's surface water and aquifer system
- Evaluation and selection of appropriate models
- Implementation and testing of computer programs using test data
- Development of model input data
- Development of calibration methodology for the model's runoff and water quality routines
- Application of the model to small test basins
- Application of the model to the entire Barton Creek watershed using available data
- Modification of the model based on experience gained through application on small sub-catchments and on the entire Barton Creek watershed

Model development began in mid-1990. However, the completion schedule for this project was delayed due to various pending reviews, the city's involvement with litigation and subsequent alternate staff assignments, and new software development. In order to meet the project goal, an addendum to the original work plan was developed; the water quality modeling capabilities of the selected model were found to be inadequate for the desired applications and an alternative approach was developed. This alternative modeling approach required computer program development that added to project completion delays. The model development phase using the SWMM model is completed with the publication of this report; however, the predictive capabilities of the model with respect to water quality are less than anticipated. With respect to water quantity, the current state of the model is suitable for prediction of changes in runoff and baseflow due to development scenarios. The model can also be used to provide quantity input flows to the Barton Springs Edwards Aquifer Model developed by CRWR through an interlocal agreement with the city (Barrett and Charbeneau, 1996). Since the initiation of the Barton Creek Watershed Modeling project, focus of the Drainage Utility has shifted to an integrated planning for future water quality controls, along with flood and erosion protection. As a result, a city-wide masterplan has been initiated, along with a less-complicated watershed pollutant modeling project to be applied to the watersheds draining the entire city ETJ. Therefore, the future development of the Barton Creek Watershed model should be evaluated in light of the more comprehensive goals of the utility. If sufficient resources exist for continued development, the formulation of an adequate predictive water quality model may be resolved. However, in the interim, the following report is provided as documentation of model development and calibration to date.

The city has also undertaken a number of related studies to assess the water quality and quantity in Barton Creek and the Barton Springs contributing zone. These studies include investigations of ambient water quality, low flow pools, potential for stormwater control retrofits, biological assessment of Barton Creek, and groundwater quality modeling. These studies are documented in separate reports (Loomis and Associates, 1995; Barrett and Charbeneau, 1996; City of Austin, 1996; and City of Austin, 1997).

The general outline of the report is as follows. Chapter 2 provides a review and assessment of the physical and hydrologic data associated with the Barton Creek watershed. This includes a characterization of flow magnitudes and loss rates from the creek over the Edwards aquifer recharge zone, and a summary of water quality conditions. Chapter 3 reviews the model selection criteria, and describes the model selected for application to the Barton Creek watershed study. Chapter 4 presents the data and results from simulation of water quantity and quality for single-land-use watersheds and for the Barton Creek watershed. Chapter 5 describes a statistical regression model that can be used in conjunction with flow modeling to predict water quality in Barton Creek. It also presents the results from an analysis of single-land-use watershed water quality data, and suggests alternative approaches for stormwater quality modeling. Finally, Chapter 6 provides a discussion and summary of stormwater issues that have been identified through this research. Recommendations toward both modeling and watershed management are suggested.

2.0 THE BARTON CREEK PHYSICAL SYSTEM

The Barton Creek watershed covers approximately 120 square miles of the Texas Hill Country from its headwaters in Hays County to its confluence with the Colorado River (Town Lake) near downtown Austin, Texas (Figure 2.1). Approximately two-thirds of the watershed lies within Travis County. The remaining upper basin is located in northern Hays County. The eastern portion of the watershed lies within the City of Austin's 5-mile extraterritorial jurisdiction (50 square miles), but only a small portion of the basin is inside the Austin city limits. The Barton Creek stream length is approximately 48 miles. The watershed is approximately 25 miles long and 4 to 8 miles wide.

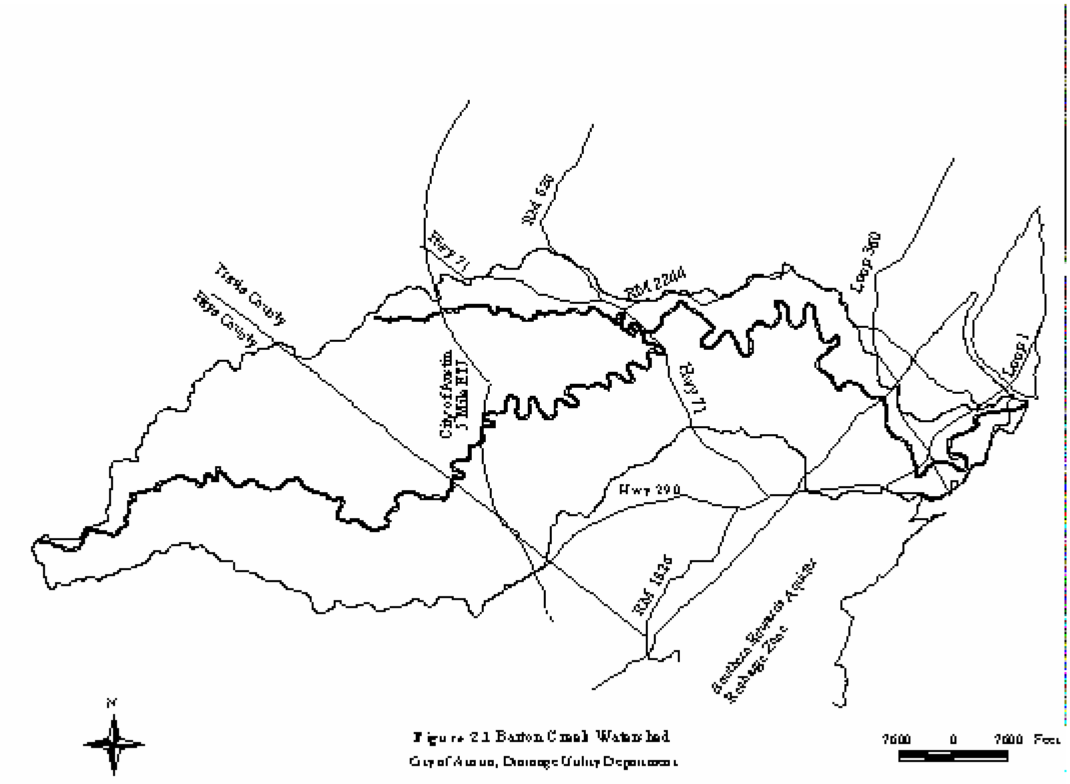


Figure 2.1 Map of the Barton Creek Watershed

This chapter provides an overview of the Barton Creek watershed hydrologic system, including discussions of its geology, soils, vegetation, water quality and watershed land uses. Rainfall and evaporation data for the Austin area are reviewed, and features of the water balance of the watershed are described. Results from an analysis of Barton Creek stream flow are presented, including estimates of channel losses and aquifer recharge.

2.1 Geology, Soils and Vegetation

2.1.1 Geology

The hydrology of Barton Creek is strongly influenced by the underlying geology. The Barton Creek watershed can be divided into an upper and lower portion demarcated by the change in geology and its effects on the hydrology of the creek. The upper portion of the watershed lies on the Edwards Plateau, which is underlain primarily by the Glen Rose Limestone. The eastern portion lies in the Balcones Fault Zone, where porous Edwards Limestone has been preserved in the downthrown fault blocks, creating the Barton Springs Edwards aquifer. The boundary between the two portions is marked by the Mount Bonnell Fault. Figure 2.2 shows a conceptual cross section of the geologic units in the Edwards aquifer region.

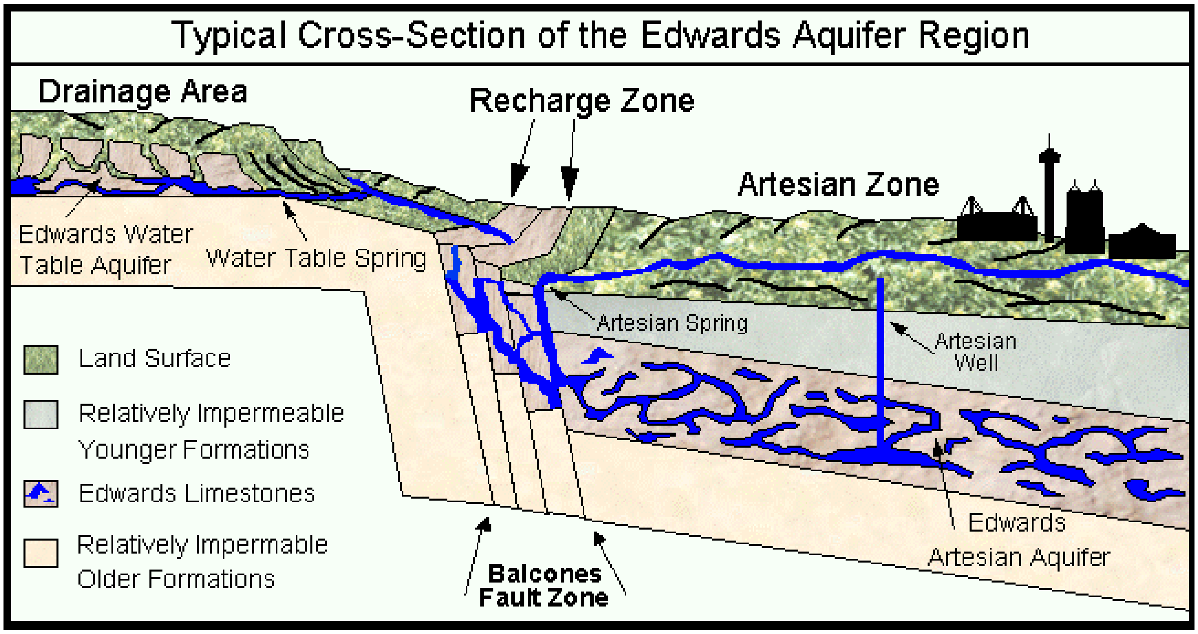


Figure 2.2 Dip Oriented Cross-section

A description of the major geologic units in the Barton Creek watershed based on the work of Garner and Young (1976) is presented below.

The vast majority of the bedrock in the Barton Creek watershed is composed of the Glen Rose Formation, which outcrops on the northwest side of the Mount Bonnell Fault. It was deposited northwest of (behind) the Stuart City reef in a variety of shallow subtidal to supratidal environments. It ranges from 500 to 1,000 feet thick, thickening to the southeast. It consists of alternating layers of relatively soft, erodible marl and hard dolomite and limestone strata.

Steep slopes and stair-step landforms generated by contrasting erosion rates characterize the topography of the upper portion of the Barton Creek Watershed. Soils, alluvium, and weathered limestone material range in depth from zero inches, at limestone outcroppings, to as much as 3 meters (Woodruff et al. 1992). The lower portions of the Glen Rose are not exposed in the Barton Creek area. The erosion-resistant limestone and dolomite layers form the ledges that stand out, while the softer marls erode forming slopes. Erosion of soft marl layers may be responsible for much of the suspended sediment found in Barton Creek. In some cases, severe erosion of the marly strata will undercut the overlying limestone beds to the point of collapse.

The lower portion of the Barton Creek watershed overlies the Edwards Limestone. The Edwards Limestone is exposed mostly to the south and east of the Mount Bonnell Fault, where it is preserved in downthrown fault blocks. The Edwards Limestone is about 300 feet thick in the Austin area. Four members of the Edwards Formation have been mapped locally.

The lowest member of the Edwards Formation is about 200 feet thick, consisting of dolomite, dolomitic limestone, and hard gray limestone containing rudists (long conical bivalves) with gray to black chert common. The second member of the Edwards Formation is comprised of about 40 feet of thin-bedded, fine-grained dolomitic limestone with nodular chert common. The third member consists of 10 to 15 feet of soft, burrowed limestone (micrite) that forms a marly slope. The fourth member consists of about 40 feet of flaggy limestone beds with a 1-meter thick rudist bed overlain by dolomitic limestone. Its top is calcarenitic limestone with sparse glauconite grains.

The top and base of the Edwards Limestone are gradational. The lower Edwards gradually grades into the upper Walnut Formation to the north and the uppermost Edwards grades into Georgetown beds to the north. The rocks of the Edwards Limestone were deposited in a wide variety of carbonate environments including reef, lagoonal, shoal, basinal, and supratidal. Many of the limestones were altered to dolomite by the invasion of meteoric waters shortly after deposition. Outcroppings of Edwards Limestone can be observed at many locations along lower Barton Creek.

The Barton Springs Edwards aquifer is the subsurface water body contained within the local Edwards Limestone. The high porosity of much of the formation, a result of vertical faults, fractures, and internal cavities in the rock, is responsible for the high flow rates and recharge capacity of the aquifer. Because of its location within carbonate rocks, and because it contains sinkholes, springs, caves, and sinking streams, the Barton Springs Edwards aquifer is classified as a karst aquifer.

There is a great variation in porosity and permeability of the Edwards over the entire watershed. Most is of secondary origin and is located along solution enlarged joints, faults and bedding planes. Cavernous porosity was created along vertical fractures as well as along bedding planes (St. Clair, 1979). The largest volume of recharge to the aquifer occurs through these abundant and highly permeable conduits. Inside the Edwards aquifer recharge zone, as many as 17 faults are in the outcrop along Barton Creek. Flow from creekbeds in this area is lost as vertical flow. Figure 2.3 presents a conceptual schematic of a karst aquifer showing potential hydrologic features similar to those found in the Barton Creek recharge and contributing zones. In some areas, inter-particular spaces are filled by recrystallized calcite and fractures are generally closed or only slightly open. All of these features produce a complex process-response pattern of flow, recharge, and sedimentation that is difficult to characterize.

Several other minor geological formations are present in the watershed. Fine-grained, highly erodible clays of the Del Rio Formation and soft shales and clays of the Eagle Ford Formation are often preserved in down-dropped fault blocks, and may contribute significant amounts of suspended sediment to the creek. Buda Limestone outcrops occur on some hills, and deposits of St. Elmo bench terrace deposits are present at relatively high elevations in the eastern portion of the watershed; both may contribute to alluvial deposits in creek beds. The St. Elmo bench may also contribute fine sediment loads.

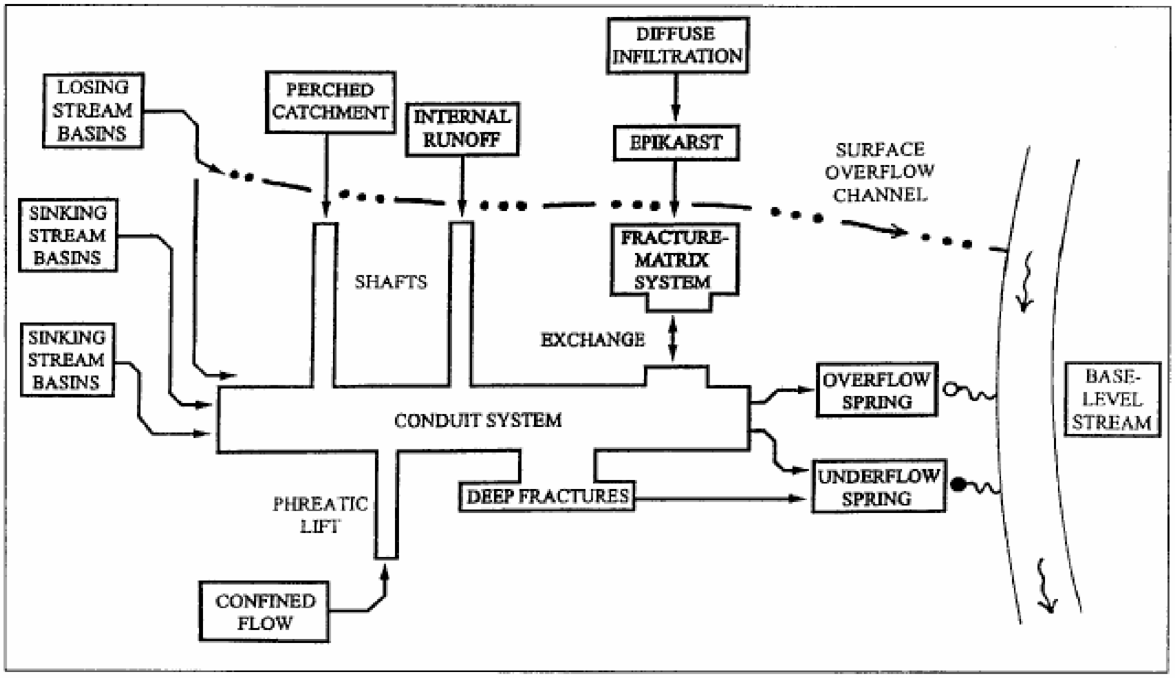


Figure 2.3 Conceptual Schematic of Karst Aquifer Characteristics

Tributary terrace deposits are common along Barton Creek, and normally consist of gravel, sand, silt, and clay. These deposits average 20 feet thick, and are a source of groundwater seepage (COA,1992).

2.1.2 Soils

Soils in the basin vary with local bedrock, as most soil is formed by the breakdown of the bedrock, supplemented by material carried in runoff. Two major soil groups comprise the bulk of the topsoil in the watershed. Soils of the Brackett Association, by far the most common, are found throughout the central and western portions of the watershed, west of the Mount Bonnell Fault. The soils in this group are very shallow, with depths to bedrock of less than 20 inches, and consist of "gravelly, calcareous, loamy soil overlying interbedded limestone and marl" (Werchan, as cited in *Town Lake Study).* The Speck-Tarrant Association is predominant only in the far southeast part of the watershed, east of the Mount Bonnell Fault, and is made up of "shallow, stony, loamy soils and very shallow, stony, clayey soils overlying limestone" (Werchan, cited in *Town Lake Study*).

Overall, soils within the watershed are considered to have moderately high to high runoff potential due to their shallow depth, fine texture, and/or high clay content. The vast majority of the soils within the basin are classified as Hydrologic Soil Group "C" by the U.S. Soil Conservation Service (USDA 1984, 1974)**,** indicating slow infiltration rates and moderate to high runoff potential. A few areas are classified as Group "D" soils, exhibiting very slow infiltration rates and high runoff potential. Only a very small section of the basin, the floodplain near the mouth of the creek, contains Group "B" soils, which have relatively low runoff potential.

Due to the basin's large size and to the character of its soils and geology, Barton Creek transports approximately 93 million pounds of suspended sediment per year to Town Lake. However, the creek has the lowest sediment per acre load (950 lb/ac/yr) of the nine tributaries emptying into the Colorado River in Austin (COA, 1992). The soils and vegetation in the watershed can hold significant amounts of rainfall, especially following extended drought conditions. Only large rainfall events generate sufficient runoff to transport large amounts of sediment. During dry conditions, rainfall events of 1 inch or more may not generate runoff or baseflow in the creek.

A recent geological study carried out in the Barton Creek watershed found that the soils commonly associated with the Glen Rose Formation are deeper and more diverse than previously reported. The soils were found to exhibit "varying thickness, higher abundance of organic matter contents, greater subsoil development, and greater biological activity than previously recognized" (Woodruff et al. 1993). While these soils do not appear as typical soils, the study found them to exhibit most of the criteria for classification as true soil, as follows:

> **Chemical**: high organic carbon contents, appreciable cation retention, translocation of soluble salts and carbonates, and subsoil carbonate enrichment and cementation;
> **Biological:** widespread fibrous root systems, macro faunal activity, and active microbiological communities;
> **Physical:** development of soil structure, moderately high water-retention capacities and a dynamic soil-moisture flux system (Woodruff et al. 1993, p. 3-2).

The soils of this type were observed to vary in depth from zero to as much as 3 meters over distances of 10 to 25 meters. The deepest soils lie over the marly strata, while the thinnest can be found over the hard limestone and dolomite layers. Roots are numerous in the surface horizons, becoming fewer with depth. While the soils are highly variable, several general characteristics can be identified. Soils are moderately to highly rocky (rock content of 15-90 percent), high in calcium carbonate (50-90 percent), and high in pH (7.6-8.4 in H_2O). In addition, they exhibit the following:

- Moderate to high organic matter content (1-7 percent);
- Moderate to high chemical retention in surface horizons, moderate in subsoil;
- Moderate to high soil-water retention in fine-earth fractions (11-20 percent).

Woodruff et al. (1993) measured infiltration rates at a range of sites using a portable infiltrometer. Their findings indicate that infiltration rate depends on the soil depth and amount of vegetative cover present. Deep soils located over marly sediments had infiltration rates that exceeded 5 in/hr in the presence of well-established vegetation or litter ground cover, in spite of steep slopes. Thinner soils found over hard limestone layers were often heavily encrusted with algae or mineral deposits, and exhibited low infiltration rates of 0.8 in/hr or less.

2.1.3 Vegetation

Vegetation in the Barton Creek watershed is typical of that found along the eastern portion of the Edwards Plateau. As noted by many observers, including Cuyler (1931), Tharp (1952), and Lyday (1989), there is a strong correlation between the exposed geologic strata and the resident plant community. Hilly areas and bluffs, usually composed of Glen Rose or, occasionally, Edwards Limestone, are characterized by mixed timber growth, while level areas containing thin loamy soils tend to be grasslands. Small portions of the basin have been cleared for cultivation and grazing. Figure 2.4 shows a map of vegetative cover in the watershed, which was developed from high-resolution aerial photographs taken in 1979, and updated in 1990, 1991, and 1992.

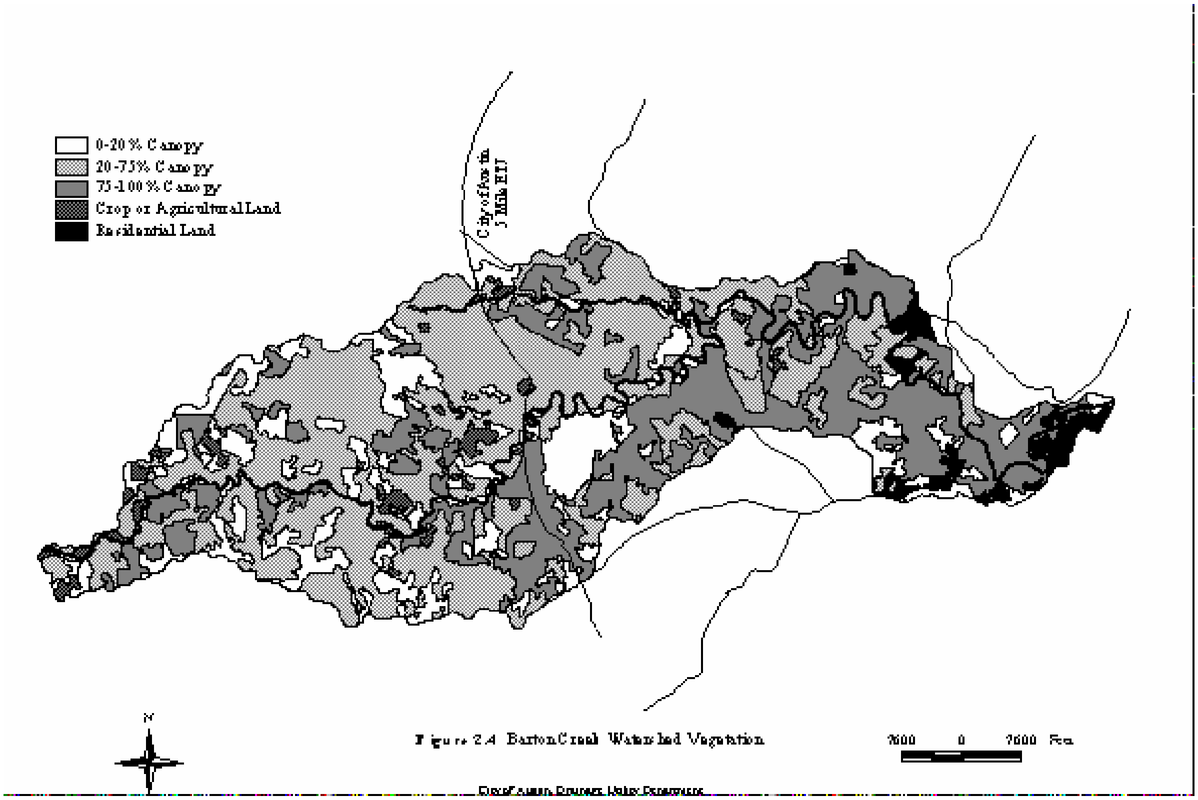


Figure 2.4 Barton Creek Watershed Vegetation

The vegetation categories described on the map are based upon the density of the tree canopy. Category 1 represents grassland having little or no tree cover (less than 20 percent). Category 2 represents medium tree cover (20 to 75 percent) and Category 3 represents high density tree cover (greater than 75 percent). Categories 4 and 5 represent cultivated land and residential land, respectively.

2.2 Watershed Land Use

Currently, about 11 percent of the Barton Creek watershed is urbanized (COA Land Use GISverage, 1994). Most development has occurred over 6,500 acres in the lower portion of the basin, adjacent to downtown Austin. In 1992, the City of Austin's Planning Department estimated impervious cover upstream of Loop 360 to be 5.5 percent. The impervious cover in the watershed, including the developed area downstream Loop 360, is approximately 6.2 percent.

Development in the basin upstream of Loop 360 includes newer single family residential land uses. Several of these subdivisions are located directly adjacent to or near the creek. One development, comprising approximately 650 acres, is Lost Creek, which is located adjacent to the creek. The subdivision is a medium-density residential development with lots of one acre or less. It also contains some larger homes, as well as a few multi-family housing units. The Lost Creek Country Club, with several buildings and tennis courts, is located opposite the residential area, on the south side of the creek. An 18-hole golf course straddles the creek. The Foothills of Barton Creek, Estates Above Barton Creek, and Estates Above Lost Creek subdivisions are also located on the south side of the creek and together comprise over 700 acres. These subdivisions consist of medium- to low-density single family homes, generally on lots of one acre or larger. Other significant residential developments include the Rob Roy subdivision, which totals over 800 acres, Travis Country, which comprises approximately 300 acres, and Camelot, which is slightly smaller than Travis Country. Most of the development in these subdivisions is medium- to low-density single-family residential.

Barton Creek Square Mall, located along Loop 360, has a contiguous impervious area of approximately 86 acres, and represents a significant large-scale commercial land use in the basin. A few office buildings are also located in the lower portions of the watershed along Loop 360. The Barton Creek Country Club and Conference Center, which includes a hotel, several club buildings, tennis courts, and two 18-hole golf courses, is located adjacent to the creek between Loop 360 and Highway 71, about one mile upstream of the Lost Creek Country Club. Saint Michael's Academy, a private school, is classified as a commercial land use, and sits between the Rob Roy and Estates Above Lost Creek subdivisions in the center of the lower basin.

There is little development in the watershed upstream from Highway 71. The community of Oak Hill straddles a portion of the southeastern boundary of the watershed, along Highway 290. Approximately 10 to 15 other small subdivisions exist within the basin, west of Highway 71, but inside Austin's ETJ. Development in the upper basin is widely scattered rural, large-lot residential, and ranch properties.

2.3 Hydrologic Relationship between Barton Creek and Barton Springs

The Barton Creek watershed is a component of an extensive and complex hydrologic system that transmits rainfall runoff to the portion of the Edwards aquifer that discharges into Barton Springs. In addition to Barton Creek, the Barton Springs contributing zone includes the drainage basins of Slaughter Creek, Williamson Creek, Onion Creek, Bear and Little Bear creeks, which drain to the 90-square-mile outcropping of Edwards Limestone. In this region, the carbonate Edwards Limestone is characterized by faults, fractures, and dissolution cavities, which promote storage and rapid, nonhomogeneous movement of groundwater.

2.3.1 Barton Springs Edwards Aquifer

The Barton Springs Edwards aquifer is the subsurface water body contained within the local Edwards Limestone. Although the water-bearing Edwards Limestone extends north to Bell County and southwest to Uvalde County, this segment of the Edwards aquifer is separated from the other segments by hydrologic divides, which include the Colorado River to the north, the Mount Bonnell Fault to the west, a potentiometric high to the south, and the "bad water line," a zone of decreased water circulation, to the east. The Barton Springs Edwards aquifer is classified as a karst aquifer because of its location within carbonate rocks, and because it has characteristics such as sinkholes, springs, caves, sinking streams, and dissolutionally enlarged conduits.

The aquifer discharges primarily at Barton Springs and other associated springs located in and near the Barton Creek creekbed immediately upstream of its confluence with the Colorado River (Town Lake) near downtown Austin. Barton Springs consists of five major springs. Of these, three discharge to Barton Springs Pool and two immediately below Barton Springs Pool. A 4.0 square mile portion of the Edwards aquifer in and around Rollingwood discharges about 3.0-4.0 cfs at Deep Eddy and Cold Springs near Valley Springs Road. Since well water elevations are unresponsive to hydraulic head changes at Barton Springs Pool (Slade et al. 1986), this Rollingwood portion of the Edwards appears to be hydraulically independent from the portion discharging at Barton Springs. Other sources of discharge from the Barton Springs Edwards aquifer include well pumpage (approximate mean discharge rate of 5 cfs), discharge along the creekbed of lower Barton Creek during periods of high water table elevation, possible subsurface flows to the San Marcos Springs portion of the Edwards, possible additional springflow directly into Town Lake, and possible lateral subsurface leakage into adjacent formations.

About 85 percent of the recharge to the Barton Springs Edwards aquifer occurs as infiltration of stream flows in the creeks crossing the Edwards outcrop. Secondary inflow sources to the aquifer include rainfall infiltrating directly into the outcrop area and subsurface inflows from adjacent formations (Slade et al. 1986). The USGS recharge contributions by watershed and maximum recharge rates are shown in Table 2.1.

The Barton Creek watershed contributes the second-largest recharge volume and strongly influences flow conditions at Barton Springs. Barton Creek appears to be more directly connected to Barton Springs than the other creeks because of its proximity and the karst conditions near the lower reaches of the watershed.

Table 2.1 Recharge Contributions to the Barton Springs Edwards Aquifer Estimated Under Steady-State Flow Conditions (after Slade et al. 1986)

Watershed	**Percent of Total Recharge**	**Maximum Recharge Rate** (cfs)
Barton Creek	28	30 to 70
Williamson Creek	6	13
Slaughter Creek	12	52
Bear Creek	10	33
Little Bear Creek	10	30
Onion Creek	34	120

Based upon 18 years of flow measurement, the mean discharge at Barton Springs is about 50 cfs (Slade et al., 1986). The median discharge is approximately 46 cfs. The minimum and maximum recorded discharge rates are 10 and 166 cfs.

2.3.2 Barton Creek

For the purposes of model development, the Barton Creek watershed has been divided into 26 subcatchments, as shown in Figure 2.5. The upper portion of the watershed that is underlain by the Glen Rose Limestone contains 24 subcatchments, which are delineated based mostly on single land use and topography. The subcatchments above the Highway 71 gauging station are mostly rural, agricultural and undeveloped. Those between the Highway 71 and Lost Creek Boulevard gauging stations consist mostly of rural area land use, although noticeable single family, golf course, roadway and park lands are present.

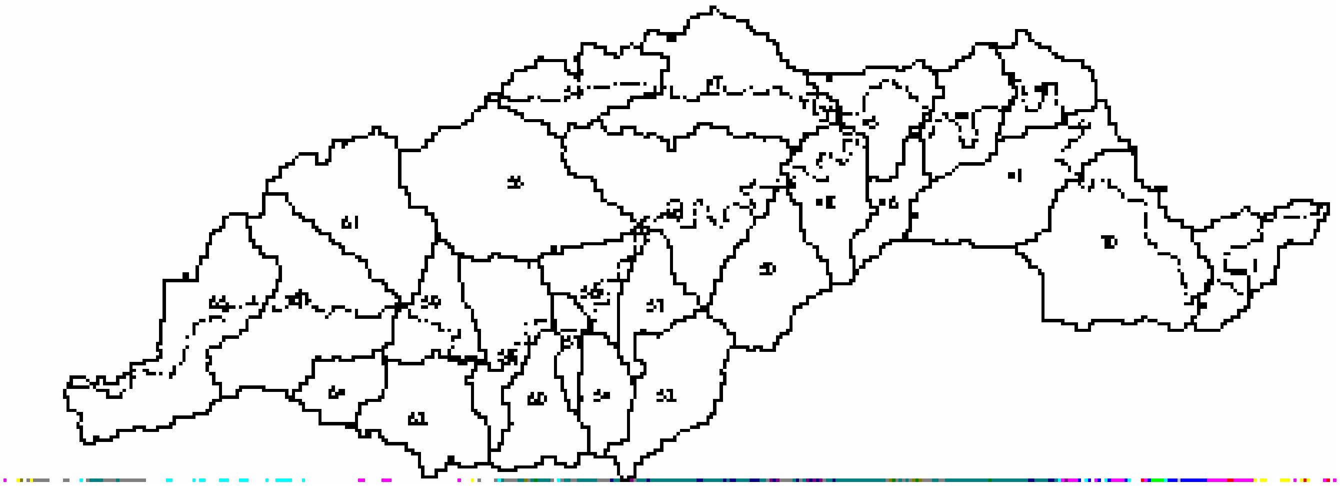


Figure 2.5 SWMM Model Sub-watershed Schematic

The lower portion of the basin that is situated (except at its extreme lower extent) on the Edwards Limestone contains two subcatchments wholly or partially inside the Edwards aquifer recharge zone. The total area for the recharge zone in the lower portion is approximately 5,600 acres (8.8 sq. miles). Thirty-nine percent of the watershed between the Lost Creek Boulevard and Loop 360 gauging stations (catchment 30) is outside of the recharge zone. The lower part of the Barton Creek watershed, below the Loop 360 gauging station, consists of a single developed watershed (catchment 1).

Table 2.2 summarizes some of the general information and subcatchment characteristics of the Barton Creek watershed. There are 57,000 acres of the watershed above the Highway 71 gauging station, 3.4 percent of which is impervious. The Barton Creek stream length above this station is 27 miles. There are 12 miles along Barton Creek between the Highway 71 and Lost Creek Boulevard stations. Between the Lost Creek and Loop 360 stations, there are 1.5 miles of Barton Creek above the recharge zone and 2.8 miles inside the recharge zone. Barton Springs pool is 3.9 miles downstream of the Loop 360 gauging station. An additional 0.6 miles outside of the recharge zone leads from the pool to Town Lake.

Table 2.2 Barton Creek Watershed Characteristics

Subcatchments Inside Recharge Zone					**Subcatchments Outside Recharge Zone**			
Watersheds	Sub catchments	Area (Acres)	Stream Length (Mile)	Impervious Area (Acres)	Sub catchments	Area (Acres)	Stream Length (Mile)	Impervious Area (Acres)
Upper Portion								
Highway 71					47 thru 65	57,000	27	1,900
Lost Creek Boulevard					41 thru 46	11,000	12	1,200
Lower Portion								
Loop 360	30	3,600	2.8	300	30	2,300	1.5	650
Lower Watersheds	1	2,000	3.9	600	1	240	0.6	100
Total		5,600	6.7	900		71,000	41	3,900

There is a significant difference in the water loss rate along the length of Barton Creek inside and outside of the recharge zone. Although the USGS (1971) found observable baseflow losses upstream of the recharge zone, the loss of water along the 41 miles outside the recharge zone is generally insignificant. However, the loss of water along the 6.7 channel miles within the Edwards aquifer recharge zone is significant and important for maintenance of flows at Barton Springs.

Recharge rates to the aquifer along Barton Creek vary from approximately zero to 300 cfs or more, depending upon the elevation of the local groundwater table and on the creek flow rate. This estimate was made from flow measurements above and below the recharge zone during periods when little or no runoff was being introduced into the creek from the recharge zone (see Section 2.7). Increasing recharge with higher flows is attributed to larger areas of the stream directly in contact with openings to the aquifer and to increased hydrostatic heads along the creekbed. When the water table in the lower section of the Edwards aquifer rises above the level of the creekbed in lower Barton Creek, the creek in this section becomes a discharge (as opposed to recharge) reach. The maximum discharge rate from the Edwards into lower Barton Creek is estimated to be about 6 cfs with discharge occurring about 30 percent of the time (Slade et al. 1986).

2.4 Austin Rainfall and Potential Evaporation

National Weather Service analyses, based upon 60 years of gauged rainfall data (1930-1989) measured at Mueller Airport, indicate Austin's mean annual rainfall is approximately 32.5 inches. The highest measured calendar year rainfall was 52.2 inches (1991) and the lowest measured calendar year rainfall was 11.4 inches (1954). Figure 2.6 shows average monthly rainfall totals for Austin. Historically, average monthly rainfall volumes are high in the spring and then again in September and October during the tropical storm season. The lowest average monthly rainfall volumes occur in January, March, and during midsummer. In general, rainfall events in the winter months are of longer duration and lower intensity. Late spring and summer storms are shorter in duration and, on average, exhibit mean rainfall intensities two to three times higher than winter storms. The number of rainfall events is distributed fairly evenly throughout the year at about four to five events per month.

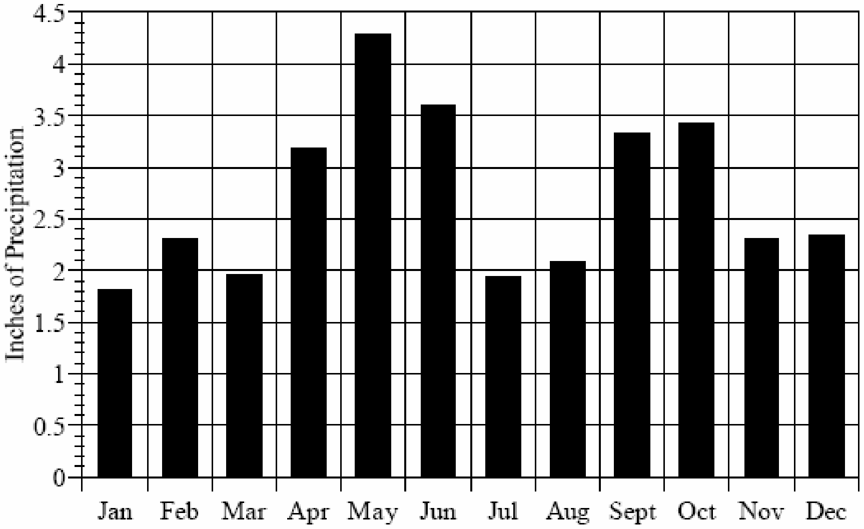


Figure 2.6 Average Monthly Rainfall for Austin, Texas, 1939-1991
(Source: National Weather Service, 1991)

To evaluate the distribution of rainfall events by size, individual storms were identified from 60 years of record (1930-89). Individual events were separated by at least a six-hour dry period, and a total of 3,572 such events were identified. These were grouped by volume category into increments of 0.10 inches. Category midpoint volumes were 0.05, 0.15, 0.25, etc., inches. The total number of events and volumes for each category were noted, resulting in the average annual distribution shown in Figure 2.7. This figure shows the average annual volume contribution from events of various sizes. For example, rainfall events between 0.0 and 0.1 inches contribute a total of 0.7 inches of rain per year on average. Events of magnitude 2 inches contribute about 0.5 inches to the annual rainfall total. About 50 percent of the rainfall occurs in events of magnitude greater than 1 inch, though they contribute less than 15 percent of the total number of events per year. About 50 percent of the events have volumes less than 0.25 inches.

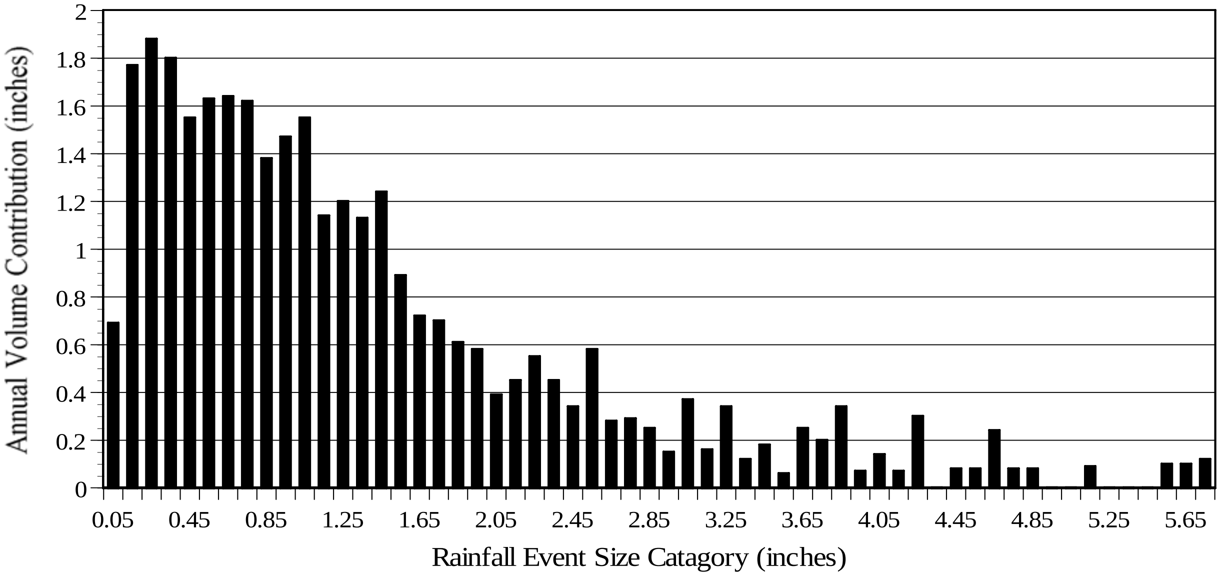


Figure 2.7 Mean Annual Rainfall Volume Contribution Occuring in Each Storm Event Volume Category for Austin, Texas

2.4.1Evaporation Data

Pan evaporation data were obtained from the National Weather Service Bureau. Since pan evaporation is greater than would occur from a lake or surrounding vegetation, the rates were multiplied by an empirical coefficient of 0.7 to calculate equivalent open-water evaporation values (Chow et al. 1988).

Figure 2.8 displays the total monthly open-water potential evaporation values for Austin. The total yearly potential evaporation is in excess of 70 inches. This is more than twice the average rainfall in Austin. The potential evaporation during the summer months is more than three times higher than during the winter months. This clearly shows that an accurate estimate of evaporation is required for continuous water balance modeling.

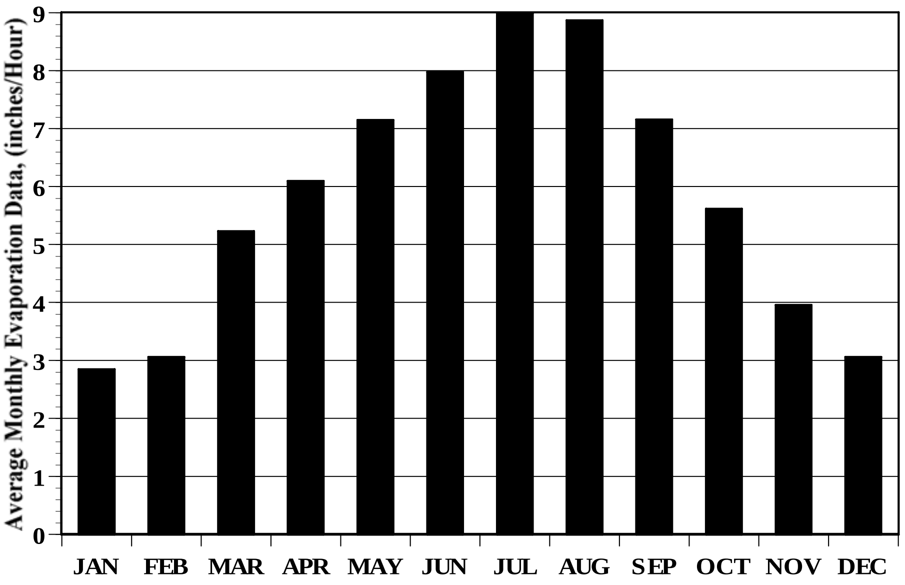


Figure 2.8 Monthly Open Water Potential Evaporation for Austin, Texas

2.5 Hydrologic Water Balance

Stream flow can be divided into two regimes: base flow and direct runoff. Direct runoff occurs in Barton Creek during and immediately following rainfall events. It consists of overland flow and shallow subsurface flow (interflow). Interflow contributes to direct runoff when the travel time of this flow to the creek falls within the time of the storm pulse in the stream hydrograph. Interflow occurs through shallow limestone soils in the upper watershed areas, and through alluvial deposits adjacent to the main channel.

Baseflow occurs between storm runoff events. It is distinguished from direct runoff by the shape of the stream flow hydrograph. The duration of stormwater runoff measured in Barton Creek at Lost Creek Boulevard has ranged from four hours to 6.5 days; and the length of time of base flow has ranged from 15 hours to 50 days.

Maximum measured flow rates at each monitoring station during runoff and base flow conditions are shown in Table 2.3. A typical segment of the continuous hydrograph in Barton Creek at three monitoring stations is presented in Figure 2.9. The difference between storm and baseflow discharges between Highway 71 and Lost Creek Boulevard is associated with inflows along the channel between these two stations. The lower flows for the Loop 360 station are associated with recharge over the outcrop of the Edwards Limestone.

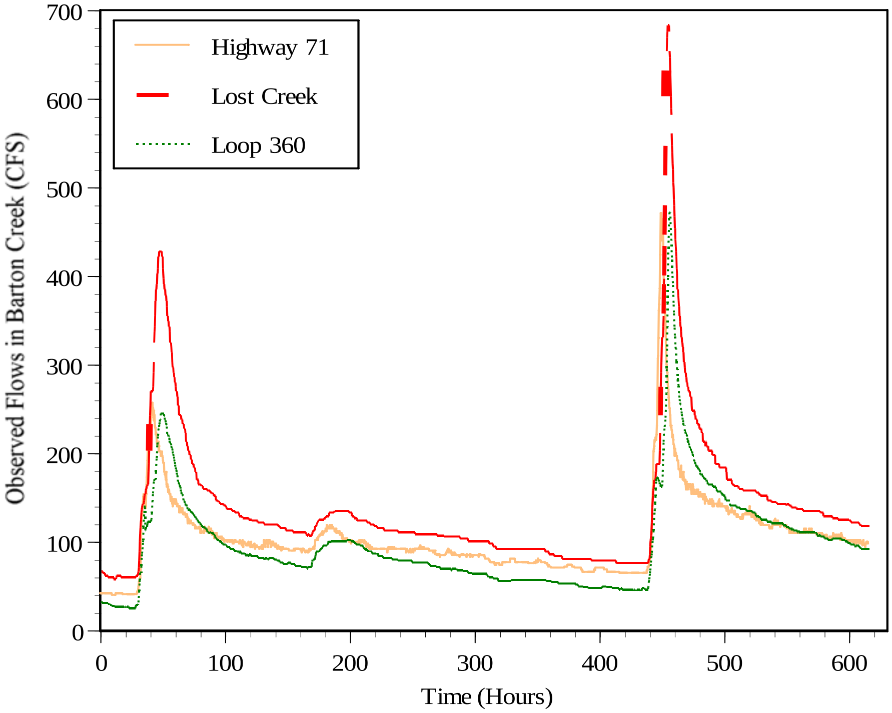


Figure 2.9 Barton Creek Hydrograph at Three Gaging Stations

Table 2.3 Summary of Quantity and Quality Measurements in Barton Creek

Station	Period of Record	Peak Baseflow (cfs)	Peak Runoff (cfs)	Number Baseflow Samples	Number Runoff Samples	Number Total Samples
Highway 71	12/88 to present	2,500	14,000	25	29	54
Lost Creek Boulevard	12/88 to present	2,400	15,400	21	43	64
Camp Craft Rd.*	1/82 to 12/85	255	220	16	14	30
Loop 360	10/82 to present	3,900	17,200	23	77	100

* short term monitoring near present Lost Creek Boulevard Station

Other hydrograph records show that peak flow rates for certain runoff events are lower than baseflow rates at other times. This overlap occurs because runoff generated by a small storm when the soil conditions are dry is often less than baseflow in the creek following a prolonged rainy period.

Approximately 70 percent of the rainfall events over the Barton Creek watershed generate little or no runoff in Barton Creek. Only about 25 percent of the total volume of rainfall was measured as stream flow at Lost Creek Boulevard between 1989 and 1993. For smaller rainfall events, water is retained on vegetation (interception storage), in depression storage, and in the soil profile. Vegetation in the basin is primarily a juniper-oak scrub woodland. The canopy of this vegetation can capture significant amounts of water. Even after several hours of rainfall, soil beneath this canopy is often dry. Rainfall also may be retained in surface cavities and pockets of soil and limestone. This depression storage may have little connection with the subsurface, since the captured water is eventually lost to evaporation.

Rainfall which neither runs off, nor is retained by interception or depression storage, may move into the soil profile or into underlying aquifers. Northwest of the Mount Bonnell Fault, groundwater resides within the Glen Rose Formation. This area corresponds to the upstream reaches of the Barton Creek watershed. Southeast of the Mount Bonnell Fault, groundwater resides in the Edwards Formation. Based on the relationship to the Barton Springs Edwards aquifer, the Barton Creek watershed over the Glen Rose Formation is designated as the contributing area. That portion over the Edwards Formation is the recharge area.

Groundwater in the Glen Rose Formation is usually under water-table conditions, and occurs in the marly beds and solution zones of the dolomite and limestone. Drainage from these beds occurs at numerous seeps and springs at the limestone interfaces (Brune and Duffin, 1983). There is little downward migration of water due to the bedded nature of the Glen Rose Formation. Water that infiltrates into this shallow groundwater system is either stored in the perched water zones, discharged into the creek and its tributaries through seeps and springs, or returned to the atmosphere through evapotranspiration. Perched groundwater seeps in the Glen Rose contribute significantly to Barton Creek baseflow.

The recharge zone of the Barton Springs Edwards aquifer consists of the area where the Edwards Limestone outcrops. All recharging water, whether it originates as rainfall on the contributing zone or on the recharge zone, moves into the aquifer through the karstic Edwards Limestone. Approximately 85 percent of the total recharge to the aquifer has been calculated to occur from stream losses (Slade et al. 1986).

In the recharge zone, rainfall may move directly into the aquifer through soils, faults/fractures, or vuggy and cavernous porosity. These distributed avenues of recharge through the exposed limestone are not completely known. A cloaking mantel of alluvium, sediment and soil covers potential recharge features.

Soils in the recharge zone are rarely saturated, even by heavy rainfall events, indicating extensive subsurface drainage.

Watershed monitoring by the City of Austin indicates that runoff from the recharge zone is less than that from the contributing zone. The estimated average annual runoff coefficient for undeveloped areas outside the recharge zone is 0.049. For similar areas within the recharge zone, the runoff coefficient is 0.025 (City of Austin, 1993). This means that during an average year (32 inches of rainfall) the depth of runoff from the contributing zone is 0.77 inches greater than from the recharge zone. This difference can be attributed to direct losses to the aquifer in the recharge zone.

Water loss from the creek-bed and areal infiltration affect flow in Barton Creek downstream of the Mount Bonnell Fault. Stream flow decreases downstream, indicating a losing stream reach. The losses are reflected in the percentage of time with zero stream flow, which increases from 0.7 percent at Lost Creek Boulevard to 63 percent at Loop 360. Loop 360 is approximately 3.9 stream miles above Barton Springs Pool. Additional streambed losses occur downstream of the Loop 360 monitoring station. Stream losses through this entire reach were estimated (Slade et al. 1986) to range between 30 and 70 cfs, depending on water levels within the aquifer, during steady flow conditions. Maximum recharge rates are greater when flood flows inundate larger areas of streambed and overbank recharge features.

2.6 Water Balance Study

The Barton Springs contributing zone receives an average of 32.5 inches of rainfall annually. A hydrologic water balance study by Woodruff (1984) reports that evapotranspiration accounts for approximately 85 percent of the total rainfall volume in the Barton Springs contributing zone (Slade et al. 1986). The study area included the 90-square-mile recharge and the 264-square-mile contributing zones. The study analyzed data from July 1979 to December 1982. Rainfall inputs were derived from 13 rain gauges in the area. Measured outflows from the system were recharge and runoff (including baseflow) volumes. Since changes in water storage in the soil profile and aquifer and withdrawals of well water were insignificant over the study time frame, evapotranspiration was calculated as follows:

$$\text{Evapotranspiration} = \text{Precipitation} - \text{Recharge} - \text{Runoff}$$

where:

Recharge is the amount of the total precipitation volume entering the Barton Springs Edwards aquifer via cracks and crevices in the creek bottoms or uplands areas; and

Runoff is the amount of the total precipitation volume conveyed in the creeks that passes over the recharge area but does not pass into the aquifer.

During the study period, recharge to the Barton Springs Edwards aquifer was 6 percent of the total rainfall volume, leaving 9 percent of the total rainfall volume to drain to the Colorado River. Approximately 62 percent of the total runoff volume during the reporting period was attributed to the flooding around Memorial Day 1981. This extreme event may have caused the study period's rainfall/runoff ratio to be unrepresentative of the basin's long-term rainfall/runoff ratio, so that the average evapotranspiration rate in the study area is probably greater than 85 percent and the runoff rate less than 9 percent.

2.7 Barton Creek Stream Flow

The amount of runoff generated in the Barton Creek watershed for a given rainfall event depends upon antecedent moisture conditions in the basin. During dry conditions, measured rainfall volumes as high as 1.2 inches in one hour at Highway 71 have produced only insignificant flows in Barton Creek. Storm flow features of interest for the Barton Creek study include the separation of direct runoff and baseflow contributions to creek discharge, the magnitude and frequency of flows, and the seasonal variation in the rainfall-runoff relationship. Stream flow analyses were conducted on USGS 15-minute flow records from January 1989 to May 1993 at the Highway 71, Lost Creek and Loop 360 gauging stations.

2.7.1 Direct Runoff and Baseflow Hydrograph Separation for Flows in Barton Creek

A stream flow or discharge hydrograph is a graph or table showing the flow rate as a function of time at a given location on a stream. The hydrograph consists of two separate hydrologic components. During and immediately following a rainfall event, the rainfall that runs overland into the creek and interflow that moves through the shallow subsurface make up the direct runoff contributions to the hydrograph. The baseflow component of the hydrograph consists of that water that infiltrates to the water table, and seeps back into the channel from groundwater storage. Direct runoff carries most of the stormwater contaminant load, which is washed off the watershed. Baseflow is generally of better water quality, and is responsible for prolonged creek flows between storm events.

Separation of the base flow and direct runoff components of the hydrograph is an important part of the Barton Creek water-quantity modeling effort. Calculations for volume, rainfall/runoff ratios, and load from observed data are based on the separation of hydrographs into different components of flow.

There are numerous methods to separate base flow (Dreiss, 1989; Littlewood and Jakeman, 1991; Pilgram, 1987). Some are physically based while others are more analytical. Due to the large quantity of flow data available for this study (approximately 250 storms), none of the methods reviewed offered practical approaches that met the requirements of this project. Because of the large number of events, a WINDOWS-based hydrograph plotting program called HYDROLOG was developed to separate baseflow from runoff. This program allows users to identify the beginning and ending points of direct surface runoff. The program then interpolates base flow, and subtracts this quantity from total stream flow for runoff estimates. Locating the end of runoff on the recession curve may be difficult and is often a matter of the user's judgment. Figure 2.10 shows how the Barton Creek hydrographs are separated. The time axis is usually limited to 80 to 120 hours for optimum display. The HYDROLOG program is described in more detail in Appendix A.

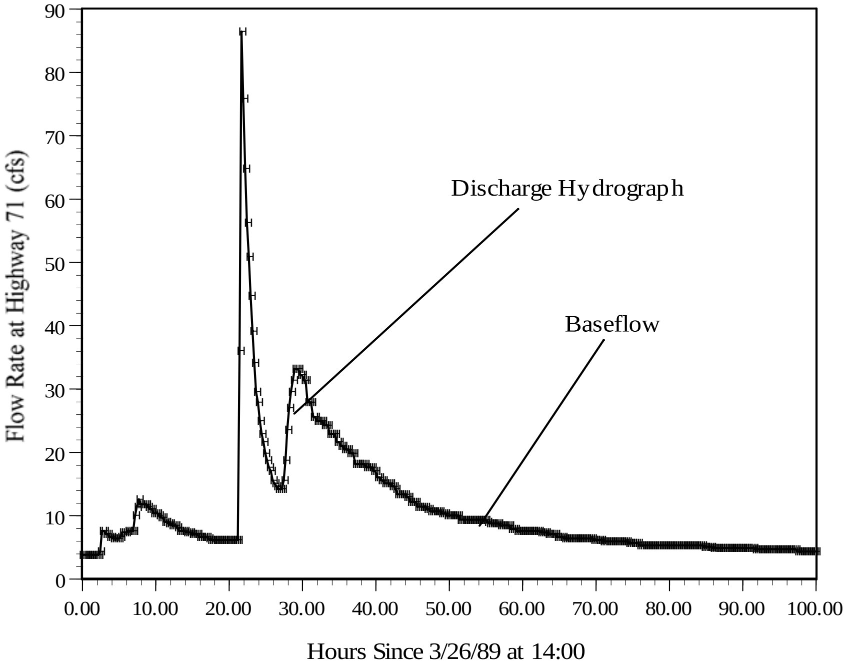


Figure 2.10 Total discharge and Baseflow in Barton Creek from 3/26/89 to 3/30/89

The fraction of base flow and runoff flow in the creek can be quantified based on the hydrographs from the monitoring sites at Highway 71, Lost Creek Boulevard, and Loop 360. Runoff versus base flow volume calculations and frequency analyses were performed using the entire stream flow data set. Volumetric base flow separation results are summarized in Table 2.4. The flow records for all stations extend from January 1989 to May 1993. The USGS reports that there was no flow in the channel at Highway 71 for 7 percent of the time between 1989 and 1993. In Table 2.4, the percentage of flow below the measurement limit is labeled as no-flow percent.

Table 2.4 Hydrologic Components of Barton Creek Stream Flow

Site	**Drain. Area** (Acres)	**Imper. Cover** (%)	**Recording Periods Analyzed**	**No-flow Percent** (%)	**Tot. Volume** (10^9 Ft^3)	**Baseflow Volume** (%)	**Runoff Volume** (%)
Highway 71	57,000	3.4	1/89-5/93	6.7	8.3	77	23
Lost Creek	69,000	4.6	1/89-5/93	0.7	10.3	78	22
Loop 360	74,000	5.3	1/89-5/93	63	9.5	65	35

No flow was measured at the Lost Creek Boulevard station for 0.7 percent of the monitoring period. The Lost Creek station is located approximately 1.5 miles below Short Spring Branch. This spring can produce a discharge of up to 20 cfs. In addition, Lost Creek dam, located just upstream of the Lost Creek station, helps sustain a water level in the channel at this station. The time percent of no-flow at the Loop 360 station increases dramatically to 63 percent due to recharge to the Edwards aquifer. As noted previously (Table 2.2), 61 percent of the intervening Loop 360 watershed is inside of the recharge zone.

The volume calculations in Table 2.4 show that 23 percent of the stream flow at the Highway 71 station is associated with direct runoff flow conditions. Similar results are found for the Lost Creek station, with 22 percent of the flow volume associated with direct runoff conditions.

There is a significant decrease in the base flow component downstream of the Lost Creek station. At Loop 360, the direct runoff component increases to 35 percent (a jump of 13 percent). There are two major reasons for the differences in the flow fractions. First, the local intervening watershed at Loop 360 has a higher percentage of impervious cover. Second, there is a significant stream flow loss along the channel over the recharge zone. The base flow recession at Loop 360 is more rapid than at the Lost Creek station (see Figure 2.11).

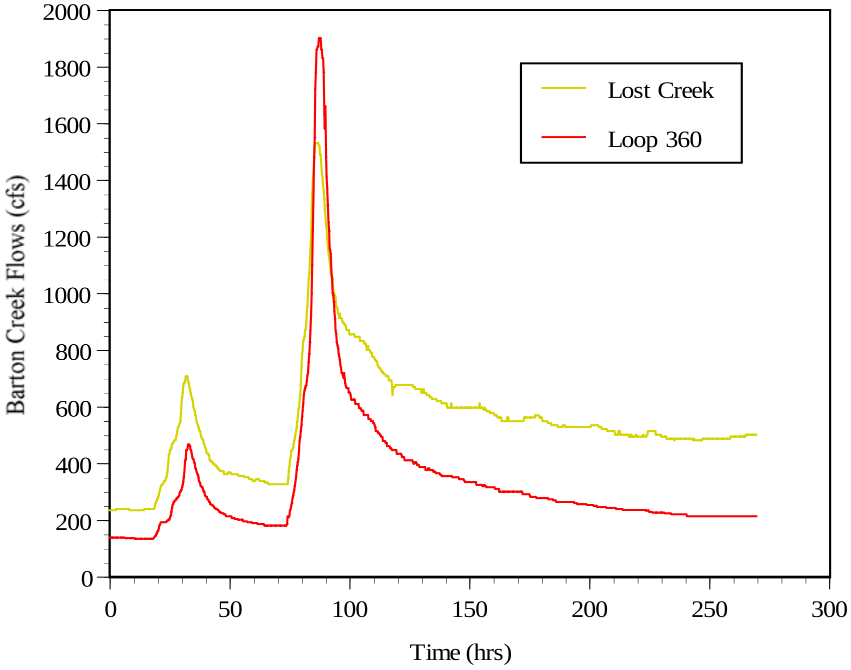


Figure 2.11 Barton Creek Base Flow Recession Curves

2.7.2 Flow Distribution Analysis of Direct Runoff

Frequency analyses were performed for direct runoff and total stream flow for each station. The data used for the direct runoff analysis were generated by the flow separation procedure previously discussed. The flow record is segregated into increments of 5 cfs for flows below 1,000 cfs, and increments of 100 cfs for flows above 1000 cfs. The frequency percentage is calculated by taking the number of occurrences in each flow range, and dividing by the total number of measurements. Figure 2.12 shows direct runoff versus the percentage of the time the flow rate is not exceeded.

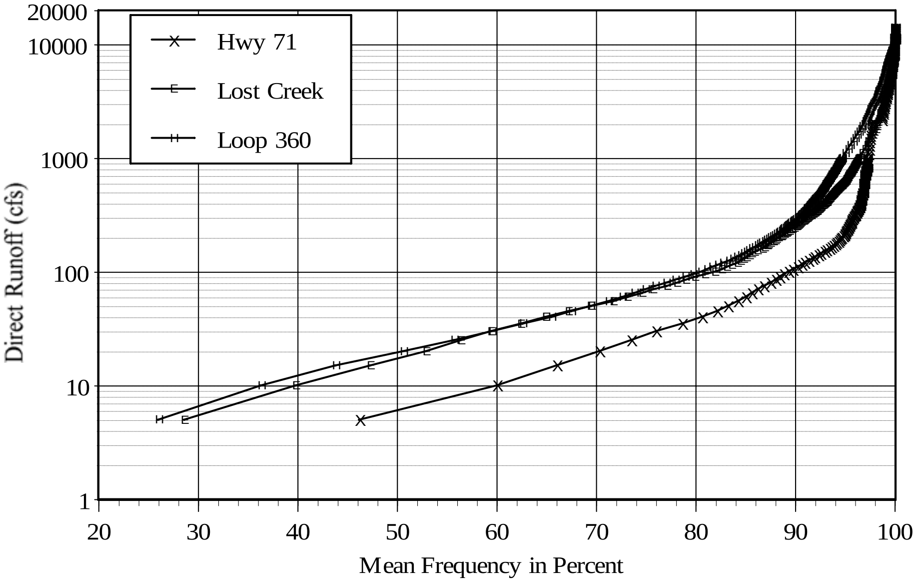


Figure 2.12 Barton Creek Flow Distribution Analysis of Direct Runoff

There is a significant difference in frequency of direct runoff magnitude when one compares Highway 71 to the Lost Creek and Loop 360 stations. The downstream watersheds have a higher percentage of impervious cover, and thus larger runoff flow rates would be expected for a given rainfall. This relationship holds for most storm events; however, when flows exceed approximately 1,000 cfs at the three stations, the maximum flow rate measured is generally higher at Highway 71 than at the downstream sites. This may indicate problems with the stage/discharge relationships (rating curves) developed by the USGS for the three sites. Any errors in the rating curves will create difficulties in reproducing peak flow rates with a computer model of the creek.

Maximum flows at the three stations generally are well below 1,000 cfs. Fifty percent of the time, runoff at Highway 71 is less than 6 cfs. This compares with 50th percentile flows of 19 cfs at Lost Creek and 20 cfs at Loop 360. Ninety-five percent of the time, direct runoff at Highway 71 remains below 200 cfs, compared with 600 cfs at Lost Creek Boulevard and 1,020 cfs at Loop 360. The differences in magnitude of runoff among the monitoring stations are greater than can be explained by the differences in the size and impervious cover of the watersheds. Even though the contributing watershed area of the Loop 360 station is only 8 percent larger than that of the Lost Creek station (116 square miles versus 107 square miles), and there is only a 0.7 percent increase in impervious cover (5.3 percent versus 4.6 percent), there is an even larger difference in direct runoff response when a series of rainfall events are compared.

Recharge losses in the upland areas and channel losses are primarily responsible for minimizing the difference in volume and flow rate for small events. For large runoff events, the difference between the Lost Creek and Loop 360 flow frequency curves above the 90th percentile is greater than for smaller events. For large events, local abstractions and channel losses over the recharge zone are small compared to runoff flow rates, and thus the larger drainage area and impervious cover result in larger flows at Loop 360.

2.7.3 Flow Distribution Analysis of Total Stream Flow

Frequency analysis was also applied to total stream flow in Barton Creek. Except for the largest events, the magnitude of stream flow observed at Lost Creek is larger than at Highway 71 or Loop 360. Figure 2.13 shows that 43 percent of the time the flow rate of Barton Creek at Highway 71 was less than 5 cfs. At Lost Creek, a stream flow less than 5 cfs occurs only 36 percent of the time, but at Loop 360, this value jumps to 65 percent. Although the magnitude of stream flows above the 98 percentile level are similar for all three stations, the largest occur at Loop 360 and smallest at Highway 71.

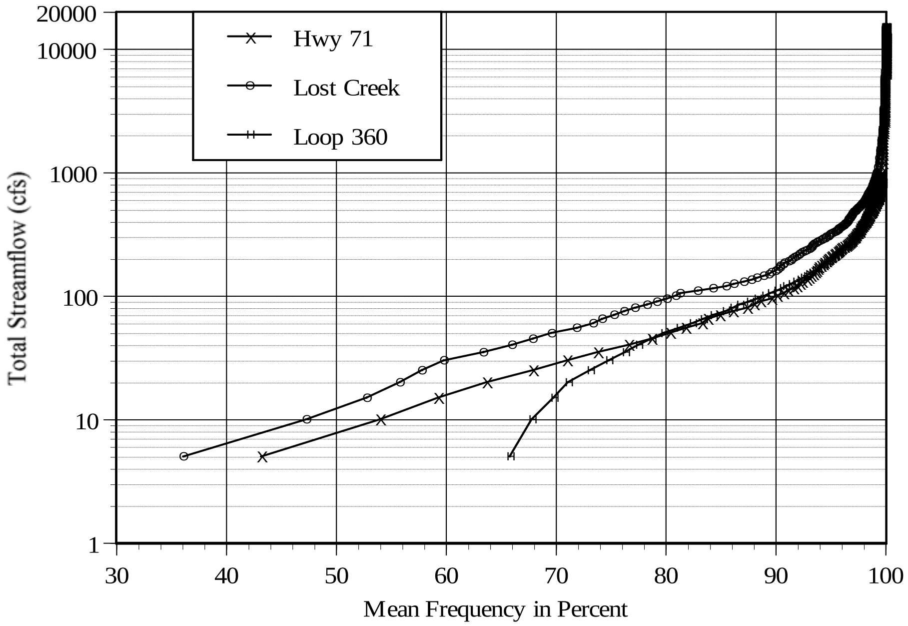


Figure 2.13 Barton Creek Flow Distribution Analysis of Total Streamflow

2.7.4 Runoff Coefficient, Rv

The runoff coefficient, Rv, is the ratio of the total runoff to total rainfall volume for all storms over a watershed. The calculation of runoff coefficients presented here is based on 15-minute flow records for the time periods shown in Table 2.5, and rainfall records from Barton Creek at Highway 71. Correlation analyses supporting the validity of using this gauge to represent the entire watershed are discussed in Chapter 4. The in-house developed program HYDROLOG was used to perform Rv calculations. Rv analyses were based on 151 storm events at Highway 71, 159 storms at Lost Creek, and 103 storms at Loop 360. HYDROLOG uses the record of direct runoff to determine the runoff volume, and then divides the runoff volume by the rainfall volume to estimate Rv. Table 2.5 summarizes the Rv results generated for the 1989 to 1994 stream flow records. The average rainfall depth used for this analysis is 0.75 inches. The mean Rv values for Highway 71, Lost Creek Boulevard, and Loop 360 are 0.020, 0.027, 0.049 respectively. These results are consistent with and reflect increasing impervious cover over the intervening areas in the lower portions of the Barton Creek watershed. They are also consistent with the frequency analyses discussed earlier.

Table 2.5 Barton Creek Runoff Coefficient, Rv

	Hwy 71	Lost Creek Boulevard	Loop 360
Year-Round Average			
Mean	0.020	0.027	0.049
Range	0 - 0.34	0 - 0.45	0 - 0.61
November - May Average			
Mean	0.026	0.035	0.063
June - October Average			
Mean	0.008	0.015	0.016

In December 1991 there was more than 10 inches of rainfall over a five-day period. The ground became saturated and a significant runoff occurred. For this event, the Rv value for Highway 71 is 0.34, while those for Lost Creek and Loop 360 are 0.45 and 0.61, respectively.

The average Rv value is found to vary significantly with season. During the hot and dry periods of the summer, evaporation is higher, the ground is dryer, and water storage potential in the soil is greater than in the winter. Naturally, in the months of June through October, the runoff volume is expected to be significantly lower than between the months of November through May. The average Rv values in Table 2.5 show a consistent seasonal trend for all three gauging stations.

Uncertainty is a factor in estimating Rv values. The differences in impervious cover are small, and the potential factors that may affect the estimated Rv values are great. The estimates are affected by uncertainties in rainfall volume measurements, location of gauges, base flow separation, the rating curve equations for each station, and gauging station calibration variations. The continued long-term monitoring program for Barton Creek, along with an appropriate quality control program, will improve the accuracy of the estimates.

2.8 Calculation of Channel Losses and Aquifer Recharge

As noted previously, the part of the Barton Creek watershed lying southeast of the Mount Bonnell Fault resides on the outcrop of the Edwards Limestone. In this area, Barton Creek is within the Barton Springs Edwards aquifer recharge zone. The Barton Creek Edwards aquifer receives recharge from channel losses from creeks crossing the Edwards outcrop, and from diffuse recharge occurring from infiltrating rainfall on the watershed. The Lost Creek gauging station lies northwest of the fault on the Glen Rose Formation. The Loop 360 gauge lies on the recharge zone. When comparing observed streamflow hydrographs at these two stations, the increased drainage area and area of impervious cover at Loop 360 and the channel losses which occur between the stations must be addressed.

During baseflow conditions, the computation of channel losses is straightforward. The channel flow rate changes only slowly through time, there are no significant inflows between the stations at Lost Creek and Loop 360, and evaporation is insignificant compared to channel flow. Therefore, aquifer recharge between the two stations is equal to the channel losses:

$$Q_{recharge}(t) = Q_{Lost\ Creek}(t) - Q_{b}(t) \qquad (2.1)$$

Equation (2.1) can be used to develop a relationship between the creekbed recharge rate between the two stations to the discharge recorded at the Lost Creek station.

Estimation of the aquifer recharge rate during periods of direct runoff is more difficult. During these periods, flow rates vary more rapidly with time such that flow rates measured at Lost Creek do not necessarily match flow rates at Loop 360. To accommodate this effect, a method was developed to address the time lag between the flows at Loop 360 and Lost Creek. In addition, during direct runoff conditions from large storms, significant inflows to the creek occur from overland flow between the two stations, which offset some of the channel losses. These inflows cannot be directly measured. Because of these difficulties, estimation of recharge under large flow conditions remains uncertain.

To estimate recharge from the observed data, two approaches were taken. First, only baseflow records were utilized with equation (2.1) to relate the aquifer recharge rate to the flow at Lost Creek. Second, to examine the influence of direct runoff, the total storm runoff was calculated for a number of events at both stations, and the flow magnitudes were compared. Equation 2.1 was applied to eight baseflow records (Figure 2.14). The flow at Lost Creek Boulevard was plotted against the difference between the flows at Lost Creek and Loop 360 for each record. This figure indicates that the recharge at Loop 360 increases with the flow rate at Lost Creek.

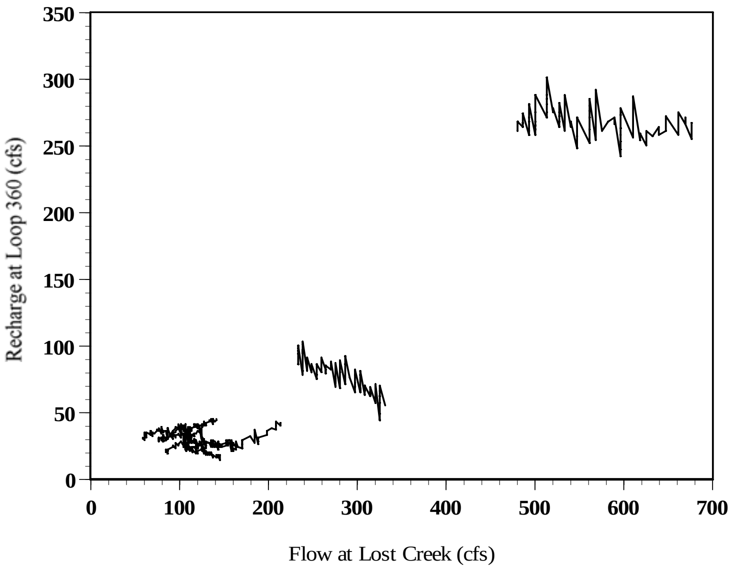


Figure 2.14 Eight Aquifer Recharge Records for Barton Creek at Loop 360

To carry through the analysis for the entire period of record, all baseflow time periods were first identified. The average of all recharge rates was assigned for each Lost Creek flow range [small increments were used for low discharges and larger increments for higher flows]. The results are shown in Figure 2.15. When the flow at Lost Creek Boulevard is less than 20 to 30 cfs, all of the flow is lost to recharge. At flow rates of 30 to 130 cfs, the recharge rate remains approximately constant at about 30 cfs. For flows greater than 130 cfs at Lost Creek, the recharge rate appears to increase with increasing channel discharge. The recharge model is formulated as follows:

$$\begin{aligned} Q_{\text{Recharge}} &= Q_{\text{Lost Creek}} \text{ for } Q_{\text{Lost Creek}} < 30 \text{ cfs} \\ Q_{\text{Recharge}} &= 30\text{cfs for } 30\text{cfs} < Q_{\text{Lost Creek}} < 130 \text{ cfs} \qquad (2.2) \\ Q_{\text{Recharge}} &= 0.23 \times Q_{\text{Lost Creek}} \text{ for } Q_{\text{Lost Creek}} > 130 \text{ cfs} \end{aligned}$$

The equation for the best fit line through the points with flow greater than 130 cfs, is $Q_{\text{recharge}} = 0.23\ Q_{\text{Lost Creek}}$ and is shown in Figure 2.15.

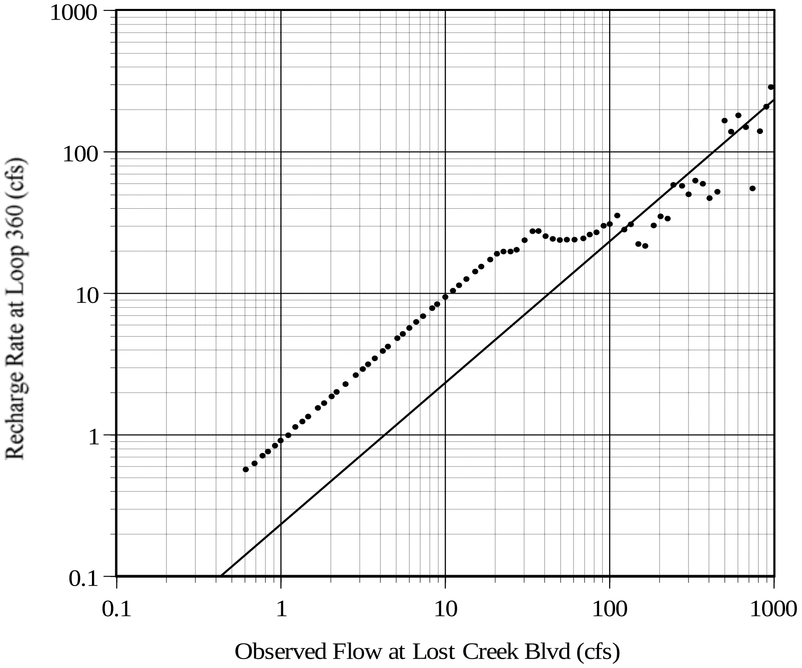


Figure 2.15 Edwards Aquifer Recharge Rate at Loop 360 as a Function of Flow at Lost Creek

A second way to look at the question of recharge is to compare total flow volumes at Lost Creek Boulevard and at Loop 360 (Figure 2.16). For each storm event, the total flow volume (direct runoff plus baseflow) was calculated. The diagonal line represents equal storm volumes at the two gauges. For smaller volumes (i.e., less than 10 million ft^3), flow losses are significant and volumes at Loop 360 are less than those at Lost Creek Boulevard. For large storms, volumes are larger at Loop 360 than at Lost Creek Boulevard This is due to the larger drainage area of the Loop 360 site and relatively small recharge volume compared to storm flow for larger events.

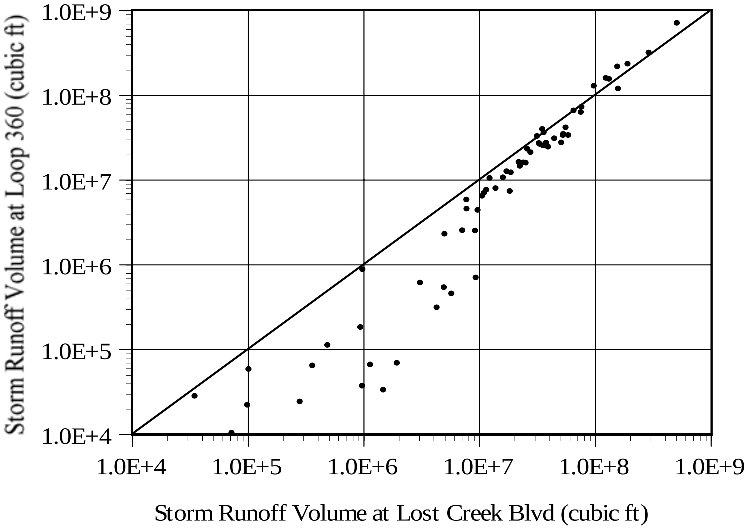


Figure 2.16 Comparison of Storm Runoff Volumes at Lost Creek Blvd. and Loop 360

2.9 Barton Creek Water Quality

General information regarding the quality of Barton Creek water is presented in Table 2.6, which contains mean values and standard deviations for each constituent for all samples, for samples from either baseflow or direct runoff conditions in Barton Creek, and for samples from each monitoring station. For some constituents, particularly metals, many samples had concentrations that were below detection limits. The table was left blank when there were an insufficient number of reliable samples available to calculate the summary statistics.

Table 2.6 Barton Creek Water Quality Summary Statistics

Constituent	Baseflow Conditions						Storm Flow Conditions					
	Hwy 71		Lost Creek		Loop 360		Hwy 71		Lost Creek		Loop 360	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Flow (cfs)	53	132	101	194	89	90	1735	2805	1735	2790	2410	3322
TSS	3	4	4	3	5	5	203	309	225	321	563	637
TDS	254	26	409	266	253	30	216	63	307	142	189	62
BOD5	0.43	0.28	0.48	0.34	0.45	0.34	2.76	3.37	3.23	4.02	3.76	3.10
TOC	2.16	1.71	1.85	0.34	2.18	1.54	10.01	11.35	10.88	11.40	21.18	27.70
FCOL(x1000)	0.09	0.29	0.07	0.08	0.03	0.03	9.18	14.76	7.67	8.77	20.53	21.42
FSTR(x1000)	0.63	1.41	0.15	0.20	0.10	0.15	21.85	32.42	17.63	22.23	27.76	26.59
TP	0.02	0.03	0.04	0.10	0.01	0.00	0.07	0.08	0.09	0.13	0.15	0.18
NO2+NO3	0.08	0.06	0.15	0.12	0.15	0.13	0.19	0.22	0.22	0.16	0.32	0.23
NH3	0.02	0.02	0.02	0.02	0.02	0.02	0.04	0.05	0.05	0.04	0.06	0.08
TKN	0.25	0.17	0.24	0.08	0.26	0.14	0.60	0.59	0.54	0.49	1.43	1.72
Dis. CU (ug/L)							0.86	0.69	1.00	0.00	2.35	3.43
Dis. FE (ug/L)	6.71	8.62	4.64	2.42	5.50	9.34	19.58	20.82	12.33	9.63	23.33	25.23
Dis. PB (ug/L)							2.17	1.60	1.00	0.00	2.12	2.43
Dis. ZN (ug/L)	3.71	1.42	5.64	7.47	3.69	1.93	9.45	15.35	12.11	17.47	9.32	11.21
Tot. PB (ug/L)	3.74	10.27	1.23	0.83	1.14	0.38	11.15	24.65	5.58	6.22	6.88	7.14

All units mg/L except as noted

Total suspended solids (TSS) is the most widely considered indicator of stormwater quality. Table 2.6 shows a great difference in the concentration of TSS between baseflow and storm flow conditions. Under baseflow conditions, the average concentrations are very uniform for the three monitoring stations, ranging from 3 to 5 mg/L. On the other hand, storm flow average concentrations are two orders of magnitude larger, and show an increase in both the average value and variability going downstream. As will be discussed in Chapter 5, much of the storm TSS load is derived from channel erosion, so this behavior may not represent the impacts of land use changes in the lower portions of the watershed.

Most other constituent concentrations show an increase under storm flow conditions when compared with baseflow conditions. Biological oxygen demand (BOD_5) and total organic carbon (TOC) average concentrations are nearly an order of magnitude larger under storm flow conditions, as is total nitrogen (TN). The average TOC concentration at Loop 360 is double that at Highway 71 and Lost Creek Boulevard. Fecal coliform and streptoccoci average counts are about two order of magnitude larger for storm flow conditions. An exception is the concentration of total dissolved solids (TDS), which is higher for all three stations under baseflow conditions.

2.10 Summary

The Barton Creek watershed is a component of the Barton Springs contributing zone, which recharges the Edwards aquifer. The 120-square-mile watershed lies on the Glen Rose Limestone over its western portion, and on the outcrop of the Edwards Limestone over the lower portion of the basin. Although the watershed consists largely of undeveloped land used primarily for ranching, the lower portion has numerous residential and commercial developments.

Rainfall in the Austin area averages approximately 32.5 inches per year. About 50 percent of the rainfall events have volumes less than 0.25 inches. Events of magnitude greater than 1 inch contribute half of the yearly rainfall volume even though they represent less than 15 percent of the total number of events per year. More than 70 percent of the rainfall events over the Barton Creek watershed generate little or no runoff in Barton Creek. Total yearly potential evaporation is in excess of 70 inches, which is more than twice the average annual rainfall. Water balance studies suggest that more than 85 percent of the annual rainfall returns to the atmosphere through evapotranspiration, while less than 9 percent drains to the Colorado River after flowing over the recharge zone.

Flows in Barton Creek have been separated into baseflow and direct runoff volumes. Upstream of the recharge zone, more than three-quarters of the flow volume is baseflow. This fraction decreases over the recharge zone as flows contribute to aquifer recharge. When the flow at Lost Creek Boulevard is less than 20 to 30 cfs, all of the flow is lost to recharge. The recharge rate remains constant at about 30 cfs for channel discharges ranging from 30 to 130 cfs. For channel flows at Lost Creek in excess of 130 cfs, the recharge rate is about 23 percent of the Lost Creek Boulevard discharge. All of these estimates include only the recharge occurring between Lost Creek Boulevard and Loop 360.

Available water quality data for three stations along Barton Creek were analyzed. Current water quality during baseflow conditions is very good; however, mean concentrations for most of the constituents are significantly higher during storm flow conditions. Water quality concentrations in the creek during periods of storm flow tend to increase in the downstream direction as a result of channel processes (erosion and scour) and lower water quality of direct runoff to the creek.

3.0 MODELS FOR THE BARTON CREEK WATERSHED STUDY

Selection of a mathematical simulation model for the Barton Creek Watershed Study requires consideration of the objectives of the study, the characteristics of the watershed, the capabilities and availability of existing simulation models, and other potential applications of the model by the City of Austin. Models for simulation of stormwater quantity and quality are extremely varied in terms of complexity, data requirements, personnel requirements, and computational requirements. At one extreme are the simple models with pollutant loads calculated from the storm runoff volume and the event mean concentration (EMC). Such models are useful for calculation of annual loads, when runoff coefficients (ratio of total runoff volume to rainfall volume for a watershed) and EMCs are estimated from monitoring of an appropriate number of storm runoff events. At the other extreme are the complex and data-intensive computer simulation models that attempt to simulate the buildup and washoff of pollutants from the watershed and their transport through the drainage system to the point of interest. While the complexity of such models provides a significant obstacle to their application, they provide the flexibility to address significant issues in urban stormwater management.

3.1 Model Selection for the Barton Creek Watershed Study

The objectives of the Barton Creek Watershed Study include development of a model to predict the specific impacts of varying levels and types of development in the Barton Creek watershed. This objective requires that the model selected for application in this study not only be capable of predicting existing conditions over the watershed, but that it also is capable of ‘a priori’ modification to predict future conditions under various development scenarios. Such an objective provides definite limits on the type of models that may be considered.

While simple models could be appropriate for such applications on small to moderate-sized watersheds, they are not appropriate for the present study. One can find correlation between impervious cover and runoff coefficient for small catchments, and the EMC is not very sensitive to land use. However, for watersheds such as Barton Creek, an important component in the prediction of instream concentrations is the routing of flows and water quality through the various drainage systems. Such routing capabilities are not present within simple models.

Statistical models are capable of good performance in prediction of both water quantity and quality for gauged and monitored watersheds. However, the quality of these predictions depends on the amount and quality of the monitoring data. Furthermore, it is difficult to predict how coefficients in statistical models will vary with changing watershed conditions. Thus, it is difficult to apply such models to an analysis of the impacts of land use changes on quantity and quality of watershed stormwater runoff.

An ideal model for application in the present study would include the capabilities for simulation of both stormwater quantity and quality on both a single- and multiple-storm event basis using physically based parameters that could be estimated from watershed and hydrologic conditions. There are a few models available in the public domain that appear to have these capabilities. The models considered for application in this investigation include DR3M-QUAL, HSPF, STORM, and SWMM.

The Distributed Routing Rainfall Runoff Model that includes quality simulation (DR3M-QUAL) was developed by the USGS (Alley and Smith, 1982). This model uses the kinematic wave method for runoff generation and subsequent routing. Water quality is simulated using buildup and washoff functions, with settling of solids in storage units dependent on a particle size distribution. At the time this study began, this model was not available for application on a microcomputer.

The Hydrological Simulation Program - FORTRAN (HSPF) was developed by EPA (Johanson et al. 1984) from the Stanford Watershed Model. HPSF is the only comprehensive model of watershed hydrology and water quality that allows an integrated analysis of land and soil contaminant processes. Simulation of runoff quality includes simple relationships such as empirical buildup/washoff and constant concentration, and detailed soil process options including leaching, sorption, soil attenuation and soil nutrient transformations. HPSF includes storage and treatment analysis, but does not allow full dynamic flow routing or consideration of flow regulators such as overflow structures, weirs, orifices, etc.

One of the earliest models developed for continuous simulation in urban hydrology was the Storage, Treatment, Overflow, Runoff Model (STORM) developed by the Corps of Engineers Hydrologic Engineering Center (Hydrologic Engineering Center, 1977; Roesner et al. 1974). STORM was developed for analysis of Combined Sewer Overflows (CSO's) and evaluation of the trade-off between treatment and storage as control options. It uses simple runoff coefficient, SCS, and unit hydrograph methods for estimating runoff from rainfall, and does not perform flow routing. Buildup and washoff formulations are used for pre-specified pollutants. STORM is not available for application on a microcomputer.

EPA’s Stormwater Management Model (SWMM) is the most comprehensive model available in the public domain for simulation of stormwater quantity and quality. Version 4 (Huber and Dickinson, 1988; Roesner et al. 1988) of the model performs both continuous and single-event simulations, and can model backwater, surcharging, pressure flow, and a variety of regulator devices including orifices, weirs, pumps, and storage. Options for water quality simulation include buildup and washoff formulations, rating curves and regression techniques. Treatment devices may be simulated using removal functions and sedimentation theory. Because of its versatility and potential for use in other applications, SWMM was selected for application in the Barton Creek Watershed Study. Features of the model are described in more detail in the next section.

3.2 The Stormwater Management Model (SWMM)

The Stormwater Management Model was developed for simulating flow and water quality characteristics of stormwater runoff from urban watersheds. The model has a great deal of flexibility, which in turn means that it is not straightforward to apply. While there is an extensive users’ guide to the model, and many applications of its use are described in the literature, this section describes the characteristics that are of direct significance for application to the Barton Creek watershed. First, a brief overview of the model is presented. The flow routing components for water quantity simulation are then described. Finally, the formulation used for describing constituent buildup and washoff are reviewed.

The Stormwater Management Model was originally developed in 1969-71 under the sponsorship of the U.S. Environmental Protection Agency by a consortium of contractors including Metcalf and Eddy, Inc., the University of Florida, and Water Resources Engineers, Inc. The original three contractors and numerous other entities have continued to modify and improve the model since its release, including changes for the present study. Dr. Wayne Huber, Professor of Civil Engineering at Oregon State University (formerly at the University of Florida) and a member of the Barton Creek Modeling Study project team, has been the informal caretaker of the model since its initial development. Mr. Robert Dickinson, presently with XP Software, Tampa, Florida, studied under Dr. Huber at the University of Florida and is co-author of the present version of the SWMM User's Manual. Mr. Dickinson is also a member of the Barton Creek Modeling Study project team.

The basic model used for the present study is EPA SWMM Version 4.0. Numerous modifications to SWMM have been made for the present study by Dickinson, City of Austin staff and other entities. The character of these modifications is minor, and the overall performance of the model has not been changed. Dr. Huber has compiled recent model enhancements and corrections in the EPA-sanctioned version of SWMM, Version 4.31. Version 4.31 includes several code modifications developed for the Barton Creek Modeling Study.

SWMM is a deterministic, lumped watershed model in which most of the physical water quantity and quality processes from rainfall to receiving water delivery can be simulated. SWMM does not model water quality or flow within the receiving water component, although linkages have been developed with EPA WASP and DYNHYD. The model is constructed in the form of "blocks," each of which contains source code for simulation of a major component of the hydrologic/water quality system.

For the purposes of the Barton Creek Study, the following blocks were utilized:

- Runoff Block - The Runoff Block generates surface and subsurface hydrographs based upon user-defined rainfall hyetographs, antecedent subsurface moisture conditions and soil characteristics, land use characteristics, drainage area and topography. The Runoff Block also conducts accounting for the buildup/washoff of water quality constituents and surface hydrograph/pollutograph routing.
- Transport Block - The Transport Block routes flows and water quality constituents through the drainage system and serves as the location for input of watershed network configurations and point source flow rate and associated constituent concentration inflow locations.
- Statistics Block - The Statistics Block performs user-requested statistical analyses on model output.
- Rain Block - The Rain Block develops binary rainfall interface files used by SWMM from a wide variety of standard or user-defined rainfall formats, including the National Weather Service format. The Rain Block also performs standard statistical analyses on period-of-record rainfall information.

SWMM may be run for any time frame. There are no intrinsic limitations in the model regulating the duration of a "continuous" simulation except the time required by the computer to perform what can be a monumental number of calculations. Options to vary time steps during wet and dry periods are included in the model and can be helpful in minimizing computer time without significant loss of information in the model output. For less lengthy model runs, time steps may be as short as the user requires.

3.3 Simulation of Flow Quantity

SWMM uses common hydrological formulations for conducting flow modeling including surface water runoff and routing, soil-water interactions, and evapotranspiration. These water balance components are outlined below.

3.3.1 Surface Flow Routing

Simulation of flow quantity processes in SWMM begins in the Runoff Block with the introduction of rainfall input. The Runoff Block represents individual user-defined subcatchments as idealized rectangular surfaces. With the application of rainfall to a subcatchment, the model begins a time step-by-time step accounting of water movement and loss as it is subjected to runoff, infiltration, surface storage, evaporation, transpiration, subsurface storage, deep percolation and/or return to the drainageway as baseflow through seepage from channel banks.

The model can simulate three levels of flow routing in the Runoff Block: two for surface flows representing overland and channelized water movement and one for subsurface moisture accounting. Both surface and subsurface routing are performed utilizing a nonlinear reservoirs approach.

Runoff hydrographs are generated for each user-delineated subarea (subcatchment) in the watershed model. Each subarea is assigned a specific rainfall record along with values of the hydrologic parameters required to simulate the runoff and infiltration processes. Subcatchment surfaces are defined by length, width, slope, surface roughness, impervious area, and depression storage.

The first phase of flow routing when runoff is occuring is represented as uniform, overland sheet flow over the idealized subcatchment area. Equations defining conservation of momentum and energy are solved simultaneously using a simple finite difference scheme to determine the depth of overland flow for each time step. The two basic equations are:

1. Continuity Equation -

$$\frac{dV}{dt} = A \times RE - Q = A\frac{dD}{dt} \qquad (3.1)$$

where V = volume of sheet flow on the idealized subcatchment, cubic ft, A = surface area of the subarea, square ft, RE = rainfall excess, ft/sec, D = depth of overland flow, ft, and Q = overland flow rate, cubic ft/sec.

2. Momentum Equation -

$$Q = W\frac{1.49}{n}\left(D - D_p\right)^{5/3} S^{1/2} \qquad (3.2)$$

where Q = overland flow rate, cfs, W = width of the idealized subcatchment, ft, D = water depth, ft, D_p = depression storage depth, ft, S = slope of the subcatchment, ft/ft, and n = Manning's friction coefficient.

[Note that equation (2) is simply Manning's equation where the term W $D^{5/3}$ from the above equation represents the term A $R^{2/3}$ from the traditional formulation of Manning's equation.] The above two equations are combined to derive a nonlinear differential equation of the form:

$$\frac{dD}{dt} = RE - \frac{W}{A}\frac{1.49}{n}\left(D - D_p\right)^{5/3} S^{1/2} \qquad (3.3)$$

The only unknown at this point is depth. This nonlinear reservoir equation is solved for depth at each time step using a simple finite difference scheme. In the SWMM model, a parameter WCON is introduced which combines the width, slope, and roughness parameters. Thus, equivalent calibration changes in the overland flow routing may be caused by appropriate alteration of any of the three parameters.

To represent channelized flow in the Runoff Block, SWMM performs a second routing phase with idealized trapezoidal channels instead of an idealized overland flow surface. The routing algorithm is essentially identical to the regime just described for overland flow except that the drainageway configuration is that of a channel or pipe. Again, the model user must describe the relevant hydrologic parameter values, including channel cross-sectional configuration, length, slope, and roughness.

3.3.2 Infiltration

When rain falls on a watershed, part of it is intercepted while wetting plant foliage and surface structures, while the remainder reaches the ground surface. The rainfall that reaches the ground surface either infiltrates to the subsurface, is ponded as detention storage, or runs off the surface. The SWMM model includes parameters for representation of infiltration, detention storage, and runoff of excess rainfall.

When water first comes into contact with soil, it is pulled into the subsurface in much the same way as a paper towel absorbs water. The capacity of the soil profile to absorb rainfall is high at first, but decreases through time as more water enters the profile. Eventually, if rainfall continues at a high enough rate, the infiltration capacity is exceeded, and excess rainfall becomes surface storage or runoff. There are two options in the SWMM model for representing the infiltration of rainfall: the Horton infiltration model and the Green-Ampt infiltration model. The Green and Ampt (1911) model was chosen for this work because its parameters are physically based. Mein and Larson (1973) extended the Green-Ampt model to include estimation of the time at which the infiltration capacity is exceeded, and surface runoff commences. Before this time, all rainfall is assumed to infiltrate.

The Green and Ampt (1911) infiltration model assumes that the initial or antecedent water content, q_a, is uniform; that there is an abrupt wetting front; and that the water content behind the wetting front is uniform. The variation of soil water content with depth during an infiltration event is shown in Figure 3.1. Near the ground surface, the soil is wetted to natural saturation. Natural saturation is less than complete saturation because some air is trapped within the pore space, and it represents the maximum saturation attainable under normal field conditions. The water content is constant at natural saturation, q_{ns}, from the ground surface down to the wetting front. At the wetting front, which is located at a depth L_f, the water content changes abruptly by an amount Dq from q_{ns} to q_a at depth. The water content in excess of q_a is associated with the infiltration event.

The soil with water content q_a below the wetting zone has a larger capillary suction than the soil above it, so it pulls the wetting front downward. The infiltration rate is determined by the pull of gravity and the wetting front suction, and by the permeability

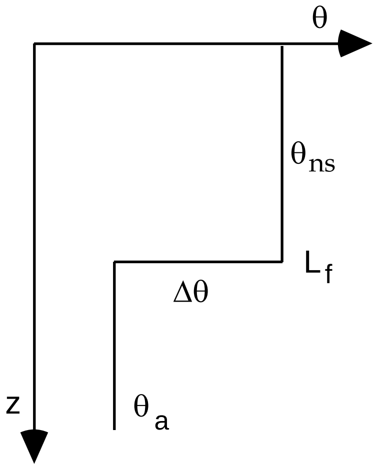


Figure 3.1 Assumed Profile for the Green and Ampt Infiltration Model

of the soil. Application of Darcy's law for the flow of water through soil says that the infiltration capacity at any time is given by

$$f_p = K_{ns}\left(1 + \frac{S_u}{L_f}\right) \tag{3.4}$$

where f_p = infiltration capacity (L/T), K_{ns} = hydraulic conductivity of soil at natural saturation (L/T), S_u = average capillary suction head at the wetting front (L), and L_f = depth of the wetting front (L). The infiltration capacity is the maximum potential rate at which the soil profile can absorb rainfall. During the initial period of a rainfall event when L_f is small, the potential infiltration rate is large, and all of the rainfall will infiltrate. As rainfall continues, the infiltration capacity decreases, and a point is reached at which the soil profile can no longer absorb the total rainfall, and surface runoff commences.

Figure 3.1 shows that the cumulative infiltration, F, is equal to Dq L_f, so that equation (3.4) may be written

$$f_p = K_{ns}\left(1 + \frac{S_u\,\Delta\theta}{F}\right) \tag{3.5}$$

Equation (3.5) gives the potential infiltration rate as a function of the cumulative infiltration, and as such, the potential infiltration rate is computationally independent of the time-variable rainfall rate. Mein and Larson (1973) used equation (3.5) to estimate the cumulative infiltration required to cause surface saturation and runoff, F_s. At the instant when runoff commences, the infiltration capacity must equal the rainfall precipitation rate, P: $f_p = P$. Using this in equation (3.5) and solving for $F = F_s$ gives

$$F_s = \frac{S_u \, \Delta\theta}{\frac{P}{K_{ns}} - 1} \tag{3.6}$$

As long as $F < F_s$, or if $P < K_{ns}$, then all of the rainfall infiltrates. For $F > F_s$, the infiltration rate is $f = f_p$, as given by equation (3.5), and the rainfall excess becomes detention storage or surface runoff. Equations (3.5) and (3.6) make up the Green and Ampt infiltration model.

3.3.3 Evapotranspiration

Evapotranspiration includes both the natural evaporative losses of water to the atmosphere and the losses due to transpiration by plants. Evapotranspiration is simulated in SWMM through user specification of potential evaporation rates in units of inches/month. Recent model enhancements allow for input of period-of-record observed monthly evaporation instead of mean monthly evaporation. The specified evaporation rate is applied uniformly throughout the month and is applied at the same rate for open water bodies and for evapotranspiration. The total evaporative capacity is met first from surface depression storage water loss. Next, water is removed from the shallow subsurface above the water table. Finally, water is removed from the saturated zone above the root plant depth. If depression storage is depleted, the shallow subsurface zone water content reaches wilting point, and the water table falls below the plant root depth, then the potential evaporation rate cannot be satisfied from the hydrologic system. Potential evapotranspiration rates are based on pan evaporation data.

3.3.4 Subsurface Moisture Accounting

Most of the Barton Creek Watershed lies in the contributing zone on the Glen Rose Limestone. The Glen Rose is a low-permeability formation and does not contain a well-defined aquifer system, which recharges surface flows in the creek. Nevertheless, there is a well-defined baseflow recession curve that follows major rainfall events. For example, Figure 3.2 shows the recession curve recorded during May 1980 at the Highway 71 gaging station. Over a 40-day period, the flow decreases exponentially through time from a rate of more than 300 cfs to about 5 cfs. Similarly, Figure 3.3 shows the recession curves measured both at the Highway 71 and Lost Creek gaging stations during June 1989. The curves at these two stations are similar and extend for a period in excess of 30 days. In hydrologic analysis, such recharge and recession behavior is usually recognized as baseflow from subsurface storage in an adjacent aquifer. It appears that water held in alluvium contained in cut-and-fill deposits on the Glen Rose and along the drainage channels of the watershed behaves in a similar hydrologic fashion, releasing water as baseflow from an aquifer. This observation plays an important role in formulating the SWMM model for application to the watershed.

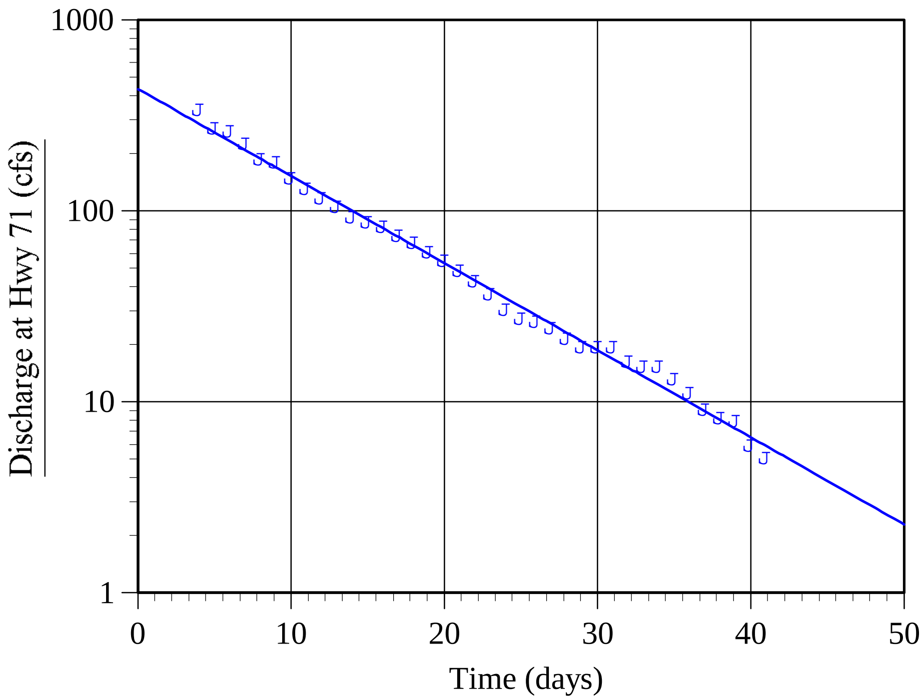


Figure 3.2 Baseflow Recession Curve for Barton Creek Recorded in May 1980 at the Highway 71 Gaging Station

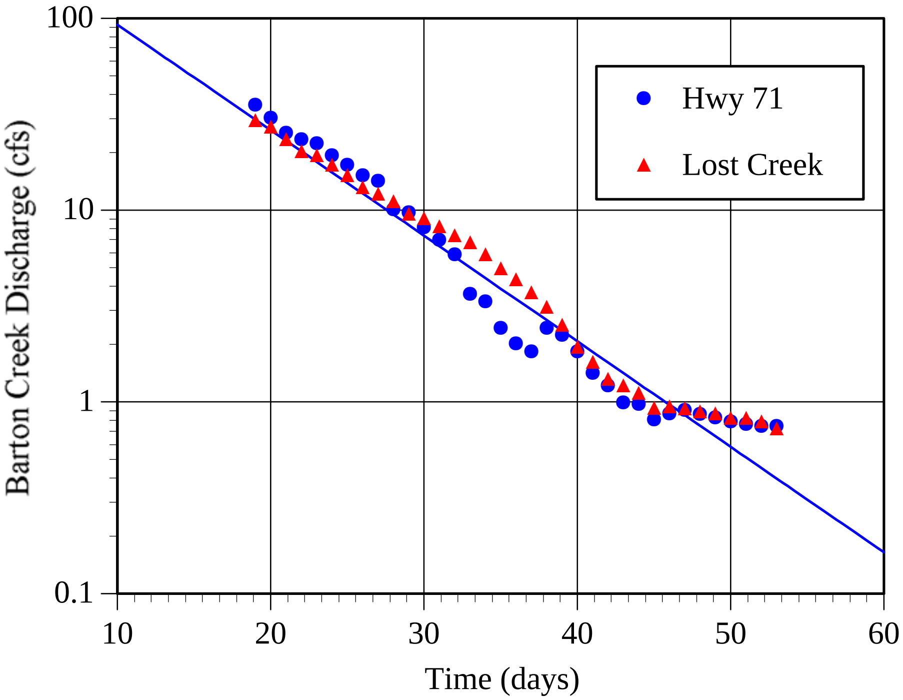


Figure 3.3 Baseflow Recession Curves for Barton Creek Recorded in June 1989 at the Highway 71 and Lost Creek Gaging Stations

The following paragraphs describe the subsurface water flow characteristics of the SWMM model. As described in Section 3.3.2, the water balance at the ground surface is modeled using the Green and Ampt infiltration equations. Rainfall is partitioned into that which infiltrates, that which is held in surface storage, and the remainder, which forms stormwater runoff.

As outlined in Figure 3.4, the subsurface is represented by three zones. The upper region is the vadose zone or unsaturated zone, which receives infiltration from surface rainfall. Water is lost from the vadose zone through evapotranspiration of soil water back to the atmosphere, and through percolation of soil water to the water table and the lower saturated zone. The lower region is the saturated zone or the "aquifer." It receives recharge from percolation of vadose zone soil water. Water is lost from the saturated zone through evapotranspiration, baseflow to the surface water drainage system, and through deep percolation. Deep percolation is an unquantified loss from the flow system, and water lost to deep percolation is considered outside the scope of the model. Deep percolation and the deep region were not considered in the simulation of the Barton Creek watershed above the recharge zone; that is, deep percolation losses were set to zero. The SWMM model performs a water balance computation for the upper and lower zones shown in Figure 3.4.

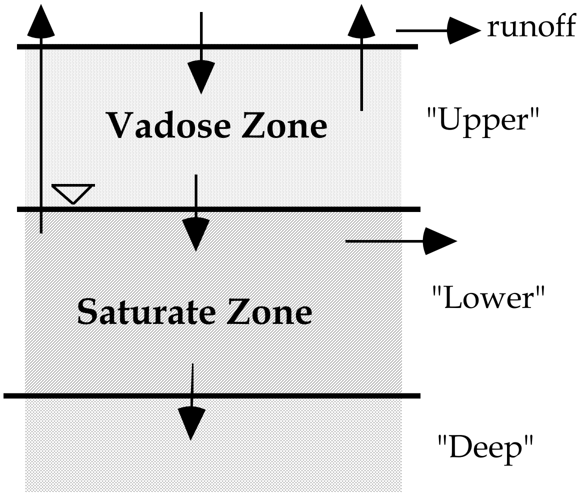


Figure 3.4 Subsurface representation of the SWMM model

For both the vadose zone and saturated zone, the calculation of evapotranspiration is physically based. A monthly maximum evaporation rate is specified in the SWMM input file, as is the fraction of potential evapotranspiration apportioned to the vadose zone and saturated zone. Evaporation is assumed to occur first from surface detention storage. If there is sufficient water ponded on the ground surface to meet the evapotranspiration demand for the simulation time step, then only surface storage is depleted and no water is evapotranspired from the subsurface. If there is not sufficient water in detention storage, then water is removed next from the vadose zone as limited by the fraction apportioned to the zone. Further, if the vadose zone water content drops below the wilting point for the soil-plant complex or if infiltration is occurring, then no evapotranspiration occurs from the upper zone. Any remaining evapotranspiration demand is exerted on the saturated zone, subject to limitations by the fraction apportioned to it in the input file, and by the fraction of the depth of the root complex that remains below the water table. If the water table drops below the level of the plant root complex, then no transpiration occurs from the aquifer.

The calculation of the percolation rate from the vadose zone to the saturated zone is based on Darcy's law for subsurface flow of soil water. Variation in soil hydraulic conductivity with volumetric water content is assumed to follow a decreasing exponential relationship with water content decreasing below the soil's natural saturation or porosity. SWMM represents several physical parameters with single calibration parameters. This grouping limits the identification of individual physical variables that might control transport processes, and the calibration variables may not be easily identified with those commonly used in other soil characteristic models.

The parameter HCO appears as a calibration parameter that is not easily identified with other hydraulic conductivity models which find common use. The hydraulic gradient includes gravitational and capillary pressure components. The capillary pressure component is determined from the water content of the vadose zone, field capacity which is assumed at the water table, the distance between the center of the vadose zone and the water table, and the parameter PCO, which is the average slope of the capillary pressure curve between the water content of the vadose zone and field capacity. PCO is actually a variable, and a constant effective value must be estimated for a simulation. If one takes PCO = 0, then a kinematic model for percolation results, and such a model representation has been found to work satisfactorily in other water-balance applications (Charbeneau and Asgian,1991).
The remaining component of subsurface flow is the baseflow from the saturated zone to the surface drainage channel. SWMM uses a fairly general formulation of the component of the model with a number of parameters to allow the user to represent many different controlling processes. Figure 3.5 shows a schematic representation of the model used by SWMM. The following parameters are identified in this figure: GRELEV = ground surface elevation above the datum (L), STG = saturated zone stage above the datum (L), TW = channel tailwater stage above the datum (L), BC = channel bottom elevation above the datum (L), BELEV = base elevation datum (L), and GWFLW = groundwater baseflow rate (per catchment area). The general model used by SWMM is

$$\mathrm{GWFLW} = a_1 \times (\mathrm{STG} - \mathrm{BC})^{b_1} - a_2 \times (\mathrm{TW} - \mathrm{BC})^{b_2} + a_3 \times \mathrm{STG} \times \mathrm{TW} \quad (3.7)$$

In equation (3.7), a_1, b_1, a_2, b_2, and a_3 are all fitting parameters. For most applications, many of these parameters are set equal to zero, based on a physical interpretation of the baseflow process. Given the recession curves such as those shown in Figures 3.2 and 3.3, it may be appropriate to use the most common "linear reservoir" model for baseflow generation, which is achieved by setting $b_1 = 1$, calibrating against a_1, and setting the other three parameters equal to zero in equation (3.7).

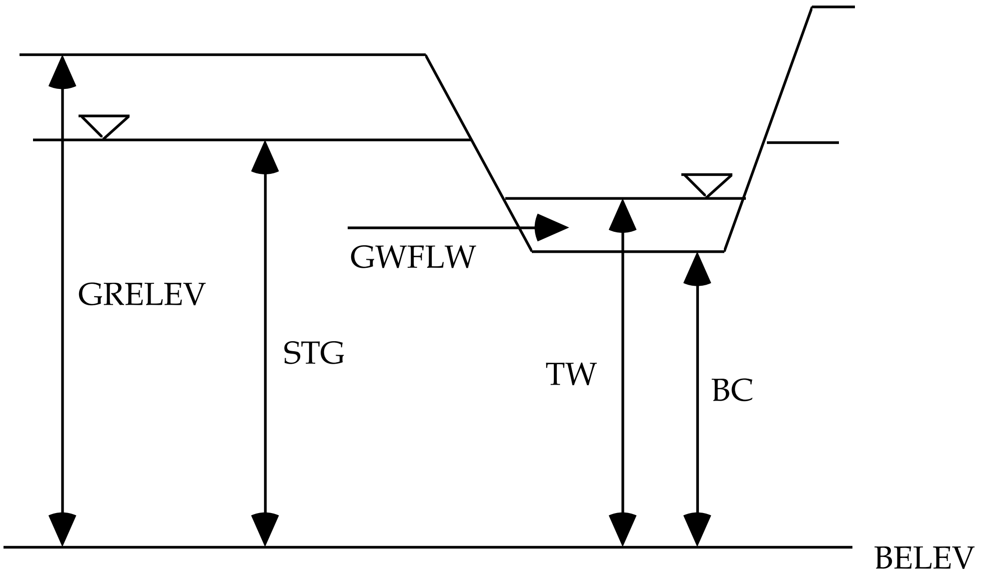


Figure 3.5 Baseflow variables in SWMM

3.3.5 Flow Routing in the Transport Block

The Transport Block was originally developed primarily to perform flow quantity and quality routing through a sewer system. It is used in this application to simulate transport processes in the Barton Creek channel and tributary channels and pipes. As such, this block coordinates all aspects of flow routing through the downstream conveyance network after hydrograph and pollutographs have been developed in the Runoff Block. The Transport Block includes simulation of flow movement, constituent movement, constituent decay, dry weather flows, sewer infiltration, and sediment erosion and deposition in channels. Specification of the network configuration also occurs in the Transport Block. Network elements include pipe or channel conduits and nonconduit flow accounting and combining elements such as manholes, lift stations, overflow structures, and other real system components. Runoff Block hydrographs and pollutographs are input to the system at nonconduit flow and quality accounting locations. Network elements fit together in a manner similar to links and nodes. Specification of network element sequencing is performed in the Transport Block and flow routing proceeds downstream though all elements during each time increment. The Transport Block performs accounting and provides summary tables for flow quantities and constituent concentrations and loads.

Flow routing in the Transport Block utilizes a kinematic wave approach in which disturbances may propagate only in the downstream direction. As a consequence, backwater effects are not modeled outside of individual conduits and downstream conditions are assumed not to affect upstream computations. Gradients in the Barton Creek watershed are steep enough that this assumption does not generally affect accuracy of results. Flow divider elements are available to model flows that branch in the downstream direction. Surcharging is modeled by storing flows exceeding the capacity of the channel or pipe conduit at the computational location of the conduit.

Water quality routing allows for tracking of any four constituents in a single model run. Constituents can be introduced to the system by four means:

1. Storm pollutographs generated by other model blocks, including the Runoff, Storage Treatment, Extran, and Transport Block itself.
2. User-defined pollutographs entered on the R1 cards.
3. Resuspension of residual bottom sediment in pipes.
4. Constant dry weather flow pollutographs as generated by Subroutine

Pollutants may be subjected to first-order decay during the routing process via user-specified decay coefficients. No interaction between constituents, such as occurs during nitrification, can be represented.

3.4 Simulation of Water Quality

The quality of stormwater runoff is variable from event to event, depending on the intensity and duration of rainfall, the number of antecedent dry days before the event, land use practices, and many other physical, chemical and biological factors. Because of this great variability and uncertainty, statistical models are often applied to estimate concentrations and loads on an event and an annual basis. Such models generally perform poorly in prediction of event loads, but may prove satisfactory for prediction of annual loads. One difficulty in the use and application of statistical models is that they are harder to use to study the effects of control and catchment modifications.

Uncertainties in the prediction of nonpoint source constituent washoff reduces with the accumulation of local water quality sampling data. With sufficient local data, the equations in SWMM can usually be manipulated to reproduce measured concentrations and loads. When no local data is available, nonpoint source water quality predictions by SWMM, or any other model, are generally of limited use.

The modeling of nonpoint source constituent accumulation, washoff, and routing is initiated in SWMM's Runoff Block. The model calculates pollutographs (time step-by- time step records of constituent concentration) in each subarea, then tracks them, adding and combining throughout the basin. The simulation of first-order constituent decay is available in the Transport Block; however, in the present context, relatively short travel times in the subject creeks and the simplicity of the available transport and fate processes in SWMM limit the usefulness of such an exercise. Alteration of the pollutograph due to water quality treatment practices can be simulated in the Storage/Treatment Block.

Application of SWMM for prediction of stormwater runoff and quality requires the capability of estimating concentrations and loads for individual events. The model must be calibrated to measured water quality data in order to estimate appropriate ranges for the various water quality parameters. The SWMM model contains three basic approaches for water quality simulation: the use of event mean concentrations (EMCs), the use of a rating curve or power law model that relates the constituent washoff rate at any given time to the water flow rate, and the use of buildup and washoff relations.

3.4.1 Use of Event Mean Concentrations (EMCs)

Use of event mean concentrations (EMCs) means that the constituent concentration is constant throughout the simulation, and calculated loads depend only on how well the EMCs are estimated, and how well the storm flows are calculated. Use of EMCs is certainly adequate if the interest in the modeling effort is to evaluate the impacts of stormwater runoff on receiving waters. Receiving water bodies respond relatively slowly to storm inflows, compared to the rate at which constituent concentrations change during a runoff event. Thus, it is the total load, or the EMC, which is the important parameter. For many watersheds, the model may be calibrated so that stormwater hydrographs are adequately represented. Then, if the EMC for a single event is used in the model, the total storm load will be adequately simulated, regardless of how the actual constituent concentration changes during the runoff event. If multiple storm events are to be simulated, then the use of EMCs is more difficult. Field data shows clearly that the EMC varies from one storm to another, and it also is a difficult parameter to predict. Thus, for long-term simulations, the yearly average EMC may be an appropriate parameter to use in the SWMM simulations.

3.4.2 Use of Rating Curves

Use of a rating curve or power law model is the second option available in the SWMM model. According to this model, the washoff rate, POFF (mg/sec), depends only on the runoff rate of the stormwater discharge, WFLOW (cfs). Specifically, the model takes the form

$$\mathrm{POFF} = \mathrm{RCOEF} \times \mathrm{WFLOW}^{\mathrm{WASHPO}} \tag{3.8}$$

where POFF = constituent load washed off at time t (mg/sec), RCOEF = coefficient that includes correct units conversion, WFLOW = catchment runoff rate (cfs) = discharge Q, and WASHPO = exponent. Using equation (3.8), the relationship between the stormwater constituent concentration and the stormwater discharge is

$$\mathrm{C} = \mathrm{RCOEF} \times \mathrm{Q}^{\mathrm{WASHPO}-1} \tag{3.9}$$

where C = constituent concentration (mg/L) and Q = catchment discharge (cfs). The SWMM Users Manual notes that when the rating curve method is applied to sediment transport, the exponent 'WASHPO' is near "2" in magnitude. According to equation (3.9), this implies that the constituent concentration would be proportional to the discharge from the catchment. While this conclusion is consistent with data on sediment transport in rivers and streams, it is not consistent with measurement data from urban stormwater monitoring.

3.4.3 Use of Buildup and Washoff Relations

The third approach for modeling stormwater quality using SWMM is through application of buildup and washoff relations. According to this model, it is assumed that a supply of constituents is built up on the land surface during periods of dry weather. With a subsequent storm, some of this material is then washed off into the drainage system. Buildup may depend on the season, land use, traffic, etc. Washoff may be a function of rainfall intensity, bottom shear stress, and other factors. Conceptually, the use of buildup and washoff relations is the most physically based and appealing approach.

SWMM has three options for predicting buildup of contaminants on the ground surface as a function of time during a dry period: a power-law model, with or without a maximum constituent load limit value; an exponential buildup model; and a model that takes the form of the Michaelis-Menton equations used for enzyme kinetics. Both the exponential buildup model and the Michaelis-Menton model have equation forms with limiting constituent loads as parameters. Choosing an exponent of unity in the power-law model gives a model predicting a linear buildup of contaminants through time. The linear and exponential models probably find most common use.

As an example of the buildup models, the exponential model takes the form

$$\mathrm{PSHED} = \mathrm{QFACT(1)} \times \left(1 - e^{-\mathrm{QFACT(2)} \times t}\right) \tag{3.10}$$

where PSHED = constituent load accumulated on the watershed (lbs), QFACT(1) = maximum constituent load which can accumulate on the watershed (lbs), QFACT(2) = buildup coefficient (d^{-1}), and t = number of dry days (d). Equation (3.10) applies after the entire constituent has been washed off the watershed during a significant storm event. If there is an initial constituent load on the watershed, then the rate of accumulation decreases in proportion to the load present.

The main feature of all of three of the buildup models is that they predict that the constituent load which accumulates on the catchment and is available for washoff increases with the number of dry days that have past since the last storm event. At first glance this appears to be reasonable, although as the discussion in Chapters 4 and 5 will show, it is not consistent with the measured stormwater runoff data.

3.4.4 The Washoff Model

Washoff is represented using a generalized form of an exponential model, where the rate of washoff is proportional to the amount of constituent present and the runoff rate. This model takes the form

$$\frac{d\,\mathrm{PSHED}}{d\,t} = -\,\mathrm{RCOEFX} \times r^{\mathrm{WASHPO}} \times \mathrm{PSHED} \tag{3.11}$$

where PSHED(t) = quantity of constituent available for washoff at time t, RCOEFX = washoff coefficient with units dependent on WASHPO, r(t) = runoff rate (in./hr.), and WASHPO = washoff exponent. Equation (3.11) gives the washoff rate, or the rate at which the constituent load on the watershed decreases through time. The washoff rate is directly proportional to the quantity of constituent available for washoff. Generally, as this amount decreases through time, the washoff rate decreases also. However, use of WASHPO > 1 in equation (3.11) allows for the simulated runoff concentration to increase during the runoff event if the runoff rate increases sufficiently.

It is very difficult to calibrate for the WASHPO parameter. If one assumes that WASHPO = 1, the washoff rate is then calculated from

$$\frac{d\,\mathrm{PSHED}}{d\,t} = -\,\mathrm{RCOEF} \times r \times \mathrm{PSHED} \qquad (3.12)$$

where RCOEF = washoff coefficient with units of inch^{-1}. Equation (3.12) leads to the simple exponential model for stormwater load and concentration, as the following shows. The cumulative runoff up to time t is given by

$$\mathrm{RUNOFF}(t) = \int_0^t r(\tau)\,d\tau \qquad (3.13)$$

Using equation (3.13), equation (3.12) may be integrated to give

$$\mathrm{PSHED}(t) = \mathrm{PSHED}(0) \times e^{-\mathrm{RCOEF} \times \mathrm{RUNOFF}(t)} \qquad (3.14)$$

where PSHED(0) = initial contaminant load on the watershed. Equation (3.14) states that the quantity of constituent available for washoff decreases exponentially with runoff during the event. The runoff event constituent load that has been washed off from the watershed at time t is given by

$$\mathrm{LOAD}(t) = \mathrm{PSHED}(0) - \mathrm{PSHED}(t)$$

The total load from washoff for the storm is given by

$$\mathrm{LOAD} = \mathrm{PSHED}(0) \times \left(1 - e^{-\mathrm{RCOEF} \times \mathrm{TRO}}\right) \tag{3.15}$$

where TRO = total runoff from the storm (inches).

These results may be used to estimate the constituent concentration in stormwater runoff. The watershed stormwater discharge, Q, and runoff rate, r, are related through

$$\mathrm{Q} = \mathrm{AREA} \times \mathrm{r} \tag{3.16}$$

where Q(t) = stormwater discharge at time t from watershed, and AREA = watershed area. The constituent concentration and washoff rate are related through

$$-\frac{\mathrm{d\,PSHED}}{\mathrm{d\,t}} = \mathrm{Q} \times \mathrm{C} = \mathrm{AREA} \times \mathrm{r} \times \mathrm{C}$$

Using this with equations (3.12) and (3.14) gives

$$\mathrm{C(t)} = \frac{\mathrm{RCOEF} \times \mathrm{PSHED}(0)}{\mathrm{AREA}} \times e^{-\mathrm{RCOEF} \times \mathrm{RUNOFF(t)}} \tag{3.17}$$

Equation (3.17) states that the constituent concentration in stormwater runoff decreases exponentially with runoff throughout the storm runoff event. Equation (3.17) may also be written

$$\mathrm{C(t)} = \mathrm{C}(0) \times e^{-\mathrm{RCOEF} \times \mathrm{RUNOFF(t)}} \tag{3.18}$$

where C(0) is the initial stormwater concentration in washoff. The initial stormwater concentration and the initial contaminant load on the watershed are related through

$$\mathrm{PSHED}(0) = \frac{\mathrm{AREA} \times \mathrm{C}(0)}{\mathrm{RCOEF}} \tag{3.19}$$

Application of these relationships to Barton Creek is discussed in Chapter 5.

3.5 Summary

This chapter has provided a brief overview of the SWMM model and the features used for application to the Barton Creek watershed. Only four of the simulation model blocks are utilized: the runoff, transport, statistics, and rain blocks. Future applications that may investigate use of various BMP’s will probably use the storage/treatment block also. This block simulates the effect on flow quantity and quality of capture and residence processes occurring in structural water quality or quantity control devices. The Green and Ampt infiltration model is used, though it is found that the overall performance of the model is not very sensitive to this choice. The subsurface flow system is modeled as a linear reservoir, with flow rate from the saturated groundwater zone to the stream channel being based on the head difference between the aquifer and channel bottom. Constituent buildup and washoff models are described. The WASHPO parameter is set to unity, which simplifies the model and its calibration.

4.0 SWMM MODEL CALIBRATION AND VERIFICATION

Application of models such as SWMM for predicting stormwater quantity and quality is a multi-step process. The first step is to *calibrate* the model against a measured record of flows and water quality data. During this calibration step, the model parameters are adjusted so that the model produces a simulated record that closely matches the observed record. The second step is to *verify* the calibrated model through comparison with an independent set of records. If the verification step proves satisfactory, then the model may be used to *predict* how the watershed will respond to various storm input records under existing watershed conditions. If the model is to be used to analyze the impacts of various development scenarios for management purposes, then one must be able to predict the effect that land use changes have on the values of the many parameters that enter the model.

This chapter first reviews the available data for use with SWMM in model calibration and verification. The data provided through the City and the USGS stormwater monitoring programs provide the basis from which to estimate model parameters. Analysis of continuous rainfall data generated from nine rain gauges is discussed and the methodology for water quantity and quality calibration and verification are presented. The water quality modeling effort was based on the analysis of single land use stormwater quality data which were simulated in the SWMM program with buildup and washoff models. The goal was to represent the larger Barton Creek watershed as a collection of smaller, single-land-use watersheds. The Barton Creek watershed was subdivided into 26 subcatchments, each with numerous parameters, which could be varied to calibrate the model. Many of these parameters have a physical basis and could be estimated from the characteristics of the watershed, ‘a priori.’ The calibrated SWMM model for the Barton Creek watershed accurately predicted flow; however, the single land simulations using buildup/washoff models were not successful. Because the subwatersheds could not be modeled individually, building an aggregate model to simulate Barton Creek was not feasible and, therefore, the goal was not met.

4.1 Available Stormwater Data Base

The City of Austin has had an extensive stormwater monitoring program in place for the last 15 years. Rainfall and creek water levels are continuously monitored at a number of locations as part of the Flood Early Warning System (FEWS) program. Water quality is monitored on a periodic basis to provide data for evaluation of changes in stream and stormwater quality. The next section describes the monitoring programs from which data was developed for the SWMM modeling applications.

4.1.1 Flood Early Warning System (FEWS) Rainfall Data

All rainfall data required by the SWMM model for the Barton Creek study were generated by the City of Austin's FEWS rain gauges. This monitoring started in mid-1986. The FEWS stations record precipitation, stream flow level, wind speed, relative humidity, temperature, and barometric pressure. Nearly eighty precipitation gauges are located throughout the city. Rain data read by the sensors are sent back to the central office and stored in a database.

Fifteen FEWS precipitation gages are located inside and adjacent to the Barton Creek watershed. Two gauges were installed in 1986, but most were installed after 1989. All of the locations of the Barton Creek rain gages are east of the State Highway 71 area. Attempts to install new rain gauges in the western part of the watershed failed because they were out of range of the system used to download data.

The data from eight FEWS gauges provides the continuous rainfall record necessary for modeling. These records are screened for errors using a program called DOFEWS (a FORTRAN program developed in-house). HYDROLOG (described in Chapter 5) reads the output file from DOFEWS, reformats the record, and creates standard SWMM-readable precipitation records. Much of the needed rainfall record from 1986 to the present has been converted, stored, and is frequently updated.

4.1.2 Software Development and Treatment of Missing Values

Missing values or missing records are a significant problem for continuous modeling with multiple catchments. Sensors commonly malfunctioned, resulting in missing records. If missing data are not handled properly before conversion to an interface file, it may be difficult to detect. This can cause complications in calibration, or it may produce unrealistic statistics. This problem is solved by a two-step approach. First, the HYDROLOG program provides a graphical diagnostic tool to compare the cumulative rainfall volumes among specified gauges over time. Second, the HYDROLOG program is capable of modifying each record with the following options:

- Duplicate down time records from the next nearest sensor;
- Synthesize continuous records from a weighted computation using the cumulative volume of rainfall data;
- Average volumes from a group of sensors over time (arithmetically); and
- Average volumes from a group of sensors using the Theissen’s polygonal method.

4.1.3 Rain Gage Density Studies

In the Barton Creek watershed modeling study, the validity of rainfall records used for the model calibration is a concern. For calibration using continuous simulations, accurate accounting of rainfall volumes entering the drainage basin is essential. A correlation analysis was performed to evaluate the accuracy of using data of one gage to represent rainfall over a given area. The correlation coefficients among gauges were calculated using the PROC CORR (Pearson product-moment correlation) method from the SAS program.

The data used for the correlation analysis comes from the SWMM Rain Block, which was used to generate a summary of rainfall volumes since 1986 on a continuous-event basis. Different events are separated by a dry period of two hours. Gauge 1300 is the most upstream gauge in the Barton Creek watershed. It covers about two-thirds of the total watershed area and is approximately 16 miles from the most upstream point in the watershed. The distances and correlation coefficients between gauge 1300 and all other gauges were tabulated and plotted in Figure 4.1. The results from the analysis of spatial variation show that the mean correlation coefficient for the entire observation period is over 0.8 within 16 miles of FEWS 1300. This suggests that the FEWS 1300 gauge is well correlated with other rain gauges, and it is reasonable to conclude that the upstream rainfall record is well represented by this gauge. However, during the summer, when rainfall is derived mainly from localized thunderstorms, the correlation between the gauges is lower and consequently the model predictions will be less accurate.

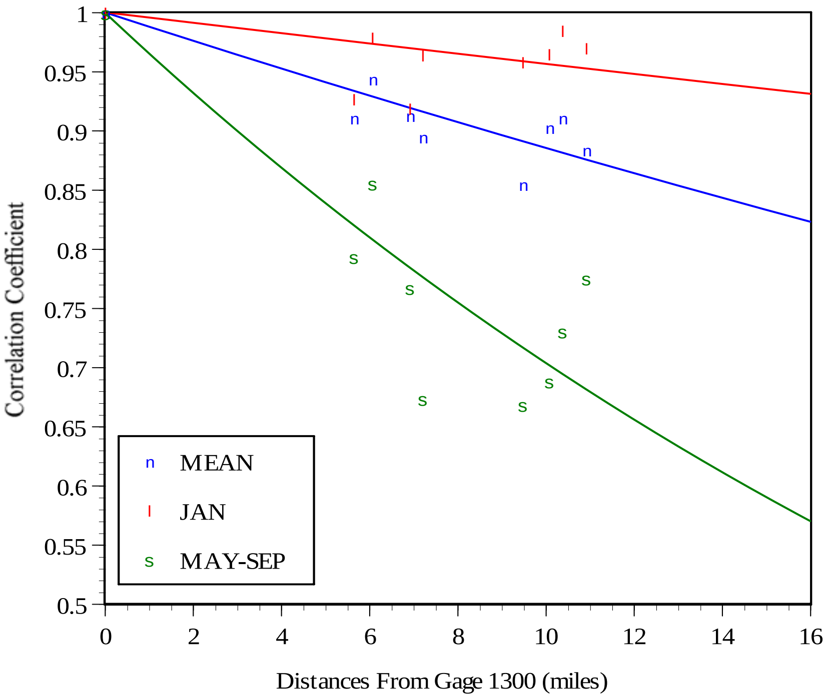


Figure 4.1 Spatial and Temporal Variations Among Raingages

4.1.4 City of Austin Stormwater Quality Program

In 1980, the City of Austin began its first stormwater monitoring program, as a part of the EPA-sponsored Nationwide Urban Runoff Program (NURP). Stormwater monitoring stations were installed at four sites to sample runoff from specific land uses. Water quality data was collected for one year at each site during 1981. Subsequently, a monitoring program was established to test structural water quality treatment facilities that were identified as Best Management Practices (BMP’s).

Based on the results of the NURP and BMP monitoring programs, the City initiated a five-year stormwater monitoring program (SWMP) in mid-1984. The goals of the five-year program were to relate levels of stormwater pollution to watershed characteristics and to test the treatment efficiency of filtration, sedimentation, and wet ponds. Sixteen monitoring stations were installed at locations, including the NURP sites. The first five-year SWMP monitoring sites are listed in Table 4.1.

Table 4.1 Sites and Monitoring Information for the COA's Five-Year Program

Monitoring Site	**Land Use**	**Impervious Cover**	**Drainage Area**	**Period of Record**	**No. of Events Monitored**
Bear Creek near Lake Travis	Undeveloped	3 %	310 acres	10/84-11/87	26
Hart Lane of NW Austin	Med. Density Res.	39%	371 acres	4/85-11/87	23
Rollingwood near Town Lake	Low Density Res.	21%	63 acres	1/84-8/88	21
Highwood Apts. of NW Austin	Multi-Family Residential	50%	3 acres	1/85-11/87	27
Barton Creek Square Mall (BCSM)[1]	Commercial	86%	49 acres	3/85-11/87	30
Maple Run subdivision	Med. Density Res.	36%	28 acres	1/84-5/86	26
Brodie Oaks Shopping Center (BOC)[1]	Commercial	95%	47 acres	10/84-8/88	17
Jollyville Road in NW Austin	Roadway	76%	11.2 acres	9/88-4/92	34

[1] These sites have frequent parking lot sweeping practices (everyday at BCSM and every three days at BOC). The pollutant concentration values of these sites may be impacted by the street sweeping programs.

The current SWMP includes 55 stormwater monitoring stations. Runoff samples collected at the stations are analyzed for the conventional parameters listed below. In addition, volatile organics, pesticides and herbicides are tested at specific sites for some storms.

Biochemical Oxygen Demand (BOD)
Chemical Oxygen Demand (COD)
Total Suspended Solids (TSS)
Total Dissolved Solids (TDS)
Total Organic Carbon (TOC)
Total Phosphorus (TP)
Ammonia as Nitrogen (NH_3-N)
Total Kjeldahl Nitrogen as Nitrogen (TKN-N)
Nitrate plus Nitrite as Nitrogen (NO_2+NO_3-N)
Total Cadmium (Cd)
Total Copper (Cop)
Total Lead (Pb)
Total Zinc (Zn)
Fecal Coliform (FC)
Fecal Streptococci (FS)

4.1.5 Adequacy of Water Quality Calibration Data

Austin's stormwater sampling program is more comprehensive than the vast majority of municipalities. However, of the eight single-land-use sites with existing data, only two monitoring sites are situated inside the Barton Creek watershed, and these do not include single-family residential, ranch or undeveloped conditions, the primary land uses in the basin. Eleven new monitoring have been constructed since this project began. These stations collect data from one undeveloped area on the recharge zone, one undeveloped area in the contributing zone, three single-family subdivisions, one office site, and five BMPs. Table 4.2 describes the site locations, the number of stations per site, land uses, and type of structural control (if applicable). Future refinement of the model will require incorporation of sampling data from these planned stations.

Table 4.2 Stormwater Monitoring Program Sites in Barton Creek

Site Location	Number of Stations	Land Use / BMP Type
Barton Creek Recharge Zone	2	Undeveloped
Windango Way	1	Undeveloped
Lost Creek Subdivision	2	Single-Family Residential
Travis Country Pipe	1	Single-Family Residential, Recharge Zone
Travis Country Grassy Swale	1	Single-Family Residential, Recharge Zone
Spy Glass	1	Office Complex
Barton Creek Square Mall	2	Shopping Mall / Sand Filtration Pond
Brodie Oaks	3	Shopping Mall / Retention, Irrigation, Sand filtration
Barton Ridge Plaza	4	Shopping Mall / Sedimentation, Filtration
Highway BMP System No. 5	3	Roadway / Sediment and Vertical Filtration
Highway BMP System No. 6	3	Roadway / Sediment and Vertical Filtration

4.1.6 Cooperative City of Austin/USGS Monitoring Program

The City of Austin has cooperated with the USGS since 1975 to monitor flow and water quality in creeks, lakes, and aquifers around the city. Monitoring is currently carried out at 12 streamflow gauging stations, one site at Barton Springs, one site below Barton Springs, and 23 groundwater wells. The USGS collects water quality samples from each of the 14 in-stream monitoring sites for 1-3 storm events, or 8-10 samples per year. Five of these in-stream sites are within the Barton Creek Watershed:

Barton Creek at State Highway 71,
Barton Creek at Lost Creek Boulevard,
Barton Creek at Loop 360,
Barton Springs, and
Barton Creek below Barton Springs.

Flow data used to support calibration of the Barton Creek SWMM model were collected from the USGS Barton Creek stream flow gauges located at Lost Creek Boulevard and State Highway 71. The other stations are located on the recharge zone of the aquifer and cannot be used for flow calibration because SWMM cannot simulate flow losses in the creek. Automatic water quality samplers were installed at the Lost Creek Boulevard and Highway 71 sites in 1988 and 1989, respectively. The gauge periods-of-record and drainage areas used in the modeling effort are as follow:

Gage Location	USGS Identifier	Period of Record	Drainage Area
Lost Creek Boulevard	#08155240	12/88 - present	107 sq. miles
Highway 71	#08155200	78 - 9/82, 1/89 - present	89.7 sq. miles

4.2 Model Calibration Methodology

The calibration methodology described in this section applies to the SWMM modeling of the Barton Creek watershed as well as the single-land-use watersheds. Application of SWMM for a watershed requires calibration of parameters describing the physical characteristics the watershed, as well as calibration of parameters used to represent the buildup and washoff of constituents. The calibration is performed by running the model, comparing the model results with observed monitoring data, and adjusting the parameters to obtain a better fit between the model and observations. It is an iterative and interactive process.

Calibration of flow quantities in SWMM is performed largely through adjustment of hydrologic parameters in the Runoff Block to develop an improved comparison between observed and simulated flows. The parameters that may be modified include those which represent surface water processes (runoff, infiltration, depression storage, surface evaporation, etc.) and those which represent subsurface flow accounting (percolation, subsurface storage, baseflow generation, evapotranspiration, etc.).

Judgments as to the effectiveness of the flow calibration effort were based upon the following factors:

- Matching of peak flow rates - Lack of information regarding the true spatial distribution of rainfall for the calibration events prevented perfect continuous matching of peak flows. The goal was to avoid systematic over-prediction or under-prediction over the long term.
- Matching of hydrograph shapes - Significant effort was expended in refining the shape of the hydrographs, particularly with respect to the transition period between the trailing leg of the direct runoff hydrograph and the onset of pure baseflow recession.

- Matching of baseflow recession rates - Substantial effort was also expended in matching observed baseflow recession hydrographs with respect to:
    - a. the slope of the recession curve, and
    - b. the baseflow rate immediately following completion of runoff

  The ability to effectively match the baseflow recession rate and total baseflow volume implies a reasonably good accounting of the subsurface storage system. As with peak flows, the goal here was to avoid systematic under-prediction or over-prediction.
- Matching of the basin sensitivity to rainfall - Depending upon antecedent moisture conditions, Barton Creek will or will not respond with runoff and/or baseflow to a given rainfall event. Significant calibration effort was spent on matching the basin's observed hydrologic sensitivity.
- Matching the total runoff volume - A general overall measure of the effectiveness of the calibration effort comes from comparison of the total simulated hydrograph flow volume with the observed volume.

4.3 Single-Land-Use Watershed Modeling

In order to apply SWMM to the Barton Creek watershed and use the model to estimate the potential impacts of changing land use, one must be able to estimate the runoff quantity and quality from various types of land use. The data from the City of Austin stormwater monitoring program provides a basis for making such estimates if this data can be adequately fit to the pollutant buildup and washoff functions available within SWMM. The stormwater monitoring program data were analyzed using the various buildup and washoff functions to evaluate whether there was any consistency between the estimated parameters from one storm event to the next.

Five single-land-use models were developed and calibrated. Each watershed model required both stormwater quantity and quality calibration. These watersheds are small, single-land-use suburban watersheds with drainage areas ranging from 3 to 371 acres and include Bear Creek, Hart Lane, Highwood Apartments, Barton Creek Square Mall, and Jollyville. Bear Creek (BC) is primarily an undeveloped area with land covered by scrub trees and grass. Hart Lane (HL) is a single-family residential area, while Highwood Apartments (HI) is a multi-family residential area. The Barton Creek Square Mall (SI) watershed consists of commercial development with a high degree of impervious cover. However, the parking lot of this commercial site was maintained by a daily sweeping program. Jollyville (JA) represents runoff from a highway intersection. These single-land-use watersheds are listed in Table

4.3, along with the runoff coefficients that express the ratio of long-term runoff to rainfall for the watershed.

Table 4.3 SWMM Models Developed for Single Land Use Watershed

Watershed	Land Use	Runoff Coef.
Bear Creek (BC)	undeveloped	0.007
Hart Lane (HL)	single-family residential	0.17
Highwood Apartments (HI)	multi-family residential	0.62
Barton Creek Square Mall (SI)	commercial	0.83
Jollyville (JA)	highway	0.56
Brodie Oaks Plaza (BI)	commercial	0.75

4.3.1 Single-Land-Use Water Quantity Calibration

The watersheds were modeled in SWMM as single catchments with a channel to route the water to a single node for hydrograph display. None of the single-land-use watersheds, except Bear Creek, have a subsurface flow system that contributes baseflow to the surface drainage system. SWMM subroutines used for modeling of the Barton Creek watershed were the Rainfall Block, Runoff Block and Transport Block, in that order. An interface file is generated from the Rainfall Block, which serves as input to the Runoff Block for surface (and sub-surface routing for Bear Creek). Hydrographs generated by the Runoff Block are transferred (via an interface file) to the Transport Block for flow routing.

Each model run consisted of a one-year continuous simulation, which included seven or more storms. The choices for simulation periods were constrained by the lack of localized continuous rainfall records. Runoff data were collected from 1984 to 1988 from each land use; however, there were few continuous rainfall gauges in or near the watersheds. The only continuous rainfall monitoring station for this period was located at the Austin Municipal Airport and there are significant differences between the rainfall at this site and the observed flow records of the monitored watersheds. It was not until the middle of 1987 that FEWS rain gauges were installed at the flow-monitoring sites and the local data became available for use in SWMM.

The most important parameters in the model for reproducing observed flows are those that are physically based. Table 4.4 shows these parameters and the values used for the Hart Lane model. The calibration studies for the single-land-use watersheds resulted in models that were able to adequately reproduce observed flows.

Table 4.4 Water Quantity Calibration Parameters for Hart Lane Watershed

H1 Group

Area = 371 acres
Percent Impervious = 39
Impervious Roughness = 0.02
Impervious Storage = 0.05 inch
Suction Pressure Head = 10 inch
Initial Moisture Deficit = 0.15
(Volume of air/volume of voids)

Width = 1300 ft
Slope = 0.03
Pervious Roughness = 0.15
Pervious Storage = 0.2 inch
Hydraulic Conductivity = 0.30 in/hr

Figure 4.2 shows a comparison of total storm runoff volumes (watershed inches) for the Hart Lane model. The period of simulation extends over five months and includes nine major events. The overall volume comparison is good. Figure 4.3 shows a comparison of the predicted peak discharge and the observed hydrograph. For many of the events, the peak comparison is satisfactory, although the observed peak on October 21, 1986, was larger by more than 25 percent. Figure 4.4 compares the predicted and observed storm runoff duration. While there is somewhat more variability here than for the other measures of performance, it is still believed that the results are satisfactory.

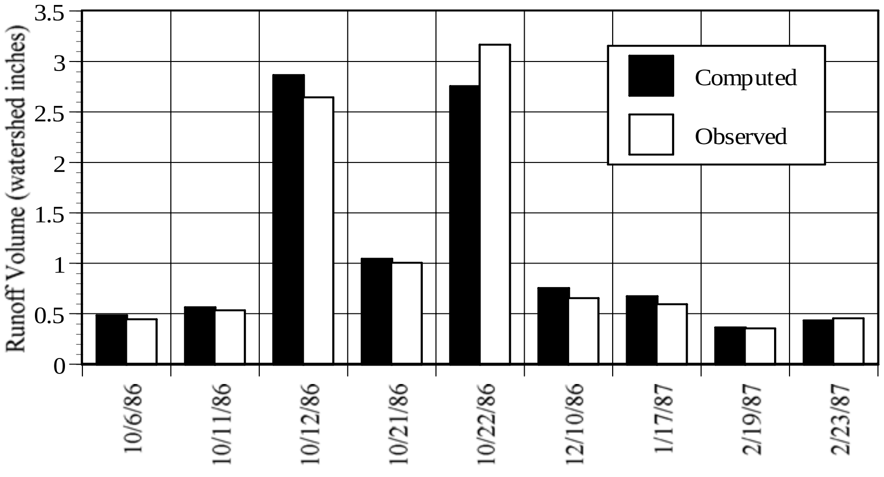


Figure 4.2 Comparison of Runoff Volumes from Continuous Simulation

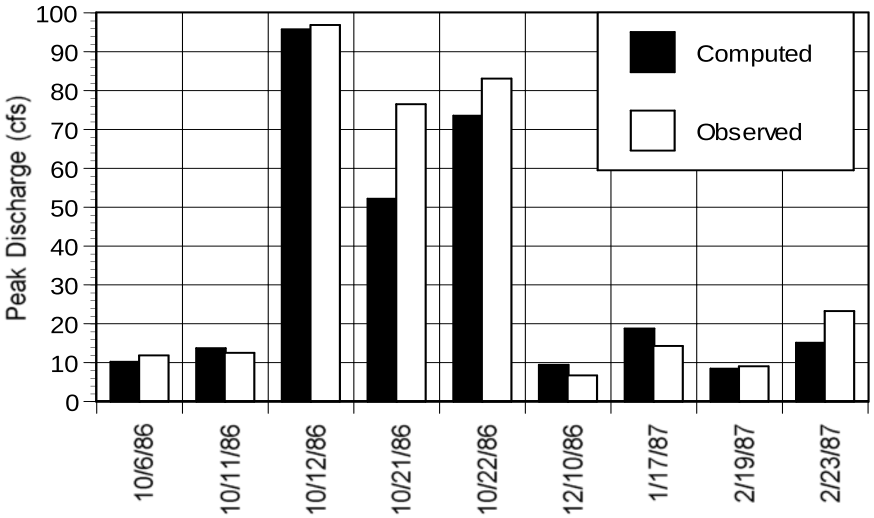


Figure 4.3 Comparison of Peak Discharge from Continuous Simulation

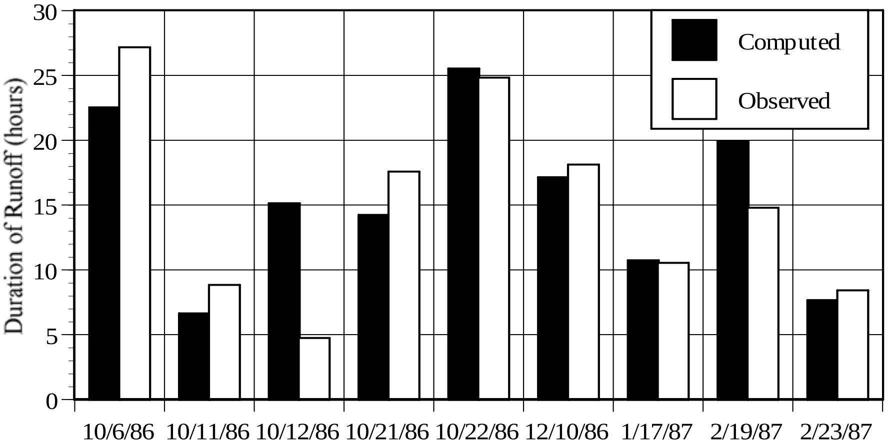


Figure 4.4 Comparison of Storm Runoff Duration from Continuous Simulation

The remaining single-land-use watersheds were also calibrated with equally satisfactory results. The general conclusion is that it is possible to calibrate SWMM for flow quantity from these single-land-use watersheds.

4.3.2 Single-Land-Use Water Quality Calibration

Initial calibration efforts were made using data from the City of Austin's stormwater monitoring program from 1984-1988. Constituent buildup and washoff were modeled using the standard exponential functions available in SWMM. A least-squares optimization routine was prepared and applied to determine the combination of buildup and washoff parameter values that produced the minimum sum-of-squared deviations between predicted pollutographs and observed data. This approach was abandoned when it was found that the least-deviation solution did not produce reasonable parameter values.

Another in-house program, CONC, was developed for the purpose of calculating buildup and washoff coefficients. Analysis of individual storm constituent loads for varying dry antecedent periods revealed no discernible buildup effect. Consequently, the use of the buildup function may not be valid for SWMM simulations of these watersheds. These investigations resulted in a detailed evaluation of the single-land-use stormwater data that also is described in Chapter 5.

The water quality calibration period for Hart Lane used the same five-month period that was used to develop the water quantity calibration. The washoff coefficient RCOEF was calculated as the mean value from 33 storms per station. The buildup limit QFACT1 is defined as the largest value obtained from an individual land use and is an estimate of the asymptote of the buildup curve. The buildup coefficient, QFACT2, is generated from the slope of the buildup curve (as discussed in Chapter 5). The values of the parameters are shown in Table 4.5.

Table 4.5 Buildup and Washoff Parameters for the Hart Lane Watershed

Constituent	QFACT1	QFACT2	RCOEF
TSS	20733	1.00×10^{-2}	20.00
TPO_4	28.50	2.71×10^{-2}	8.34

The initial calibration assumed that WASHPO = 1 and is shown in Figure 4.5. Although the predicted values shown in Figure 4.6 are much higher than observed values, the general shape of the model result is consistent with the empirical data for TSS. Empirical data for total phosphorous (TPO4), on the other hand, appears to be related to flow rate. The peak concentration typically occurs at the same time as the peak flow rate. By changing WASHPO to 1.5, as shown in Figure 4.6, a fairly good match with measured TPO4 data was obtained.

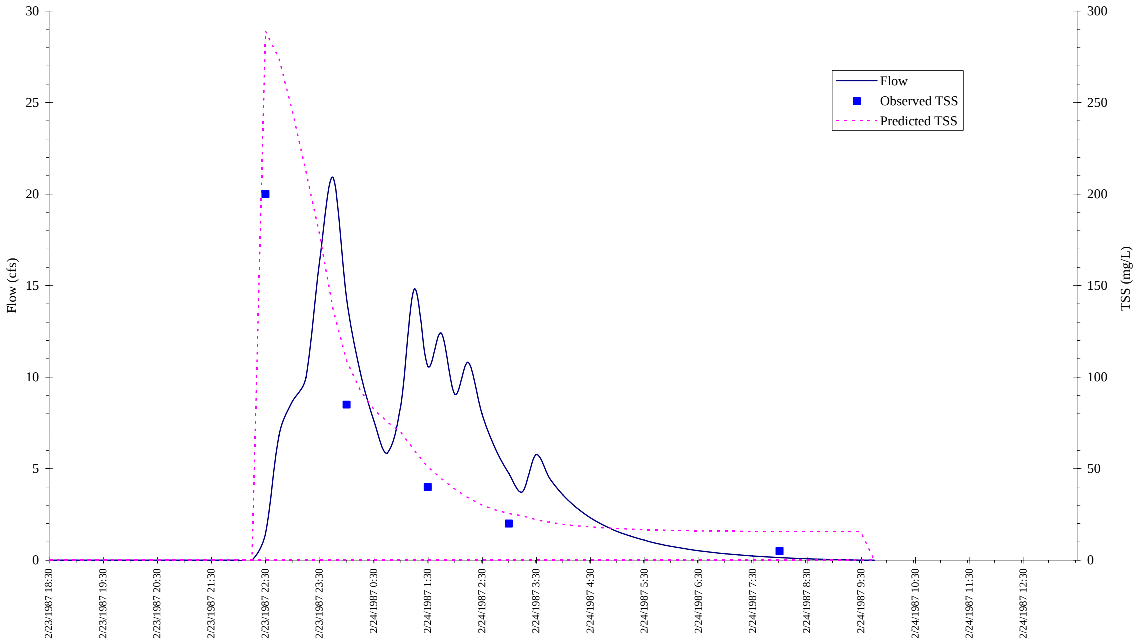


Figure 4.5 Calibration of TSS

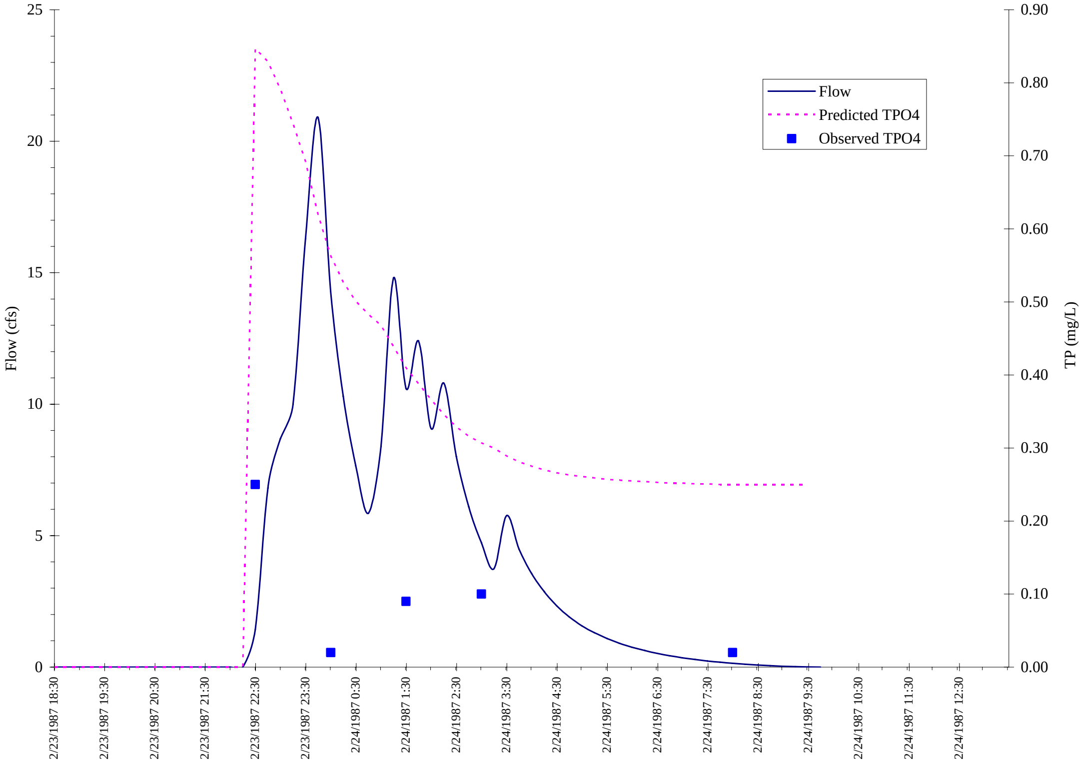


Figure 4.6 Calibration of TPO4

The results for TSS and TPO4, along with observations for the remaining parameters modeled, indicate that WASHPO is not a sensitive calibration parameter for describing all of the empirical data from single-land-use stations. WASHPO appears to be parameter specific. In addition, the estimates for the three variables in Table 4.5 are based on WASHPO=1. This was necessary to simplify the model for buildup and washoff to three equations with three unknowns.

As mentioned above, the initial runs using estimated values in the buildup/washoff model resulted in consistent over-prediction of observed pollutant concentrations. As shown in Figures 4.7 and 4.8, reduction in QFACT2 by 50 percent resulted in a comparable reduction in the pollutant concentrations. The final calibration for the single-land-use watersheds required a reduction of QFACT2 by an order of magnitude from the initial estimation. Changes in RCOEF value will change the initial slope of the pollutograph and the corresponding load; however, this change will not substantially change the initial concentration. The lack of sensitivity of the initial concentration to the calibration parameters highlights the inability of the buildup relationship to estimate the initial concentration as a function of the length of the antecedent dry period.

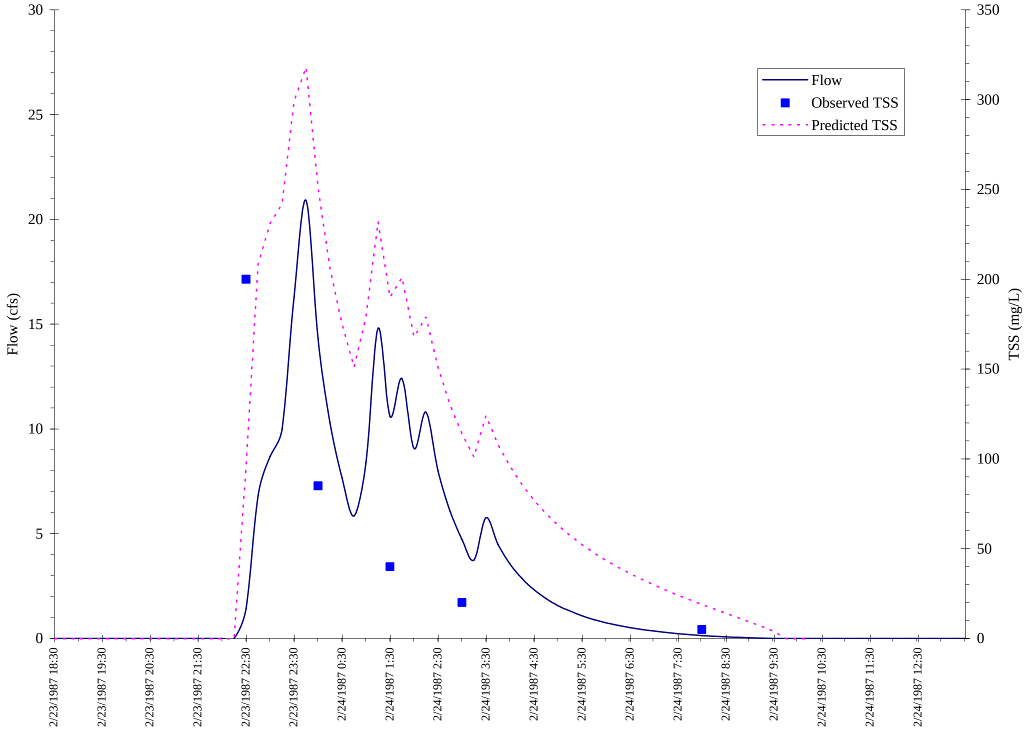


Figure 4.7 Improved Calibration of TSS

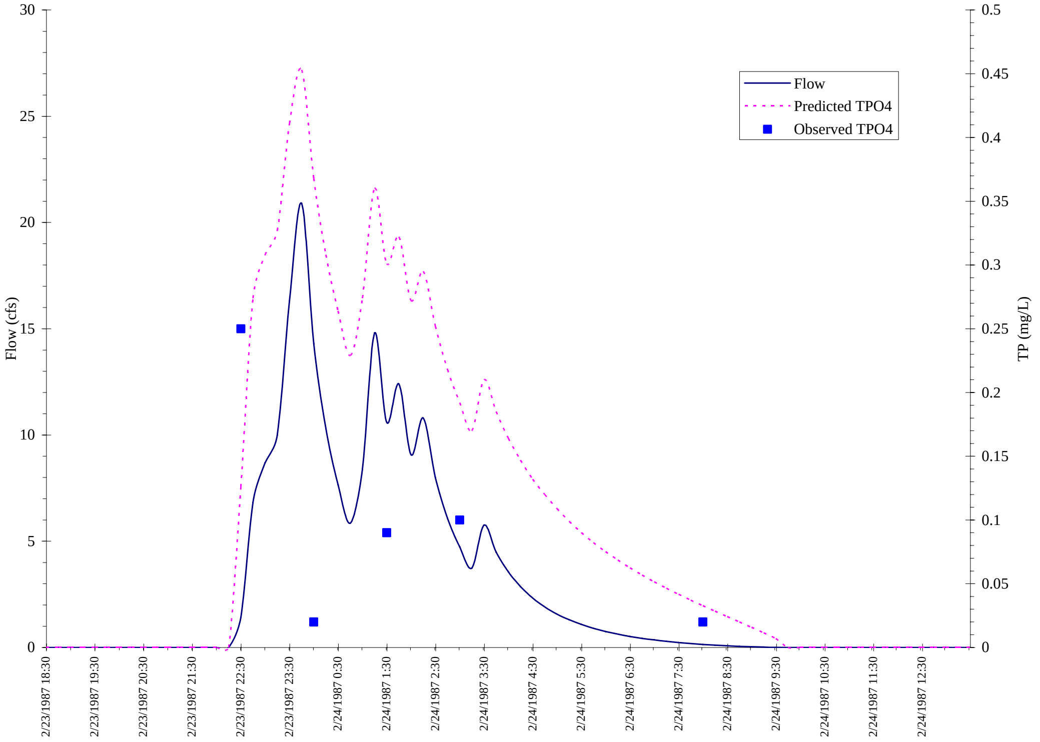


Figure 4.8 Improved Calibration of TPO4

4.4 Barton Creek Watershed Modeling

SWMM subroutines used for modeling of the Barton Creek watershed were the Rainfall Block, Runoff Block and Transport Block, in that order. An interface file is generated from the Rainfall Block that serves as input to the Runoff Block for surface and sub-surface routing. Hydrographs generated by the Runoff Block are transferred (via an interface file) to the Transport Block for flow routing. Flow routing can also be accomplished using the Runoff Block or the Extended Transport Block (EXTRAN). However, the Runoff Block is not as flexible as the Transport Block, in that it does not incorporate features such as channel storage and printing of output from multiple nodes. The EXTRAN Block was not used because it requires much smaller time steps which, for long term simulations, require very large amounts of storage space as well as very long model run times.

The Barton Creek Watershed Model has 120 trapezoidal channels connected by 26 nodes. The Transport Block offers a number of types of channel options, including trapezoidal channels and dummy channels (inflow = outflow). The trapezoidal geometry was selected, primarily because there was very little channel morphology data available for this study. In addition, trapezoidal channels tend to be the most numerically stable in a model. Measurements including channel length, top width, and slope all come from planimetric maps and USGS topographic maps. Manning's coefficients were estimated based on field experience and interpretation from the City of Austin Drainage Criteria Manual.

All of the simulated flow in the Barton Creek watershed model is generated by direct runoff flow and baseflow in the Runoff Block. Calibration is not conducted with the Transport Block. This may be done sometime in the future once more data are available. The calibrated nodes include node 48 (Barton Creek at State Highway 71) and node 41 (Barton Creek at Lost Creek Boulevard). The output generated from the Transport Block was viewed and compared with observed data using the HYDROLOG program mentioned previously. The program displays hydrographs, hyetographs, and integrated volumes directly from the SWMM output file.

4.4.1 Data for Flow Calibration

Flow data used in the calibration of the Barton Creek SWMM model was collected from the USGS Barton Creek stream flow gauges located at Lost Creek Boulevard and State Highway 71. The USGS gauges function continuously with data reported both graphically on a strip chart and on a digital punch tape at 15-minute intervals. Other stations on Barton Creek are located on the recharge zone of the aquifer and are not be used for flow calibration because the model cannot simulate flow losses in the creek. The gauge periods-of-record and drainage areas used in the model effort are as follow:

Gauge Location	USGS Gauge Number	Period of Record	Drainage Area
Lost Creek Blvd.	08155240	12/88 - present	107 sq. miles
Highway 71	08155200	78 - 9/82, 1/89 -present	89.7 sq. miles

Highway 71 represents the upper basin, most of which remains undeveloped and includes Little Barton Creek. The Lost Creek Boulevard gauge includes drainage from two golf courses as well as approximately 1,500 acres of residential land use. The availability of continuously recorded flow data provides a basis for hydrograph definition and flow calibration at both locations. The relatively short periods-of-record at Highway 71 and Lost Creek Boulevard limit the adequacy of record for calibration approaches aimed at matching long-term flow volumes.

4.4.2 Barton Creek Water Quantity Calibration

A calibrated model is verified if it can produce favorable results when compared with observed flows for a period of record that was not used in the calibration process. It should be apparent that the calibration and verification records must have similar initial conditions. If the calibration record begins with no baseflow, then the same input file cannot be used to verify a record where there is substantial baseflow at the start of the simulation because the subsurface systems will not be in a similar state.

Model calibration for flow quantity was performed using two periods during which complete USGS flow records exist for the gauges at Highway 71 and Lost Creek. These two stations were used because they are located above the Edwards aquifer recharge zone and the current formulation of SWMM cannot simulate recharge. These periods were selected because they contain several sizable runoff events, each of which recharges the basin's baseflow system, allowing for a robust baseflow recession hydrograph against which to calibrate. In accordance with the assumed initial conditions, these periods also had minimal or no baseflow at the starting time for the simulation.

The calibration began with reasonable initial estimates of parameter values based upon engineering judgment and practical knowledge of the watershed. Results from the initial model run were then plotted against observed flows. Thereafter, an iterative process of parameter adjustment, running of the model, and comparison of results with observed flow records was undertaken. The primary calibration parameters in the runoff block were the baseflow parameter (A1) and the effective subcatchment width, (WW1). Additional parameters adjusted were field capacity (FC), initial vadose zone moisture content (TH1), wilting point (WP), pervious and impervious area depression storage (PSTOR, ISTOR), and the maximum depth over which significant lower zone transpiration occurs (i.e. root zone depth) (DET).

The subcatchment effective width is one of the most sensitive calibration parameters. Initial estimates are generated from an equation recommended in the SWMM manual. This equation is an attempt to deal with shape effects, whereby a catchment is divided into two subareas along the main channel. The width is calculated using the following equation:

$$\mathrm{Width} = \left(2 - \frac{A_2 - A_1}{A_2 + A_1}\right) \times L \qquad (4.1)$$

where

Width = Subcatchment width

A_1, A_2 = Catchment sub-areas on each side of the channel

L = Length of main drainage channel

Subcatchment delineation was developed from eight 7.5 minute (1 inch = 2000ft) USGS topographic maps. At the time that this study began, SWMM 4.0 had no option for dividing land use inside a catchment. Since then, SWMM 4.05 was modified to allow up to five land uses per subcatchment. For this reason, land use was the dominant criteria used to segregate individual subcatchments. The Transport Block has significant problems with channel routing when there is a large variation in the sizes of the catchments. Numerical instability causes mass balance errors in excess of five percent of the water quantity, especially for small channel slopes. Therefore, catchments were defined in the model to be approximately the same size.

Subcatchment imperviousness was estimated from aerial photography (COA, 1988), plannimetric maps, and USGS data. The SWMM model considers only impervious areas that are hydraulically connected to the channel drainage system, and does not directly consider impervious areas that drain to pervious areas before reaching the major watershed drainage system. Data for the Barton Creek watershed does not provide a physical basis for estimating this effective impervious cover. Good calibration suggests that the effective impervious cover is approximately 5 percent of the total watershed area.

An example showing the calibrated flows on Barton Creek is shown in Figure 4.9, which compares the simulated and observed flows at Highway 71. Figure 4.10 shows the result of Lost Creek gauge calibration from December 1990 to July 1991 (5,000 hours). Observed data indicate that baseflow accumulates over a series of storms and results in a better calibration; although the recession curve does not withdraw quite as fast as observed data. Similar results were obtained from the calibration at the Highway 71 gauge.

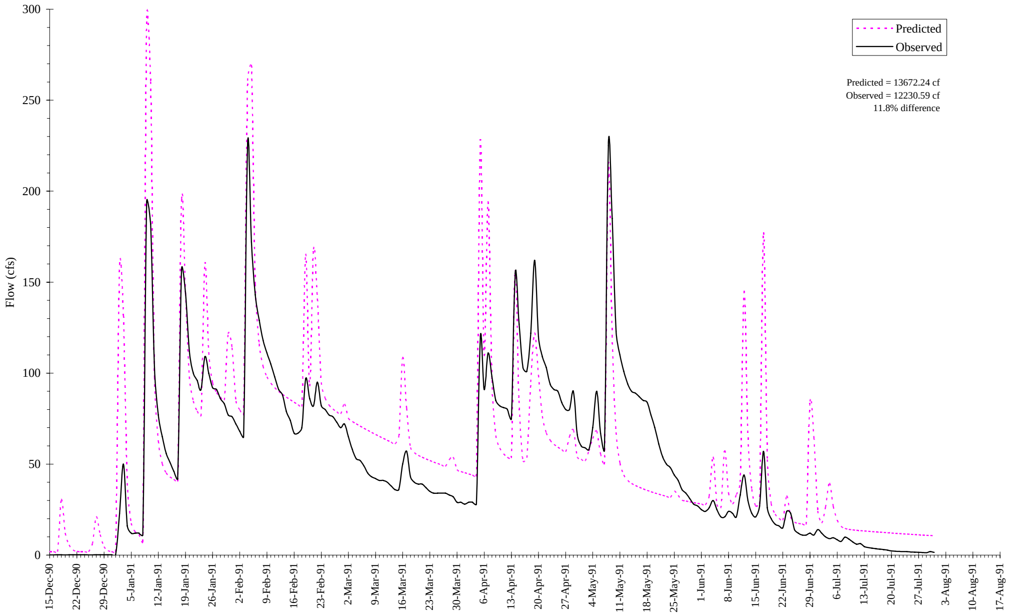


Figure 4.9 Flow Calibration at Highway 71 USGS Gage

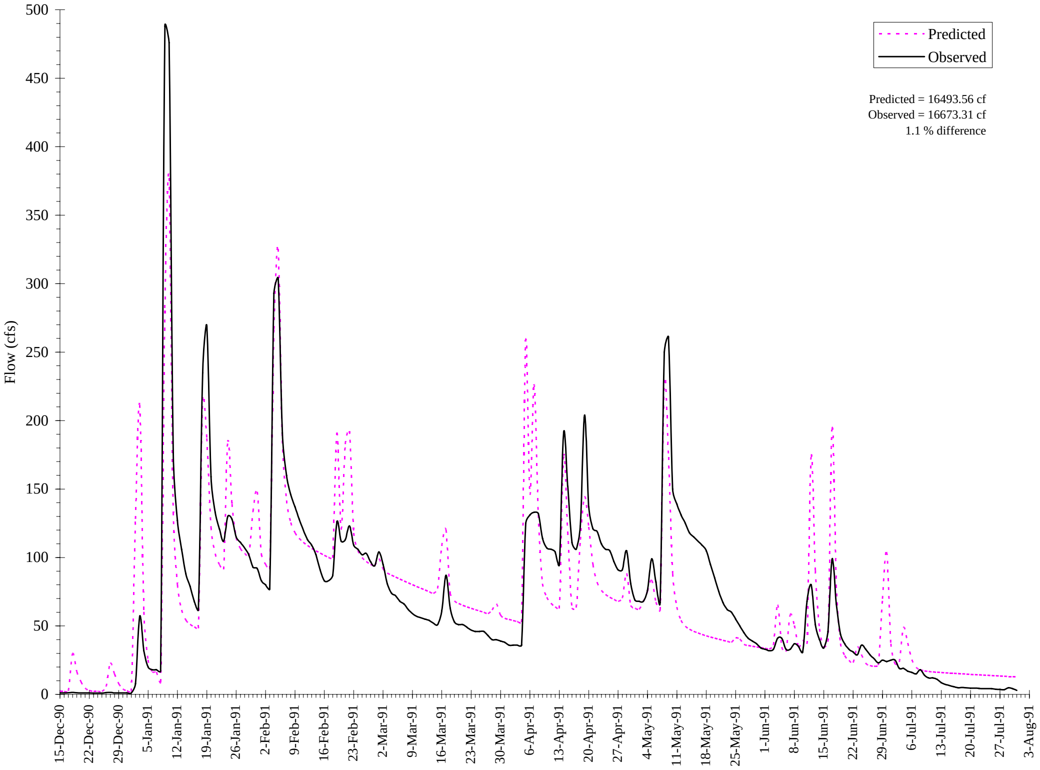


Figure 4.10 Flow Calibration at Lost Creek USGS Gage

For verification of the calibrated model, the period from November 1992 to July 1993 (6,000 hours) was selected because flow data was available from both gauges. None of the calibration parameters were changed and the results are shown in Figures 4.11 and 4.12. Although there are significant differences in predicted and measured peak flows, there is only a 1.1 percent difference in total flow at Lost Creek Boulevard and 8.8 percent at Highway 71 for this period.

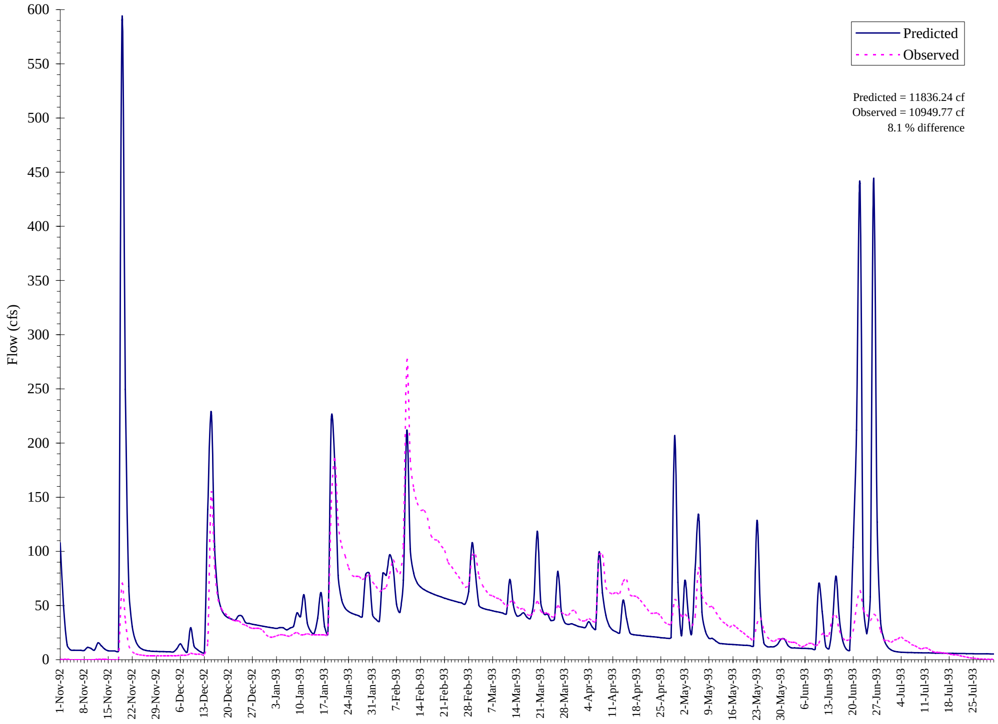


Figure 4.11 Flow Verification at Highway 71 USGS Gage

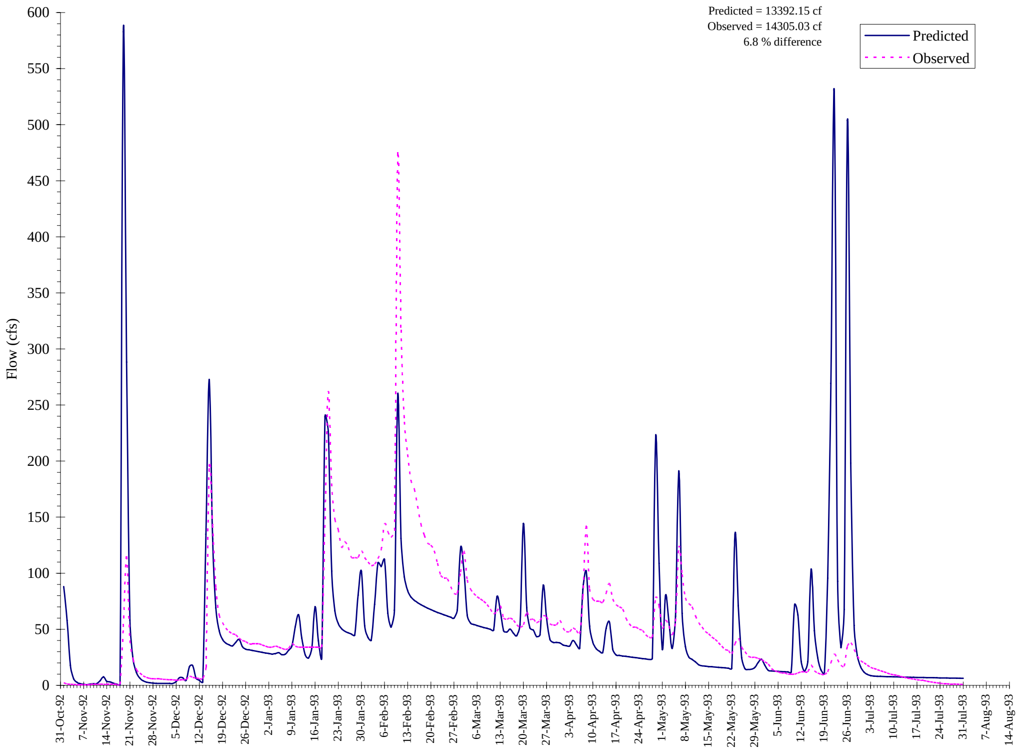
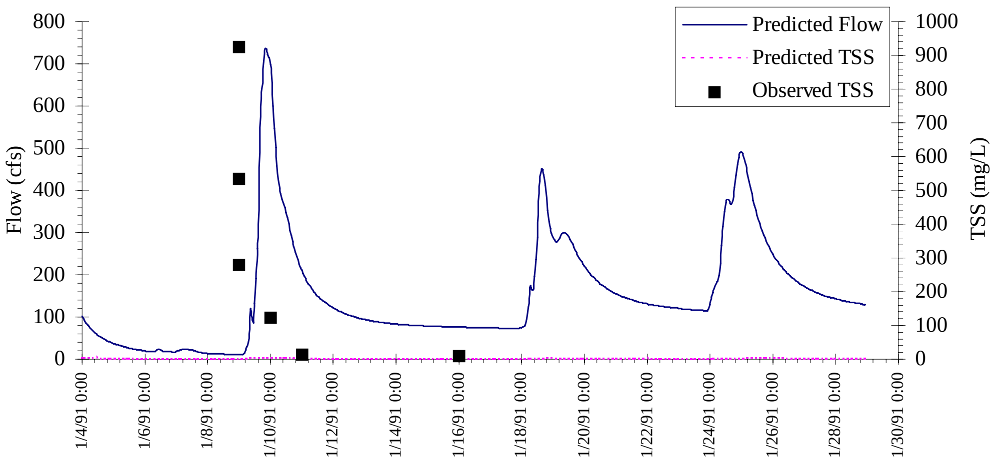


Figure 4.12 Flow Verification at Lost Creek USGS Gage

4.5 Barton Creek Water Quality Calibration

Unlike the continuous flow hydrographs that are available for flow quantity calibration, the available body of water quality data in the creek is much sparser. The sparseness and variability of water quality data make calibration of either single event or continuous simulation water quality models very difficult. However, this data may be used as a guide to evaluate general simulation magnitudes of water quality parameters. There are data for single-land-use watersheds in the Austin area which are adequate to establish the baseline conditions with reasonable confidence, and this data may also be used for water quality modeling calibration.

The water quality model calibration was first attempted using single-land-use buildup/washoff relationships to model the entire Barton Creek watershed. As shown in Figure 4.13, a conservative estimate using high buildup/washoff coefficients significantly underestimates concentrations of TSS and overestimates TPO4. This result is largely due to the influence of channel loads.



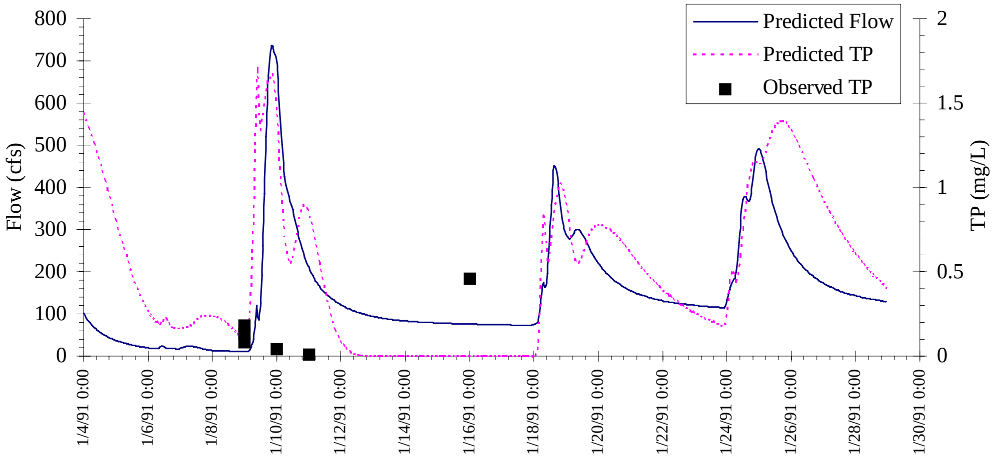


Figure 4.13 Water Quality Simulation
Barton Creek at Lost Creek Blvd.

4.6 Summary

Water quantity and quality calibrations of the SWMM model for both single land use and the Barton Creek watersheds were attempted. Long-term flow calibration was successful in both cases. Prediction of water quality was successful only for individual events in small, single-land-use watersheds. A major effort was expended to use the buildup and washoff formulation in SWMM for pollutant creation. None of the constituents examined exhibited a consistent rate of buildup on the watershed, suggesting that factors other than the length of the antecedent dry period control the amount of pollutant that is available at the start of storm events. It is also questionable whether one would expect a constituent such as TSS to “buildup” in a largely undeveloped watershed such as Barton Creek. Although washoff appeared to be a valid concept for constituents such as TSS, it was shown that the concentration of TPO4 appeared to be related to flow rate than runoff volume.

Because of the different processes involved in the creation and mobilization of specific pollutants, different formulations of the model may be required for each constituent. By using average concentrations, the model can reproduce average annual loads, but is not capable of accurately predicting the concentrations or loads from specific events during a long-term simulation.

5.0 Stormwater Quality Statistical Modeling

Since the deterministic buildup / washoff functions used with the SWMM model were not successful, investigations using statistical analyses were developed as an alternative modeling approach and applied for both Barton Creek and the single-land-use watersheds. This chapter first describes a statistical regression model for Barton Creek stormwater quality. Water quality data were analyzed from three USGS/City of Austin joint monitoring program sampling stations on Barton Creek: Highway 71, Lost Creek Boulevard, and Loop 360. Water quality samples are taken during a number of storm events each year. Statistical analyses were performed using this water quality data in conjunction with USGS 15-minute continuous flow data. The objectives, statistical methods, and results from these analyses are presented in the following sections. In addition to the statistical analyses, single-land-use watershed data are presented and analyzed in terms of buildup and washoff, and potential modifications for stormwater quality modeling are suggested. Finally, an attempt has been made to quantify channel-derived sediment loads during stormwater runoff events using monitoring data and data from single-land-use watersheds.

5.1 Statistical Analysis Objectives and Methods

Seventeen water quality variables were analyzed statistically to explore the following five research goals:

1. to describe and summarize observed water quality, including developing a set of baseline measures of water quality constituents, and to guide decisions on further monitoring;
2. to statistically determine the influence of flow rate changes, hydrograph shape, antecedent conditions, seasonal changes, and periods on intensive construction on water quality, and to determine whether urbanization activities in the watershed affect water quality in Barton Creek by examining the differences between the monitoring stations;
3. to identify groups of correlated water quality constituents that have similar characteristics in order to develop a parsimonious monitoring program for model calibration;

4. to develop a statistical water quality model using regression techniques; and
5. to make recommendations based on the analyses of these data for improving future monitoring programs.

5.1.1 Statistical Methods

Statistical calculations were performed using SAS Release 6, for the IBM PC computer. Brief descriptions of the methods used and additional references are presented in the sub-sections below.

5.1.2 Tests for Normality

Parametric tests of hypothesis are based on the assumption that samples are members of Gaussian-distributed (normal) populations. In many cases, however, environmental monitoring data are not Gaussian (Gilliom and Helsel, 1986). For non-Gaussian (non-normal) data, results from Gaussian-based tests can lead to erroneous conclusions regarding the probability of observations. Normality tests were performed to determine whether data transformations or non-parametric (distribution-free) methods would provide more reliable results.

Two methods used for normality testing were the Shapiro-Wilk test and examination of normal and de-trended normal probability plots. The Shapiro-Wilk test is one of the most powerful tests of normality (Gilbert, 1987). It is also the distribution test recommended by EPA (EPA, 1992). The test is based on the premise that data from a Gaussian distribution will be highly correlated with corresponding quantiles from a Gaussian distribution. Calculations to implement this test are described in Gilbert (1987) and EPA (1992).

Normal probability plots pair each observation with its expected value from the normal distribution. If the data are from a Gaussian distribution, these points will fall, approximately, on a straight line. In the detrended normal plot, deviations of the paired observations and expected values are plotted against the expected value. Patterns in the detrended normal plot indicate non-Gaussian data.

5.1.3 Regression

Regression analysis may be used to develop predictive models relating water quality variables and significant independent factors that influence their values. Multiple relationships among sets of independent variables and outcomes can be examined using inferential statistical techniques. The variability of the dependent variables (water quality concentrations) can be explained, to some extent, by the values of independent variables (i.e., flow rate). One goal in regression analysis is to choose the smallest number of independent variables, while at the same time achieving the smallest residual error (difference between the predicted and measured values of the water quality variable, on the average). The independent variables, which help to generate the smallest error, are called predictors.

The best-fit regression equation minimizes the summed squared difference between the equation and the observed data. Parameter estimates and confidence intervals are generated for the terms in the regression equation. Using the magnitude of the terms in the model and their confidence intervals, inferences can be drawn about the impacts of different predictors on the outcome. Multiple regression analysis can statistically remove or control other influences (flow rate and season) while showing the impact of a specific predictor on an outcome. In regression, multiple models exist to describe a single data set. This means that the best-fit model may not be unique.

5.1.4 Correlation

When two or more water quality constituents are related to one another, without having a direct functional dependence, it can be said that the variables are ‘correlated.’ The correlation coefficient provides a quantitative measure of the extent of association between two linear variables. The correlation coefficient can range from +1.0 to -1.0. A value of 1.0 indicates a perfect positive association, a value of -1.0 indicates a perfect negative association, and a value of zero indicates no association. Greater magnitudes in either direction display stronger levels of covariation. The level of association is identified by a correlation between predictors.

A positive correlation between two predictors suggests that they may explain overlapping information about the outcome of water quality. A negative or small correlation between two predictors that have a positive correlation to an outcome suggests that these indicators explain unique information about the underlying process. A partial correlation can reveal the correlation between a predictor and an outcome, while statistically removing the influence of other predictors.

The correlation matrix is used for choosing the most appropriate variables for the multiple regression equation. The multiple correlation and coefficient of determination indicate how well the regression equation explains changes in the dependent variable.

Normality tests indicated that the data were predominantly non-Gaussian; therefore, in addition to linear correlation, Spearman's rank correlation coefficients were calculated for constituent concentrations and flow. The Spearman coefficient is the Pearson coefficient based on the ranks of the data, with adjustment for ties (Norusis, 1990). Probabilities associated with the Spearman coefficients, which are independent of the probability distribution, were used as a basis for identifying constituents that exhibit significant correlation.

5.2 Development of the Step-Wise Regression Model for the Barton Creek Watershed

Step-wise regression analyses were performed for water quality parameters in Barton Creek for samples collected during baseflow and storm flow conditions. Baseflow separation was performed using the HYDROLOG program (COA, 1994) which is described in Appendix A. Statistical analyses were conducted in order to select factors that are capable of predicting water quality concentrations, which are then included in the application of a step-wise regression model.

5.2.1 Analysis of Barton Creek Water Quality

Ninety data sets (15 constituents during two flow conditions at three stations) were tested for normality. Out of 90 data sets tested, one-half did not meet the variance assumption for the tests. The remaining data were identified by the Shapiro-Wilkes tests as non-Gaussian (significance level of 0.05). A visual examination of the normality plots indicated that log transformations of the data would not result in Gaussian-distributed data. As a result, test probabilities were determined for non-parametric Spearman correlation coefficients. The summary statistics are presented in Chapter 2 (Section 2.9, Table 2.6).

Selection of Factors That Influence Water Quality

In order to predict the impacts of land use changes on water quality, one must be able to predict constituent concentrations and loads using significant determining factors. The factors that are thought to be important for prediction of water quality include location, season, flow magnitude, and antecedent conditions. However, not all of these factors are found to be statistically significant for all constituents. A general model is formulated, and parameters that are not found to be significant are eliminated to achieve a parsimonious model. A generalized form for such a model is

$$\begin{aligned} C_{\mathrm{constituent}} = \alpha_{\mathrm{base}} &+ B_{\mathrm{location}} \times \alpha_{\mathrm{location}} + B_{\mathrm{season}} \times \alpha_{\mathrm{season}} + B_{\mathrm{period}} \times \alpha_{\mathrm{period}} \\ &+ B_{\mathrm{flow}} \times \phi_{\mathrm{flow}} + B_{\mathrm{antecedent}} \times \phi_{\mathrm{antecedent}} \end{aligned} \tag{5.1}$$

In Equation (5.1), $C_{\mathrm{constituent}}$ is the constituent concentration, B_i are Boolean variables which take values of either 1 or zero (according to whether or not the component is statistically significant), a_i are constant coefficients whose magnitudes are determined through the regression analysis, and f_i are factors that are chosen to reflect the physical significance of flow and antecedent conditions on water quality. The regression analysis is performed separately for samples taken under baseflow and runoff conditions.

Constituents

The sample data are checked for each constituent to ensure data quality and that enough samples are available for a meaningful statistical regression analysis. Thus, models are not presented for all constituents under both baseflow and runoff conditions. In addition, the time from 1983 - 1986 was an active period of construction in the Austin area, and some water quality constituents have average concentrations that are different during this period as compared with their long-term average.

Location

Water quality samples are available for three locations along Barton Creek: Highway 71, Lost Creek Boulevard and Loop 360. The location of a site appears in the model only if its location is statistically significant in the regression analysis of the data.

Season

Data samples are identified according to the season (spring, summer, fall, or winter) in which they were taken, so that seasonal influences may be included in the resulting predictive models. The season appears in the model for a constituent only if the season is statistically significant in the regression analysis of the data. The period of record used for determination of seasonal factors was 1987-1994, which excluded the periods of construction from 1978-1982 and 1983-1986.

Period

As noted above, during the time period from 1983-1986, construction activity was very high in the Austin area. Although there are no water quality data that explicitly described the impact of construction on Barton Creek, tracking the record of annual construction permits during the period from 1975 to 1994 shows a high correlation with TSS. Figure 5.1 shows the number of annual commercial construction permits for the time period 1975-1994, and the normalized annual TSS concentration deviation for samples collected from Barton Creek at Loop 360, Williamson Creek at Oak Hill, Bull Creek at Loop 360, and other watersheds. Grouping of these stations was necessary in order to have sufficient data to calculate meaningful statistics. If X_i is the yearly average composite TSS concentration and $\overline{X}$ is the average over the entire period, then the normalized TSS concentration deviation for the year is calculated from

$$\frac{X_i - \overline{X}}{\overline{X}}$$

Figure 5.1 shows that there were consistently high TSS concentrations during the period 1983-1986, and that they are well correlated with construction activity. The question of whether a water quality sample was taken from this period is left as a Boolean variable in the statistical regression model, and it was identified as significant for certain constituents.

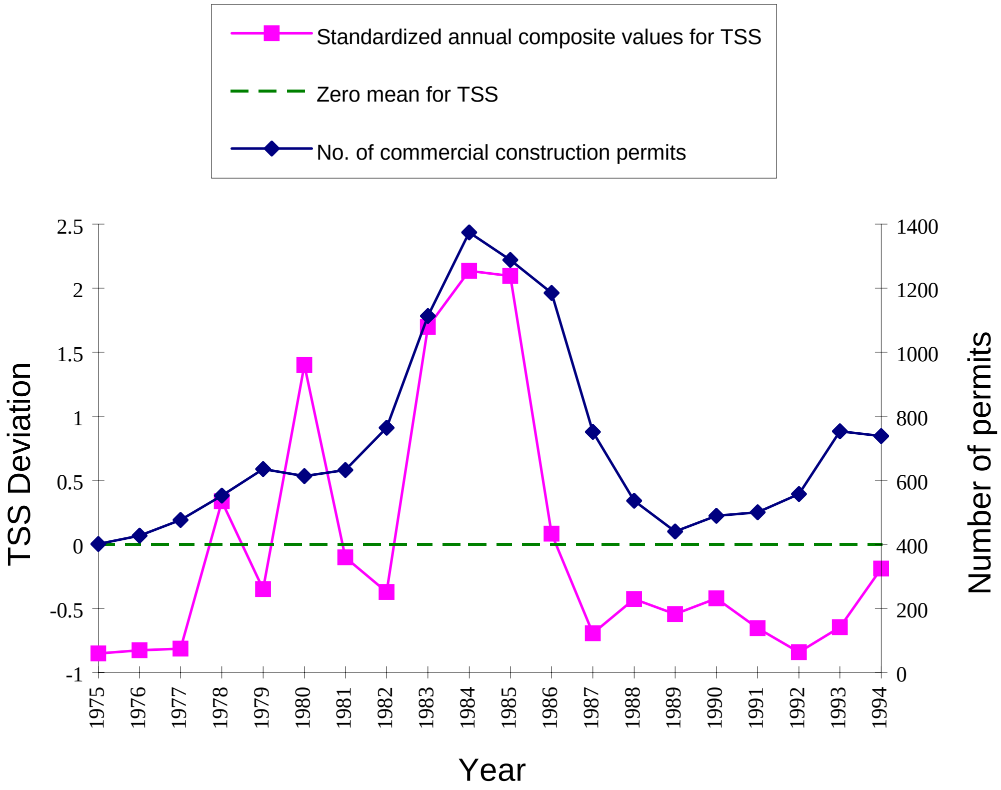


Figure 5.1 **Normalized TSS Concentration Deviation and the Number of Annual Commercial Construction Permits**

Flow Factor

In general, it is found that concentrations of most constituents vary with flow rate. To account for this, many investigations have introduced a power-law model which says that the concentration varies with the flow discharge to some power. For the regression analysis, the flow factor takes the form

$$\phi_{\text{flow}} = \alpha \times Q^{\beta} \qquad (5.2)$$

where a and b are constants determined through regression analysis, and Q is the creek discharge in cubic feet per second (cfs).

Antecedent Conditions Factor

Antecedent conditions for small watersheds without significant baseflow are often characterized by the number of dry days since the end of the last rainfall event. However, for larger watersheds such as Barton Creek, which may have significant direct runoff and baseflow for long periods following a rainfall event, the dry period may not be the best variable to characterize antecedent conditions.

For the regression analysis, antecedent conditions are characterized by the magnitude of average flows over a preceding time period. The average flow from 4 to 16 hours in the past, and the average flow from 64 to 256 hours in the past were used. These averages are calculated as follows. The former was selected to reflect the difference in concentrations on the rising and falling limbs of the hydrograph, while the latter was selected to reflect the wetness or dryness of the creek over the preceding period. If m_i is the average of the preceding *i* hours of flow, then the average flow from 4 to 16 hours, designated as m_{4-16}, is calculated from

$$\mu_{4-16} = \frac{1}{12}\left(16\ \mu_{16} - 4\ \mu_{4}\right) \tag{5.3}$$

and similarly, the average flow from 64 to 256 hours in the past is calculated from

$$\mu_{64-256} = \frac{1}{192}\left(256\ \mu_{256} - 64\ \mu_{64}\right) \tag{5.4}$$

The regression model uses the following forms for the antecedent factors

$$\phi_1 = \alpha \times (\mu_{4-16})^{\beta} \tag{5.5}$$

and

$$\phi_2 = \alpha \times (\mu_{64-256})^{\beta} \tag{5.6}$$

Once the parameters a and b in equations (5.5) and (5.6) are identified through regression analysis, the factors f_1 and f_2 may be calculated from known or simulated creek flow discharge records.

Statistical Significance of Predictors

For data sets that have a sufficient number of samples, the factors that appear in the model Equation (5.1) were tested using the t-test against the null-hypothesis that the parameter equals zero. Categorical significance for each parameter is based on the probability greater than *t* for the null hypothesis, where category 1 has the probability range 0.001 to 0.0001, category 2 has the range 0.01 to 0.001, and category 3 has the range 0.1 to 0.01. Parameters falling into category 4 with probability greater than 0.1 were not considered.

Relationships Between Flow Regime and the Barton Creek Water Quality

There is considerable evidence that flow is the dominant process influencing water quality in the creek. With only a few exceptions, the results from the correlation analysis show strong association between flow rate and concentrations for samples taken under runoff conditions. Table 5.1 summarizes the results from multiple SAS runs. The water quality variables may be separated into three groups based on flow rate. The first group includes those variables which show a positive correlation with flow rate. These variables are pollutants that wash off the surface, and sediment resulting from channel erosion. It includes BOD_5, TOC, fecal coliform (FCOL), fecal streptococci (FSTR), Kjeldahl nitrogen (TKN), total phosphorus (TP), total suspended solids (TSS), and total lead (TPB). These variables have a high partial-R^2 ranging from 0.24 (TPB) to 0.63 (TOC), which means that the flow rate is an important independent variable to model this group. All these variables rank at level one with respect to significance. NH_3 and dissolved zinc (DZN) also show a positive correlation with respect to flow rate, though with a small partial-R^2 and at a level three significance. In comparison to the other processes (which are discussed below), the statistical analyses showed the highest correlation between flow rate and concentration.

Table 5.1 Correlation Analysis of Flow and Water Quality

Runoff				
Overall R^2	Overall Prob > F	Partial R Square	Flow Significance*	No of Point
0.551	0.0001	0.43	+1	164
0.687	0.0001	0.63	+1	181
0.542	0.0001	0.29	+1	166
0.371	0.0001	0.37	+1	162
0.182	0.0001	0.04	+3	132
0.279	0.0001	0.11	-1	168
0.489	0.0001	0.32	+1	181
0.416	0.0001	0.30	+1	183
0.717	0.0001	0.18	-3	37
0.694	0.0001	0.58	+1	161
0.351	0.0172			
0.464	0.0001			
0.364	0.0086			
0.476	0.0001	0.24	+1	112
0.414	0.0001	0.11	+3	57

Baseflow					
Constituent	Overall R^2	Prob > F	Partial R Square	Flow Significance*	No of Point
BOD					
TOC					
FCOL	0.05	0.06	0.08	-3	71
FSTR					
NH3					
NO23	0.30	0.00	0.29	-1	38
TKN					
TP					
TDS	0.39	0.00	0.12	-3	36
TSS					
DCu					
DFe					
DPb					
TPb					
DZn					

or Significance

1: 0.0001-0.001
2: 0.001-0.01
3: 0.01-0.1
4: >0.1 (insignificant)
" + " Positively Correlated
" - " Negatively Correlated
" " No Correlation

The second group of water quality variables is inversely correlated with flow rate. This group includes total nitrite plus nitrate (NO_2+NO_3) at a level one significance and total dissolved solids (TDS) at a level three significance. The fact that the correlation with respect to flow is negative for this group suggests that the source of these variables is from water having longer contact times with soil. These variables are not derived primarily from washoff of the soil surface.

The third group of water quality variables shows no correlation with flow rate. This group includes dissolved copper (DCU), dissolved iron (DFE) and dissolved lead (DPB). It should be noted that most concentrations for variables in this group are generally at or below detection limits, making the analysis somewhat uncertain.

Samples taken during baseflow conditions show little or no correlation between water quality variables and flow rate. The only variables with significant results are inversely correlated with flow rate and include NO_2+NO_3, TDS, and FSTR. It appears that higher flow rates for both runoff and baseflow conditions serve to dilute NO_2+NO_3 and TDS concentrations.

Relationship Between Water Quality and Other Variables

Tables 5.2 and 5.3 present the partial-R^2 coefficients for all factors that influence water quality for runoff and baseflow conditions, respectively. The coefficients in this table were developed by formulating a linear model, which first included the variable with the largest single partial-R^2 value, and then adding the variable with the second largest value, etc. It is clear that during runoff conditions, the variables corresponding to position on the hydrograph and construction period also play a significant role in explaining the variability in measured concentrations, in addition to flow rate. The position on the hydrograph is expected to be important for many of the water quality variables since concentrations are generally greater on the rising limb of the hydrograph than on the falling limb, at the same discharge. The season, antecedent period and location along the creek are seen to play a minor role. For baseflow conditions, there is no single factor that plays a significant role for most variables.

Table 5.2 Water Quality Correlation Analysis Stormflow

				Position of the Hydrograph	Antecedant Flow Condition	Season				Period (Construction)	Station		
Constituent	Overall R^2	Overall Prob > F	Flow			Spring	Summer	Fall	Winter	1983-1986	Loop 360	Lost Creek	Hwy 71
BOD	0.551	0.0001	0.43	0.14	0.05		0.14		0.07				
TOC	0.687	0.0001	0.63	0.18					0.02	0.04			
FCOL	0.542	0.0001	0.29	0.12			0.04	0.02		0.34			
FSTR	0.371	0.0001	0.37	0.14	0.02								
NH3	0.182	0.0001	0.04	0.02	0.04	0.06				0.07			
NO23	0.279	0.0001	0.11	0.05	0.02					0.23	0.02		
TKN	0.489	0.0001	0.32	0.07			0.03			0.22			
TP	0.416	0.0001	0.30	0.13			0.03			0.12			
TDS	0.717	0.0001	0.18	0.18	0.16				0.11			0.22	
TSS	0.694	0.0001	0.58	0.20						0.30			
DCu	0.351	0.0172		0.13	0.08					0.24			
DFe	0.464	0.0001		0.21	0.15					0.23			
DPb	0.364	0.0086		0.26		0.17							
TPb	0.476	0.0001	0.24	0.13			0.22						0.03
DZn	0.414	0.0001	0.11					0.28	0.26				

Table 5.3 Water Quality Correlation Analysis Baseflow

Constituent	Overall R^2	Overall Prob > F	Flow	Position of the Hydrograph	Antecedant Flow Condition	Season			Period (Construction)	Station	
						Spring	Summer	Winter	Year 78-82	Lost Creek	Hwy 71
BOD	0.327	0.0001		0.33							0.057
TOC	0.427	0.0001							0.427		
FSTR	0.198	0.0017	0.08				0.050				0.040
NO23	0.540	0.0001	0.285		0.36			0.287		0.117	
TDS	0.385	0.0010	0.12	0.11						0.384	
DPB	0.283	0.0231				0.283					

Correlation Among Water Quality Variables

Tables 5.4 and 5.5 show the Spearman correlation coefficients for water quality constituents during runoff and baseflow conditions, respectively. For runoff conditions, the correlation coefficients among many of the constituents are positive and high. TSS shows a strong positive correlation with all variables except NO_2+NO_3, DCU, DPB, and DZN, and a strong negative correlation with TDS. TDS, on the other hand, consistently has a strong negative association with all variables, while NO_2+NO_3 has a low correlation with other variables.

Table 5.4 Water Quality Variable Spearman Correlation Stormflow

	BOD	TOC	FCOL	FSTR	NH3	NO23	TKN	TP	TDS	TSS	DCu	DFe	DPb	TPb	DZn
BOD	1.00	0.85	0.81	0.75	0.46	0.09	0.69	0.75	-0.87	0.79	0.18	0.71	0.38	0.67	0.10
TOC	0.85	1.00	0.81	0.81	0.58	0.16	0.79	0.81	-0.80	0.90	0.23	0.69	0.26	0.76	0.18
FCOL	0.81	0.81	1.00	0.85	0.56	0.20	0.74	0.76	-0.86	0.81	0.21	0.78	0.42	0.55	0.10
FSTR	0.75	0.81	0.85	1.00	0.51	0.18	0.65	0.76	-0.81	0.79	0.25	0.72	0.34	0.50	0.26
NH3	0.46	0.58	0.56	0.51	1.00	0.21	0.49	0.64	-0.72	0.58	0.31	0.44	0.50	0.30	0.07
NO23	0.09	0.16	0.20	0.18	0.21	1.00	0.31	0.30	-0.01	0.20	0.21	0.10	0.13	-0.01	0.08
TKN	0.69	0.79	0.74	0.65	0.49	0.31	1.00	0.80	-0.72	0.78	0.37	0.59	0.20	0.69	0.06
TP	0.75	0.81	0.76	0.76	0.64	0.30	0.80	1.00	-0.79	0.81	0.23	0.64	0.32	0.66	0.13
TDS	-0.87	-0.80	-0.86	-0.81	-0.72	-0.01	-0.72	-0.79	1.00	-0.77	-0.34	-0.83	-0.52	-0.08	-0.04
TSS	0.79	0.90	0.81	0.79	0.58	0.20	0.78	0.81	-0.77	1.00	0.25	0.65	0.32	0.73	0.08
DCu	0.18	0.23	0.21	0.25	0.31	0.21	0.37	0.23	-0.34	0.25	1.00	0.18	0.17	-	0.27
DFe	0.71	0.69	0.78	0.72	0.44	0.10	0.59	0.64	-0.83	0.65	0.18	1.00	0.18	0.61	0.12
DPb	0.38	0.26	0.42	0.34	0.50	0.13	0.20	0.32	-0.52	0.32	0.17	0.18	1.00	-	0.18
TPb	0.67	0.76	0.55	0.50	0.30	-0.01	0.69	0.66	-0.08	0.73	-	0.61	-	1.00	0.22
DZn	0.10	0.18	0.10	0.26	0.07	0.08	0.06	0.13	-0.04	0.08	0.27	0.12	0.18	0.22	1.00

Table 5.5 Water Quality Variable Spearman Correlation Baseflow

	BOD	TOC	FCOL	FSTR	NH3	NO23	TKN	TP	TDS	TSS	DCu	DFe	DPb	TPb	DZn
BOD	1.00	0.26	-0.02	0.18	-0.02	0.09	-0.17	0.19	-0.29	0.08	-0.20	0.05	0.05	-0.11	-0.09
TOC	0.26	1.00	0.06	-0.03	-0.14	0.04	0.14	0.17	-0.05	0.06	-0.33	-0.14	-0.35	-0.30	-0.47
FCOL	-0.02	0.06	1.00	0.33	0.06	-0.13	0.13	0.06	-0.08	0.06	-0.37	0.16	-0.11	-0.07	0.15
FSTR	0.18	-0.03	0.33	1.00	0.07	-0.14	-0.04	0.24	-0.19	-0.08	-0.19	0.15	-0.14	0.06	-0.10
NH3	-0.02	-0.14	0.06	0.07	1.00	0.24	0.29	0.25	0.17	-0.13	0.43	0.09	0.60	0.03	0.07
NO23	0.09	0.04	-0.13	-0.14	0.24	1.00	0.08	0.35	0.44	0.14	0.34	0.27	0.53	-0.43	0.04
TKN	-0.17	0.14	0.13	-0.04	0.29	0.08	1.00	0.10	-0.06	0.13	0.28	-0.17	0.48	0.56	-0.03
TP	0.19	0.17	0.06	0.24	0.25	0.35	0.10	1.00	0.09	0.03	-0.21	0.07	0.12	-0.05	-0.21
TDS	-0.29	-0.05	-0.08	-0.19	0.17	0.44	-0.06	0.09	1.00	0.05	0.21	0.17	0.55	-0.23	0.10
TSS	0.08	0.06	0.06	-0.08	-0.13	0.14	0.13	0.03	0.05	1.00	0.30	0.11	0.34	-0.01	-0.05
DCu	-0.20	-0.33	-0.37	-0.19	0.43	0.34	0.28	-0.21	0.21	0.30	1.00	-0.13	0.88	-	0.08
DFe	0.05	-0.14	0.16	0.15	0.09	0.27	-0.17	0.07	0.17	0.11	-0.13	1.00	0.05	-0.25	0.30
DPb	0.05	-0.35	-0.11	-0.14	0.60	0.53	0.48	0.12	0.55	0.34	0.88	0.05	1.00	-	0.24
TPb	-0.11	-0.30	-0.07	0.06	0.03	-0.43	0.56	-0.05	-0.23	-0.01	-	-0.25	-	1.00	0.10
DZn	-0.09	-0.47	0.15	-0.10	0.07	0.04	-0.03	-0.21	0.10	-0.05	0.08	0.30	0.24	0.10	1.00

5.2.2 Application of the Step-Wise Regression Model for Prediction of Barton Creek Water Quality

A statistical regression model was formulated as an alternative to the buildup and washoff models in SWMM. The model requires only a discharge hydrograph to predict water quality throughout a runoff event. This discharge hydrograph could be developed separately, or the model could be used in conjunction with SWMM generated flows. Equation (5.1) was developed to describe correlation between flow and water quality variables. It may also be used as a statistical model to predict water quality. Statistical analyses were performed for both baseflow and runoff conditions to determine which variables should be included in Equation (5.1). The particular form of the statistical regression model depends on the constituent and on whether baseflow or direct runoff conditions exist at the time of application of the model. This model predicts water quality at the three monitoring stations -- Highway 71, Lost Creek Boulevard, and Loop 360 -- as a function of season, time period, existing flow discharge, and average antecedent flow discharge.

Results of the many analyses are summarized in Table 5.6 for baseflow conditions and in Table 5.7 for runoff conditions. For each constituent model the tables show the significant parameter values for each factor, R^2, and the F-test probability greater than F for the resulting model. For example, the model for BOD_5 during baseflow conditions takes the form

$$C_{BOD} = 0.72 - 0.13 \times B_{HWY71} - 0.13 \times (\mu_{4-16})^{0.30} \qquad (5.7)$$

where the second term on the right-hand side is used only for the Highway 71 location. According to this model, the base concentration of BOD_5 is 0.72 mg/L. Samples taken from the Highway 71 station have an average concentration that is 0.13 mg/L lower. The sample concentration depends on the average 4 to 16 hour average antecedent flow, being smaller for larger antecedent flows.

Table 5.6 Barton Creek Baseflow Model

			Flow		Position of the Hydrograph		Antecedant Condition		**Base**	Season			Construction		Station	
Constituent	**R^2**	**Prob > F**	**Flow Coef.**	**Flow Exp.**	**f_1 Coef.**	**f_1 Exp.**	**f_2 Coef.**	**f_2 Exp.**	**Factor**	**Spring**	**Summer**	**Winter**	**Other Year**	**1983-1986**	**Lost Creek**	**Hwy 71**
BOD	0.33	0.0001			-0.13	0.30			0.72							-0.13
TOC	0.43	0.0001							1.6				2.3			
FCOL	0.05	0.061	-83	0.15					190							
FSTR	0.20	0.0017	-610	0.15					930		480					380
NH3	0.06	0.069							0.018					0.016		
NO23	0.54	0.0001	-0.017	0.60			0.042	0.40	0.036			0.12			0.067	
TP	0.05	0.055							0.015			0.031				
TDS	0.38	0.0010	-20	0.45	15	0.50			280						110	
TSS	0.08	0.016							3.0			2.8				
DPB	0.28	0.023							3.40	17						
TPB	0.08	0.076							1.1	4.4						
DZN	0.08	0.063							3.40		2.3					

Similarly, according to Table 5.7 the model for BOD_5 during runoff takes the form

$$\begin{aligned} C_{BOD} = 0.48 + 3.2 \times B_{SUMMER} - 1.3 \times B_{WINTER} + 0.99 \times Q^{0.25} \\ - 0.23 \times (\mu_{4-16})^{0.35} - 0.15 \times (\mu_{64-256})^{0.35} \end{aligned} \tag{5.8}$$

Table 5.7 Barton Creek Storm Flow Model

Constituent	R^2	Prob > F	Flow		Position of the Hydrograph		Antecedant Condition		Base	Season				Construction	Station		
			Flow Coef.	**Flow Exp.**	**f_1 Coef.**	**f_1 Exp.**	**f_2 Coef.**	**f_2 Exp.**	**Factor**	**Spring**	**Summer**	**Fall**	**Winter**	**1983-1986**	**Loop 360**	**Lost Creek**	**Hwy 71**
BOD	0.55	0.0001	0.99	0.25	-0.23	0.35	-0.15	0.35	0.48		3.2		-1.3				
TOC	0.69	0.0001	0.48	0.50	-2.2	0.25			6.2				-2.6	4.2			
FCOL	0.54	0.0001	770	0.40	-940	0.35			2200		7200	5300		22000			
FSTR	0.37	0.0001	1800	0.40	-2000	0.35	-940	0.35	12300								
NH3	0.18	0.0001	0.0022	0.35	-0.0021	0.35	-0.010	0.20	0.034	0.038				0.043			
NO23	0.28	0.0001	-0.031	0.27	0.019	0.30	-0.12	0.05	0.41					0.24	0.067		
TKN	0.49	0.0001	0.028	0.50	-0.062	0.35			0.10		0.59		.	1.2			
TP	0.42	0.0001	0.015	0.35	-0.043	0.20			0.045		0.071			0.11			
TDS	0.72	0.0001	-24	0.20	-60	0.10	17	0.25	320.00				62			73	
TSS	0.69	0.0001	14	0.50	-20	0.40			27					550			
DCU	0.35	0.017			-0.48	0.15	0.94	0.03	1.0					0.91			
DFE	0.46	0.0001			2.0	0.35	-1.2	0.35	7.3					14			
DPB	0.36	0.0086			0.21	0.40			1.6	-1.8							
TPB	0.48	0.0001	1.4	0.35	-8.0	0.15			7.1		25			.			4.3
DZN	0.41	0.0001	3.6	0.17					-3.5			34	17				

Equation (5.8) shows that the BOD_5 concentration during runoff conditions depends strongly on the creek discharge at the time of the sample, as well as the average antecedent discharge during the previous 4-16 hours and 64-256 hours. On the average, BOD_5 concentrations are 3.2 mg/L greater during the summer and 1.3 mg/L smaller during the winter. The models for other constituents take a similar form.

As suggested by the R^2 values for the various models, such a model formulation still retains a great deal of uncertainty in prediction. In general, the models for storm flow conditions are better able to explain the variability in sampling data than the models for baseflow conditions.

An example application of the model is shown in Figure 5.2. This figure, which was generated using the HYDROLOG software model developed as part of this research, shows the discharge hydrograph as well as model-predicted TSS concentrations and measured TSS concentrations at Lost Creek over the period from December 19, 1991 to December 23, 1991.

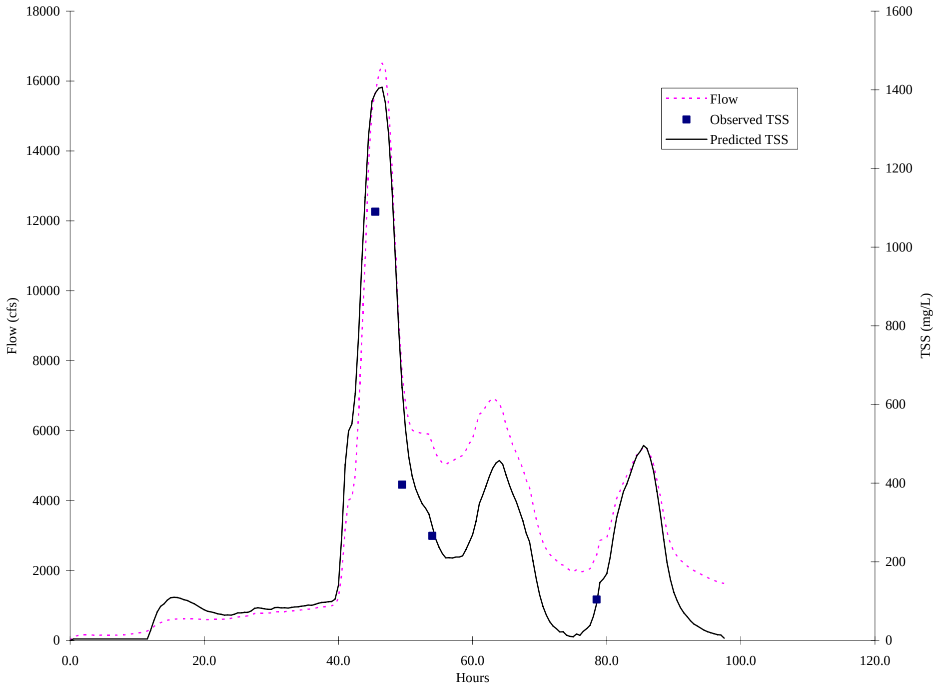


Figure 5.2 Statistical Model Flow Prediction

While the measured data is sparse, the comparison between predicted and measured data is quite good. The discharge hydrograph shown is that measured at the monitoring station. However, since the calibrated model is capable of predicting discharge hydrographs at Highway 71 and Lost Creek Boulevard, one should be able to obtain good water quality simulation results when the statistical regression models are used in conjunction with SWMM simulations.

To illustrate the performance of the statistical regression models, comparisons were developed between the measured and predicted concentrations for TSS and TKN for Highway 71, Lost Creek Boulevard, and Loop 360 stations. For example, Figure 5.3 shows the TSS data for Highway 71, where each point corresponds to a single water quality sample. The value on the x-axis is the TSS concentration computed from Equation (5.1) using the coefficients from Table 5.7 and with flow conditions corresponding to those at the time the sample was taken. The y-axis value for the sample point is the TSS concentration, which was measured for the sample. If the statistical model were exact, the computed concentration would equal the measured concentration and the point corresponding to the sample would lie along the 45^o line, which is shown. Sample points above the 45^o line correspond to the computed concentration under-predicting the measured concentration, and vice versa for points below the line. Except for the individual sample with computed TSS concentration of about 100 mg/L and measured concentration of about 800 mg/L, the sample points fall fairly close to the 45^o line, suggesting that the statistical model performs satisfactorily for predicting TSS concentrations at the Highway 71 station. Figure 5.4 shows computed and measured TKN concentrations for Highway 71 in a similar fashion to Figure 5.3. Again, it appears that the statistical model performs fairly well for TKN at this location.

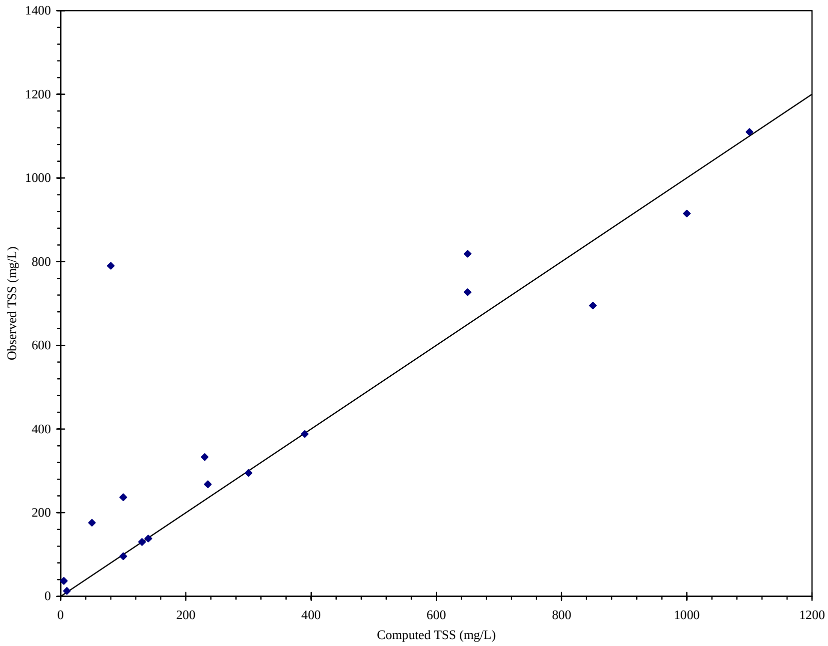


Figure 5.3 Computed and Observed TSS Barton Creek at Highway 71

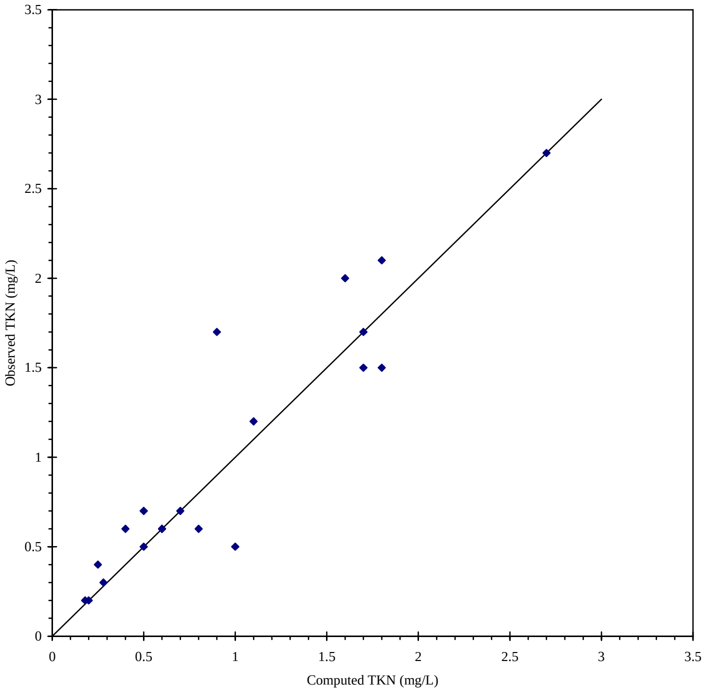


Figure 5.4 Computed and Observed TKN Barton Creek at Highway 71

Figures 5.5 to 5.8 show TSS and TKN computed and measured concentrations at Lost Creek and Loop 360 stations. For TSS at Lost Creek, it would appear that the model consistently underestimates measured concentrations. Similarly, large TSS concentrations are underestimated at Loop 360. Overall, however, the results suggest that the statistical model does retain some predictive capabilities.

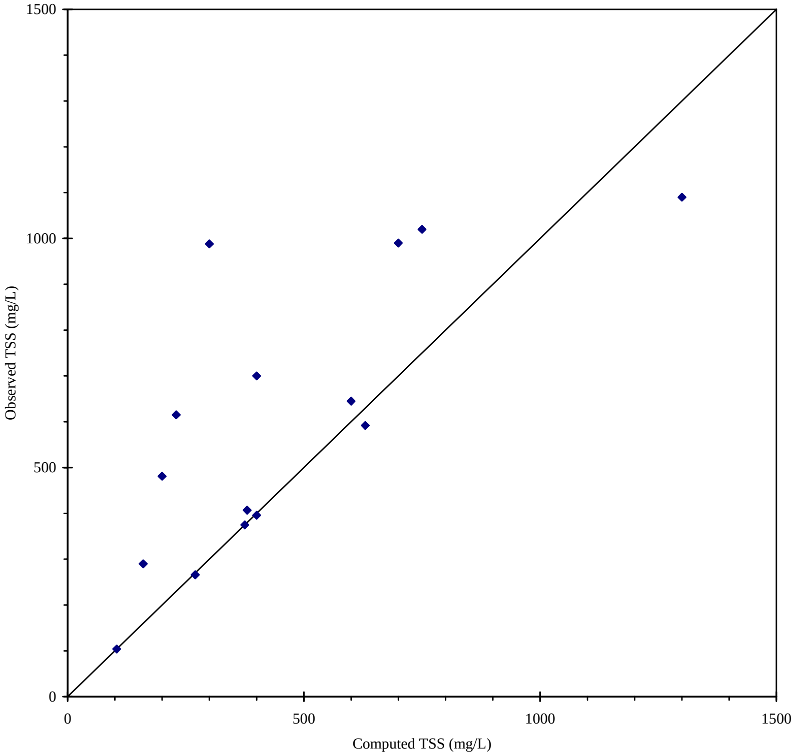


Figure 5.5 Computed and Observed TSS Barton Creek at Lost Creek Boulevard

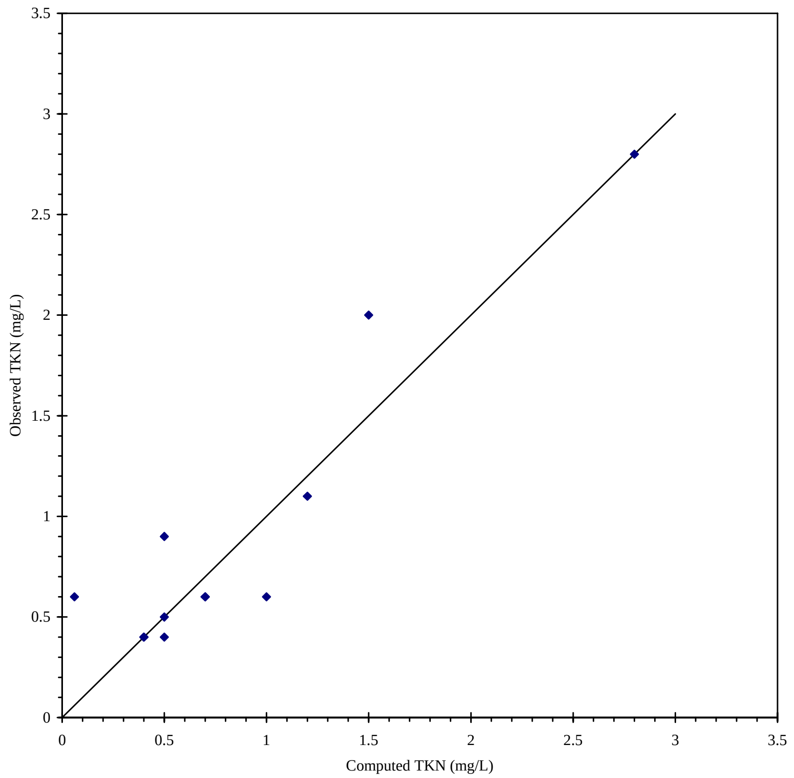


Figure 5.6 Computed and Observed TKN Barton Creek at Lost Creek Boulevard

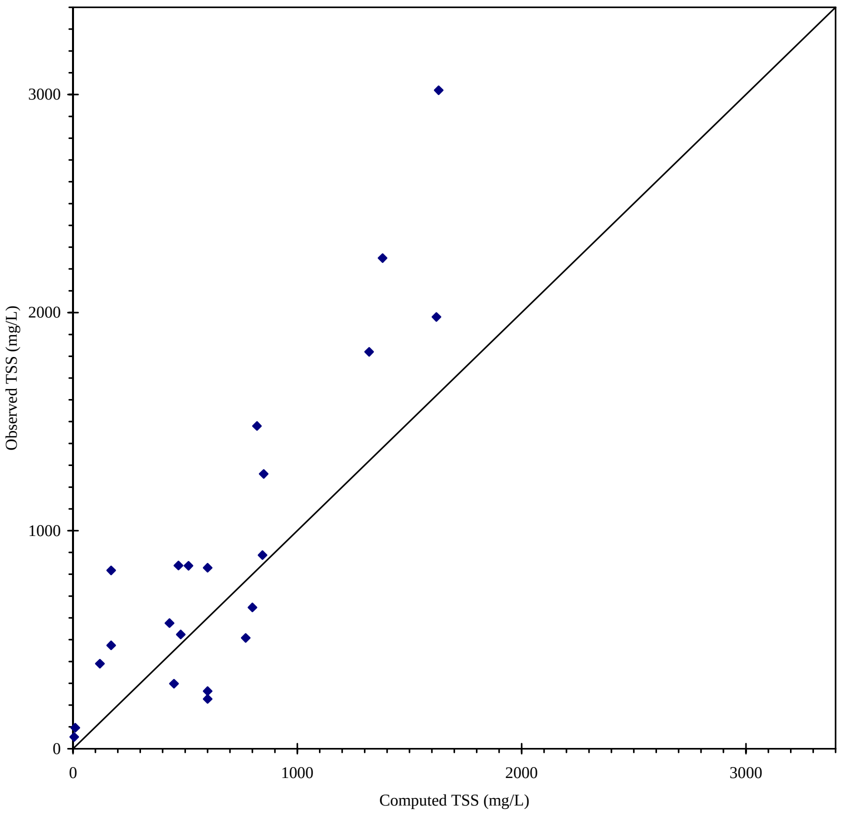


Figure 5.7 Computed and Observed TSS Barton Creek at Loop 360

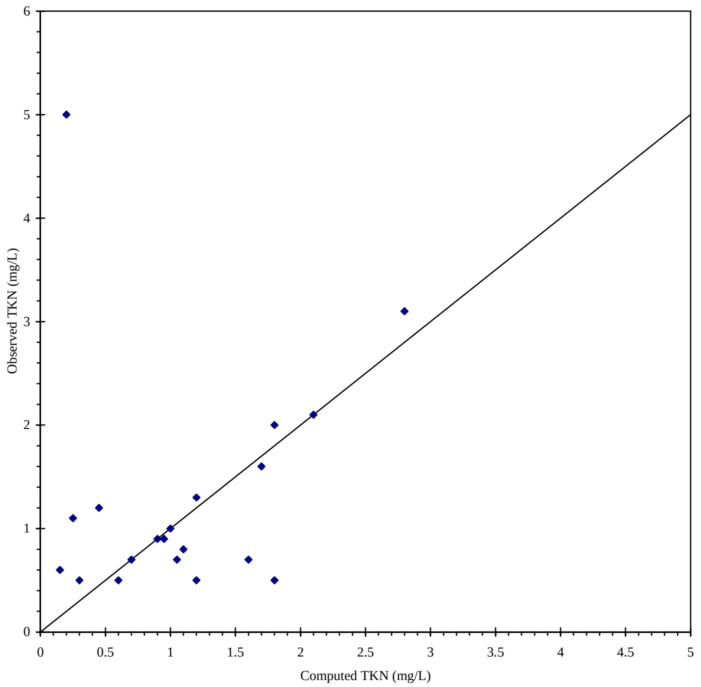


Figure 5.8 Computed and Observed TKN Barton Creek at Loop 360

The limitations of this modeling approach must be recognized. As is the case with any statistical model, the model form and parameters are based on the data used to fit the model. It is difficult, or impossible, to extrapolate the model form and parameters to changing conditions over the watershed. This implies that the statistical model cannot be used to evaluate the impacts of land-use changes on water quality in Barton Creek, except for those land-use changes that impact only the discharge hydrograph. This important limitation means that the model cannot be used to investigate application of BMPs for water quality management since they will impact both the runoff hydrograph as well as the runoff water quality.

5.3 Analysis of Single Land Use Water Quality Data

In order to move toward a management model for application to Barton Creek, the City of Austin single-land-use water quality data has been analyzed. The purpose of this investigation was to develop a deterministic model formulation that might be incorporated within SWMM or other watershed models, and could be used to simulate the impacts of land-use changes at all points within the Barton Creek watershed.

To date, the City of Austin has performed or commissioned single-land-use sampling at seven sites ranging from undeveloped (Bear Creek) to highly developed commercial (Barton Creek Square Mall).

For most monitored storms at each site, three to five samples were analyzed for each of 16 constituents. Section 4.1 describes the City of Austin stormwater monitoring program and available data.

In order to improve long-term continuous simulation of water quality, the single-land-use monitoring data were studied independently of the SWMM model, in order to obtain further insight to the nature of constituent buildup and washoff from these watersheds.

Single-Land-Use Watershed Modeling

One goal of this research was to apply the SWMM model to simulate stormwater quality on the Barton Creek watershed. This watershed consists of a number of subbasins with different land use characteristics. In order to apply SWMM to the Barton Creek watershed and use the model to estimate the potential impacts of changing land use, one must be able to estimate the runoff quantity and quality from various types of land use. The stormwater monitoring program data were analyzed using the various buildup and washoff functions to evaluate whether there was any consistency between the estimated parameters from one storm event to the next. Some of the procedures utilized are described in this subsection.

As part of its stormwater monitoring program (SWMP), the City of Austin (COA) sampled stormwater runoff events for a number of constituents during the period between 1984 and 1987. The test areas monitored included small, single-land-use suburban watersheds with drainage areas ranging from 3 acres to 371 acres. These test watersheds include Bear Creek, Hart Lane, Rollingwood, Highwood Apartments, Barton Creek Square Mall (BCSM), Brodie Oaks Plaza, and Jollyville. Bear Creek (BC) is primarily an undeveloped area with land covered by scrub trees and grass. Hart Lane (HL) and Rollingwood (RO) represent single-family residential areas, while Highwood Apartments (HI) is a multi-family residential area. Barton Creek Square Mall (SI) and Brodie Oaks Plaza (BI) represent watersheds with commercial development and high impervious cover. These two commercial sites, however, were maintained by the parking lot sweeping programs (sweeping every day at BCSM and every three days at Brodie Oaks). In addition, Jollyville (JA) represents runoff from a highway intersection. These single-land-use watersheds are listed in Table 5.8 along with the runoff coefficients, which express the ratio of long-term runoff to rainfall for the watershed.

Table 5.8 Single Land use Watersheds from COA SWMP

Watershed	**Land Use**	**Runoff Coef.**
Bear Creek (BC)	undeveloped	0.007
Hart Lane (HL)	single-family residential	0.17
Rollingwood (RO)	single-family residential	0.039
Highwood Apartments (HI)	multi-family residential	0.62
Barton Creek Square Mall (SI)	commercial	0.83
Brodie Oaks Plaza (BI)	commercial	0.75
Jollyville (JA)	highway	0.56

Estimation of Buildup Using the COA SWMP Data

It is not possible to directly measure the buildup of water quality constituents on an urban watershed. Instead, the constituent buildup must be inferred from the amount of a constituent that is washed off during a series of storm events, and this is very difficult to do. According to the buildup-washoff model, the amount of a constituent on an urban watershed increases with the number of dry days between rainfall events. During a subsequent storm event, depending on the storm duration and intensity, some or all of the constituent will be washed off the watershed with the storm runoff. Starting with the amount of constituent load remaining on the watershed at the end of the storm event, the constituent will again accumulate during the dry days following the event. According to Equation (3.10), the rate of accumulation is an exponentially decreasing function of dry days, and there is a maximum constituent load that can accumulate on the watershed. The following paragraphs will describe attempts to fit this model to observed data.

Estimation of Stormwater Constituent Load

Since the constituent buildup must be estimated from the constituent load that is washed off during storm events, one must be able to estimate this load from the monitored data. The COA SWMP data provide an essentially continuous record of stormwater depth or stage at the monitoring stations, and using an appropriate rating curve, this stage record may be translated into a record of stormwater flow or discharge. If the constituent concentration in the stormwater runoff were also measured on a continuous basis, then the load would be calculated from

$$\mathrm{LOAD} = \int_0^t C(t) \times Q(t)\, dt \qquad (5.9)$$

where LOAD = constituent load (lbs), C(t) = constituent concentration at time t, and Q(t) = stormwater discharge at time t. However, the constituent concentration is not measured on a continuous basis. Instead, the automatic samplers take only a few samples for water quality analysis during a single event, and these samples are generally not spread uniformly throughout the event. For example, Figure 5.9 shows the hydrograph and TSS data for storm HL716 on Hart Lane. There were a total of nine TSS samples taken during this event, and this represents a comparatively large number of samples. In order to calculate the TSS load, one needs to associate a volume with each of the samples. One way of doing this is as follows.

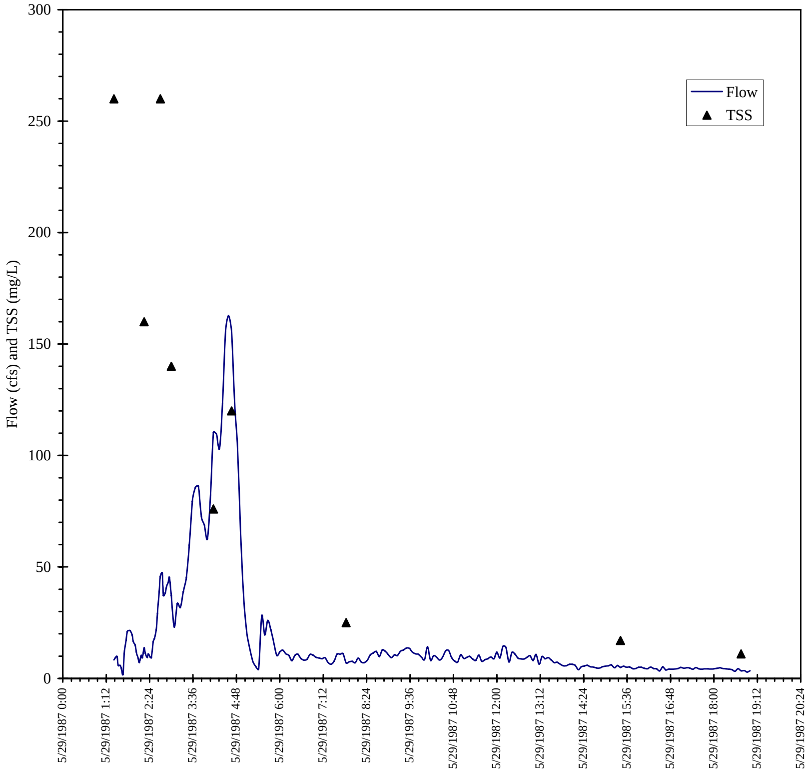


Figure 5.9 Hydrograph and TSS data for Storm HL716 on Hart Lane

From the discharge hydrograph, one can find the cumulative stormwater runoff volume associated with each sample time. The mid-sample volume is then calculated as the cumulative volume at the time of the previous sample plus one-half the difference in cumulative volumes between two sampling times. Then the difference in mid-sample volumes gives the volume to be associated with each sample. The load is then calculated from

$$\text{LOAD} = \sum_{i} C_i \times V_i \qquad (5.10)$$

where C_i = concentration of the i^th^ sample and V_i = sample volume for the i^th^ sample. A unit conversion factor of 28.317 x 2.2046/1,000,000 = 6.243E-5 converts the units of mg-ft^3/L to pounds. The volume on the hydrograph from midpoint to midpoint between sample times is the volume associated with the laboratory-measured concentration. The first sample is associated with the cumulative volume to the first midpoint between samples, while the last sample is associated with the volume from the last midpoint between samples to the end of the runoff event.

Table 5.9 shows the data for storm HL716. The first column gives the time (hours) at which the sample was taken. The second column gives the cumulative runoff volume to the time of sample, and the third column gives the sample TSS concentration (mg/L). Column 4 shows the calculated mid-sample volume between each sample and the succeeding one. The last entry in column 4 is the total runoff for the storm event.

Table 5.9 Calculation of Storm TSS Load for HL716

Time	Cum. Vol. (cu. ft.)	TSS (mg/L)	Mid Vol. (cu. ft.)	Sample Vol. (cu. ft.)	Mass (lbs)	Cum. Mass (lbs)
1:25	1243	260	19137	19137	311	311
2:15	37030	160	55836	36700	367	677
2:42	74642	260	93189	37353	606	1283
3:00	111735	140	238276	145088	1268	2552
4:10	364817	76	482963	244687	1161	3712
4:40	601108	120	720569	237607	1780	5492
7:50	840030	25	960113	239544	374	5866
15:25	1080196	17	1106776	146663	156	6022
18:45	1133356	11	**1200089**	93313	64	6086

Column 5 gives the runoff volume associated with each sample, while column 6, which is the product of columns 3 and 5 and the unit conversion factor, gives the mass associated with each sample. Finally, column 7 gives the cumulative mass runoff. The calculated storm TSS load is 6,086 lbs. The event mean concentration (EMC) is calculated from

$$\overline{C} = \frac{6086 \text{ lbs}}{1200089 \text{ ft}^3} = 81 \frac{\text{mg}}{\text{L}}$$

This method for calculating the load and the EMC is exact only if the sample volume estimates are correct, and if the sample concentrations are representative of the sample volumes. Actually, there is a great deal of uncertainty in both, especially when a storm only has three or four water quality samples for the total runoff event.

An alternative method for estimating the constituent runoff load is to fit the exponential washoff model to the monitoring data, and then use the fitted model to calculate loads. This approach was discussed in Section 3.4. The parameters appearing in the washoff model are the washoff coefficient (RCOEF), the initial available constituent load on the watershed (PSHED(0)), and the initial stormwater concentration in runoff (C(0)). These three parameters are related through Equation (3.19), so only two of them need to be estimated. As noted above, the COA SWMP data provide nearly continuous records of rainfall and watershed runoff, as well as a number of samples of stormwater quality at discrete times. The rainfall records may or may not be from rainfall gauges near the watersheds of interest. The watershed runoff rate is estimated from a record of water level or stage at a control monitoring station, and a rating curve that provides an estimate of the flow rate as a function of stage. The easiest parameters to estimate from the COA SWMP data are RCOEF and C(0), and the simplest way to do this is to proceed as follows:

1. Each discrete water quality sample provides paired values of t* and C(t*), where t* is the time at which the sample was taken. Equation (3.13) may be used to calculate the cumulative runoff to time t*, and thus provide paired data values of RUNOFF(t*) and C(t*).
2. A semi-logarithmic plot (ln C(t*) versus RUNOFF(t*)) of the paired data from step 1 is made, and a straight line is best-fit to the data points. The logarithm of Equation (3.18) gives

$$\ln\left(C(t)\right) = -\text{RCOEF} \times \text{RUNOFF}(t) + \ln\left(C(0)\right) \qquad (5.11)$$

   Equation (5.11) shows that the slope of the best-fit line is equal to -RCOEF, while the intercept will equal the estimate of ln C(0).
3. Equation (3.19) is used to calculate PSHED(0) in pounds, and then Equation (3.15) is used to calculate the stormwater load, also in pounds, for the runoff event. If AREA is measured

in acres, C(0) in mg/L, and RCOEF in inch^{-1}, then the numerical result from Equation (3.19) should be multiplied by 0.226 as a unit conversion from acre-inch-mg/L to lbs.

For example, this approach may be applied to the data for storm HL716 from Hart Lane. Figure 5.10 shows a semi-logarithm plot of the TSS data and the best-fit line. The intercept gives C(0) = 238 mg/L while the slope gives RCOEF = 3.35 inch^{-1}. Figure 5.11 shows an arithmetic plot of the same data and exponential model. With RCOEF and C(0) estimated from the slope and intercept of the best-fit line on the semi-log plot, the value of PSHED(0) is calculated from Equation (3.19) as 5,960 pounds (where the watershed area of Hart Lane is 371 acres). Finally, the TSS load is calculated from Equation (3.15) as LOAD = 5,660 pounds (where the total runoff is 0.891 inches). This estimate differs from the previous one by about 7 percent, which is certainly small compared with the large uncertainty that is common in urban stormwater data. When there are fewer data points, the second method may be preferable for estimating loads, though it is difficult to make any general recommendations.

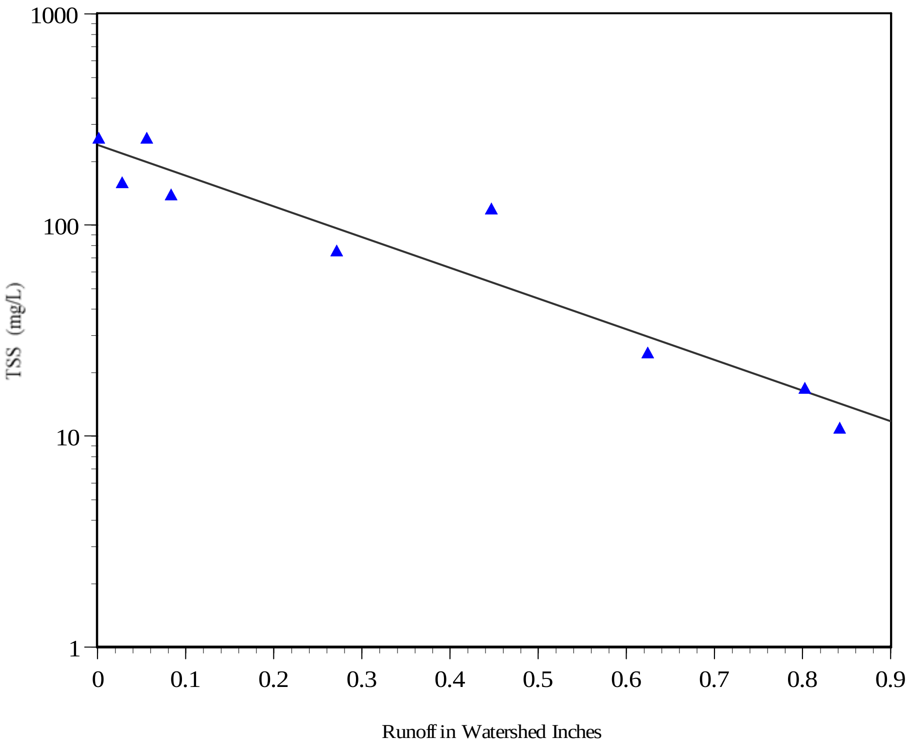


Figure 5.10 Trendline and Observed TSS data for Storm HL716

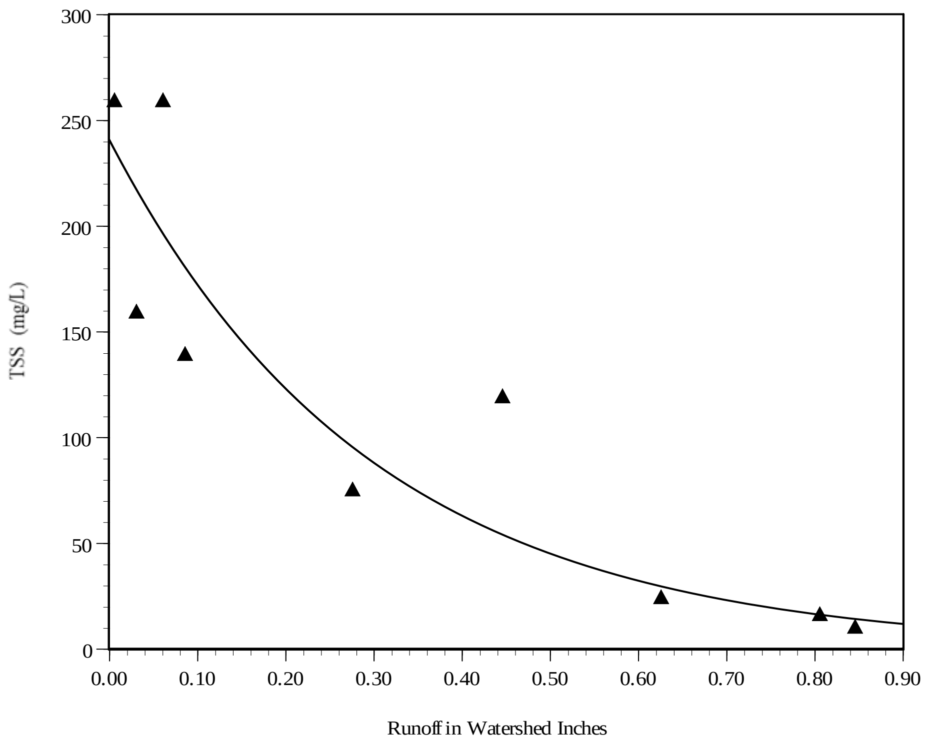


Figure 5.11 Exponential Washoff Model and Observed TSS Concentrations for HL716

Estimation of the Buildup Model Parameters

The buildup model has two parameters. The first of these, QFACT(1), is the maximum constituent load that can accumulate on the watershed. It is apparent that QFACT(1) must be greater than the largest magnitude of PSHED(0) for any measured storm, where PSHED(0) is the constituent load on the watershed at the beginning of the runoff event. Thus, if PSHED(0) is estimated for each event, then QFACT(1) may be estimated as a multiple of the largest PSHED(0), where the multiplier might be 1.1, 1.3, or a similar number.

The second parameter in the buildup model is QFACT(2), which is the first-order rate parameter for buildup as a function of the number of dry days. The buildup model from Equation (3.10) may be written for the end of a dry period as

$$\ln\left(\frac{\mathrm{QFACT(1)}}{\mathrm{QFACT(1)} - \mathrm{PSHED(0)}_{\mathrm{i}}}\right) = \mathrm{QFACT(2)} \times \mathrm{DD}_{\mathrm{i}} \qquad (5.12)$$

where $PSHED(0)_i$ = initial accumulated load on watershed for storm event i and DD_i = number of dry days preceding storm event i. If the factor within the parenthesis in Equation (5.12) is plotted against number of dry days preceding each event on a semi-logarithm graph, then the slope of the resulting best-fit line would be the estimate of QFACT(2).

The approach which was actually used for estimating QFACT(1) and QFACT(2) was to first record DD_i and estimate $PSHED(0)_i$ for each runoff event for a constituent and watershed. This set of $PSHED(0)_i$ - DD_i values were used in Equation (5.12), and the values of QFACT(1) and QFACT(2) were adjusted so that the sum of the squared differences between the data points and the model equation was minimized. The results for TSS and phosphorus are shown in Table 5.10, where the values of QFACT(1) have been normalized against the watershed areas. There are a couple of features worth noticing in this table. First, for both TSS and phosphorus, the maximum load is much less for the undeveloped area, and significantly greater for the highway land use, than for residential and commercial land use. For TSS, the maximum load is roughly 50 times greater for commercial and residential land use, and more than 200 times greater for highways, than for undeveloped land. The second feature to note is that the buildup rate is fairly slow. The time required for the watershed load to build up to 90 percent of the maximum load can be calculated using Equation 5.12, where PSHED(0) is set to 0.9 times QFACT(1). As an example, for TSS on Bear Creek, it would take 25 dry days to build up to 90 percent of the maximum watershed load, and for Hart Lane it would take 65 days.

Table 5.10 Buildup Model Parameters for Single Land use Watersheds

Watershed	Land Use	QFACT(1) (lbs/acre)	QFACT(2) (day^{-1})
	Total Suspended Solids		
Bear Creek	Undeveloped	1.16	0.0907
Hart Lane	Med. Density Res.	55.9	0.0354
Rollingwood	Low Density Res.	40.7	0.0180
Highwood Apartments	Multi Family Res.	58.3	0.0617
Barton Creek Square Mall	Commercial	45.6	0.0548
Brodie Oaks Plaza	Commercial	54.2	0.0385
Jollyville	Roadway	234	0.0301
	Phosphorus		
Bear Creek	Undeveloped	0.001	0.0314
Hart Lane	Med. Density Res.	0.077	0.0271
Rollingwood	Low Density Res.	0.145	0.0252
Highwood Apartments	Multi Family Res.	0.248	0.0610
Barton Creek Square Mall	Commercial	0.101	0.0454
Brodie Oaks Plaza	Commercial	0.148	0.1470
Jollyville	Roadway	0.585	0.0776

While the results shown in Table 5.10 appear to be consistent and reasonable, they should be viewed with some caution. Even though the parameters were estimated by forcing a best-fit of Equation (5.12), the resulting fit is not very good, suggesting that perhaps the model is not appropriate. For example, the TSS data for Bear Creek, Hart Lane, and Barton Creek Square Mall are shown in Figures 5.12 to 5.14. It is apparent that the data show a wide scatter about the best-fit line. As a more quantitative measure, it is noted that the R^2 values for the three sites are 0.105, 0.249, and 0.150, respectively. The fit for the phosphorus data is equally poor.

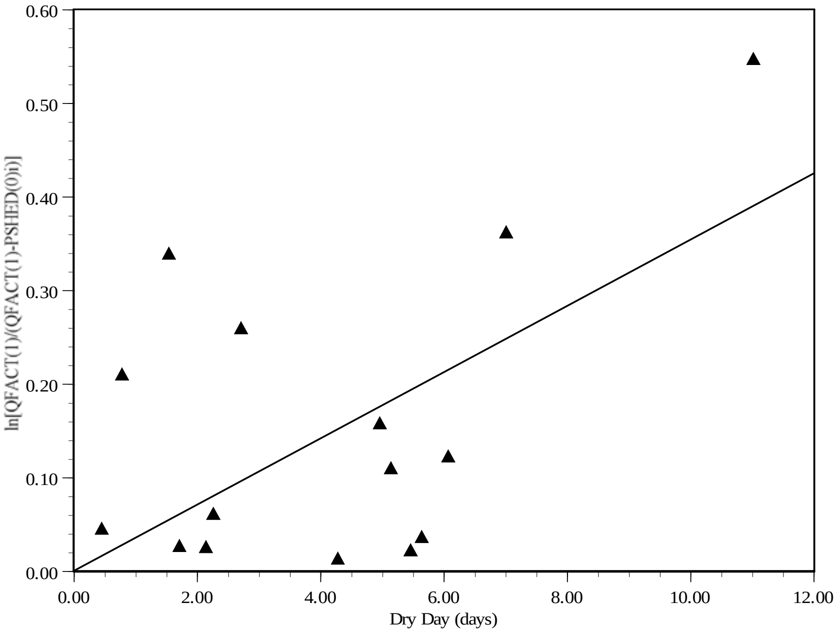


Figure 5.12 Buildup Model for Hart Lane - TSS

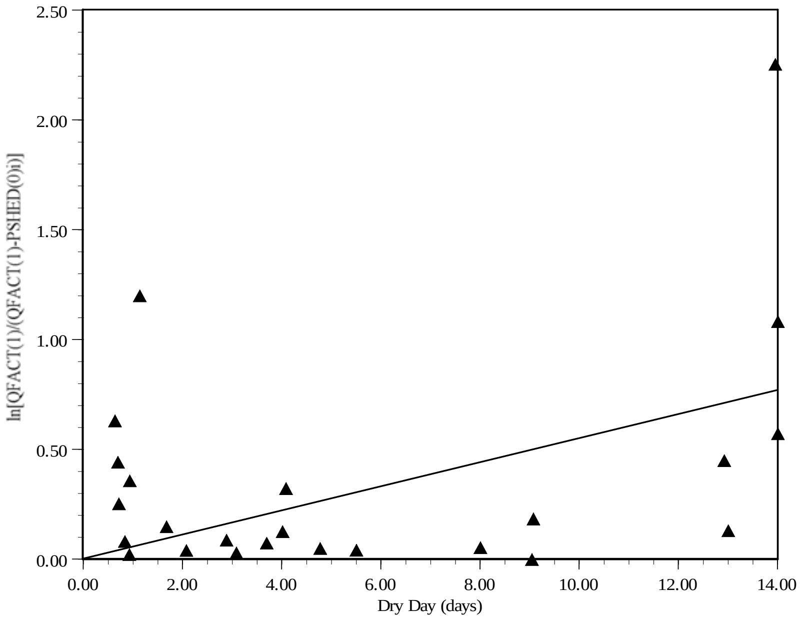


Figure 5.13 Buildup Model for Barton Creek Square Mall - TSS

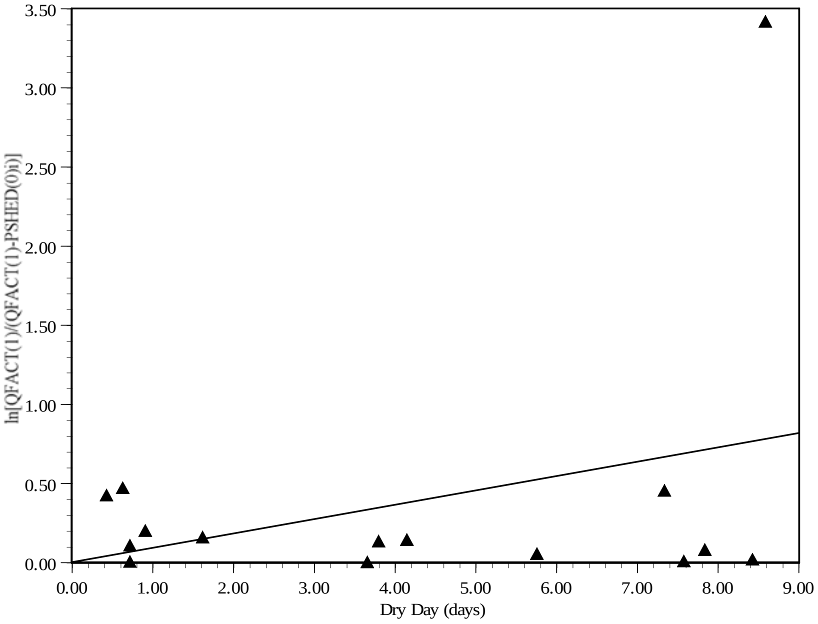


Figure 5.14 Buildup Model for Bear Creek - TSS

Another way to look at the buildup and its dependency on the number of dry days is to plot the initial load on the watershed as a function of dry days. This is shown in Figure 5.15. This figure clearly shows the wide range in initial TSS load on a watershed, with more than a two order of magnitude difference between Bear Creek, Brodie Oaks Plaza and Highwood Apartments. This figure also shows quite clearly that there is no discernible increase in load on the watershed with increasing number of dry days. In fact, additional investigations have shown that it was not possible to identify a single variable with which the initial watershed load was highly correlated. The best representation that could be found was to treat the initial load as a random variable which appeared to be log-normally distributed.

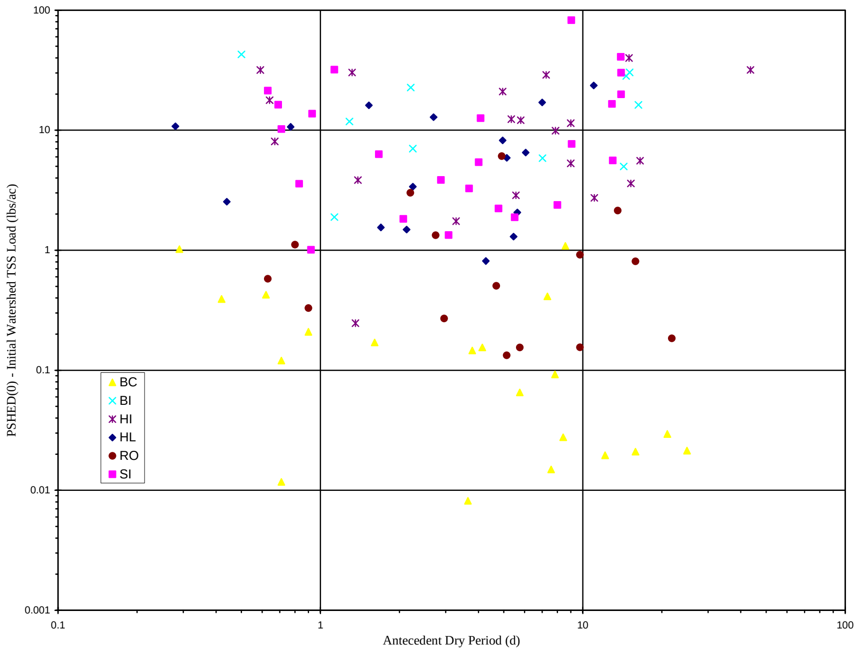


Figure 5.15 Initial TSS Load vs Antecedent Dry Period

Analysis of Constituent Washoff Using COA SWMP Data

The discussion in the last section showed that at present, it is not possible to model constituent buildup on a watershed in any reliable fashion. The question remains as to what extent it is possible to model constituent washoff given that, in general, one will not know the amount of constituent available for washoff at the beginning of a storm event. This question is addressed in the following paragraphs.

Event Load versus Runoff

The data show a general correlation of increasing storm TSS load with increasing total storm runoff. In order to compare the different land-use watersheds, it is convenient to compare the events on a load-per-acre basis. As is typical of stormwater quality data, the results are quite variable. Nevertheless, the general trend is clear. The TSS load that the stormwater carries from the watershed increases with the amount of runoff a rainfall event produces. The data are best-fit by the linear model (the best-fit line on the log-log plot has a unit slope)

$$\mathrm{LOAD} / \mathrm{ACRE} = 17.31 \times \mathrm{TRO} \tag{5.13}$$

where TRO is the total runoff for the event. The squared regression coefficient for this best-fit model is $R^2 = 0.388$ (for the logarithmic fit to the data, $R^2 = 0.771$). Thus, an average TSS load from a storm runoff event is 17.3 lbs/acre/inch of runoff. This corresponds to an effective event mean concentration of 76.4 mg/L for all watershed land uses (1 lb/acre/in = 4.41 mg/L).

A linear model was also fit to the TSS data from each land-use watershed individually, with the results shown in Table 5.11. The values of the slopes of the linear models give a measure of TSS load in units of lbs/acre/inch of runoff. In terms of this measure of potential stormwater TSS load, Barton Creek Square Mall has the lowest value; Bear Creek, Brodie Oak, and Highwood have similar values; the single-family residential areas of Hart Lane and Rollingwood have larger values; and the Jollyville highway intersection has the largest value. One must note, however, that the measures shown in Table 5.11 provide only part of the picture of stormwater load from different land-use watersheds. The most important feature is the amount of runoff produced from rainfall events on the different watersheds. The difference in runoff coefficients (ratio of runoff to rainfall amounts) is much more important in determining TSS load. Indeed, Jollyville, Barton Creek Square Mall, Highwood, and Brodie Oak yield a larger stormwater TSS load on a pounds-per-acre basis because of their larger runoff coefficients associated with land use and impervious cover.

Table 5.11 TSS Load from Single-Land-Use Watersheds

Watershed	**Land Use**	**TSS Load (lbs/acre/inch)**	**EMC (mg/L)**
Bear Creek	Undeveloped	13.55	59.8
Hart Lane	Med. Density Res.	25.05	110
Rollingwood	Low Density Res.	23.09	102
Highwood	Multi Family Res.	14.67	64.7
Barton Ck. Sq. Mall	Commercial	9.04	39.9
Brodie Oak	Commercial	14.58	64.4
Jollyville	Roadway	32.45	143

Figure 5.16 compares the measured TSS load with that predicted using the average EMC for all watersheds. The overall comparison may be adequate, though very few points fall on the “match” line, which corresponds to predicted and measured loads being equal. Most of the loads for Hart Lane are underestimated, as are all of the loads from Jollyville. Most of the loads for Barton Creek Square Mall (SI) are overestimated.

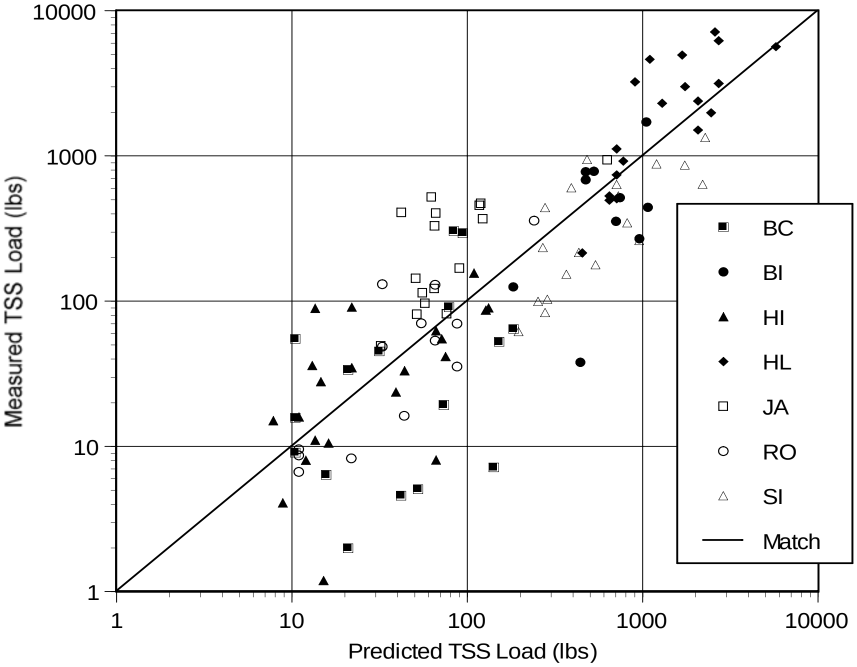


Figure 5.16 Comparison of Predicted and Measured TSS Loads Using Constant Model

Figure 5.17 shows the predicted and measured loads for a prediction model using EMCs for the individual land uses shown in Table 5.11. The predictive capability of this model is somewhat better than using an EMC independent of land use, though there is still a great deal of scatter about the “match” line. The total measured and predicted loads from the analyzed runoff events are listed in Table 5.12. The predicted values vary from the measured TSS loads by an average of about 15 percent, usually on the low side. One might conclude that the deterministic model is adequate for prediction of long-term loads, but that single-event loads remain uncertain.

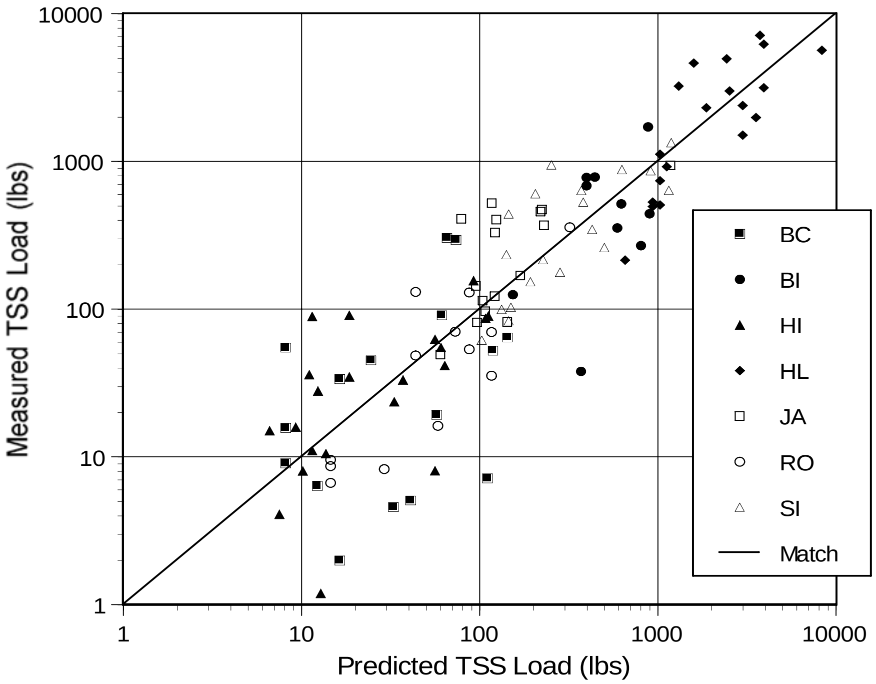


Figure 5.17 Comparison of Predicted and Measured TSS Loads Using Variable Model

Table 5.12 Comparison of Total TSS Load from Runoff Events

Watershed	Predicted (lbs)	Measured (lbs)
Bear Creek	794	1014
Brodie Oak	5,532	5,732
Highwood	758	907
Hart Lane	45,675	50,951
Jollyville	3,176	4,776
Rollingwood	1,015	950
Barton Ck. Sq. Mall	7,513	8,641

Calibration of a Single-Event Washoff Model

The parameters in the washoff model are the initial stormwater concentration C(0) and the washoff coefficient RCOEF. Under ideal conditions C(0) would depend on the antecedent dry period while a characteristic constant value of RCOEF would be found for each single-land-use watershed. However, the data show that RCOEF is quite variable, not only from one watershed to the next, but also from one storm event to the next for a single watershed. However, RCOEF does show a significant correlation with total storm runoff, as shown in Figure 5.18. The best-fit line shown in this figure is specified by

$$\mathrm{RCOEF} = \frac{2.17565}{\mathrm{TRO}} \qquad (5.14)$$

TRO is the total storm runoff for the event. For the logarithm of the data as shown in the figure, the R^2 value is 0.891, suggesting that the fit of Equation (5.14) is fairly good.

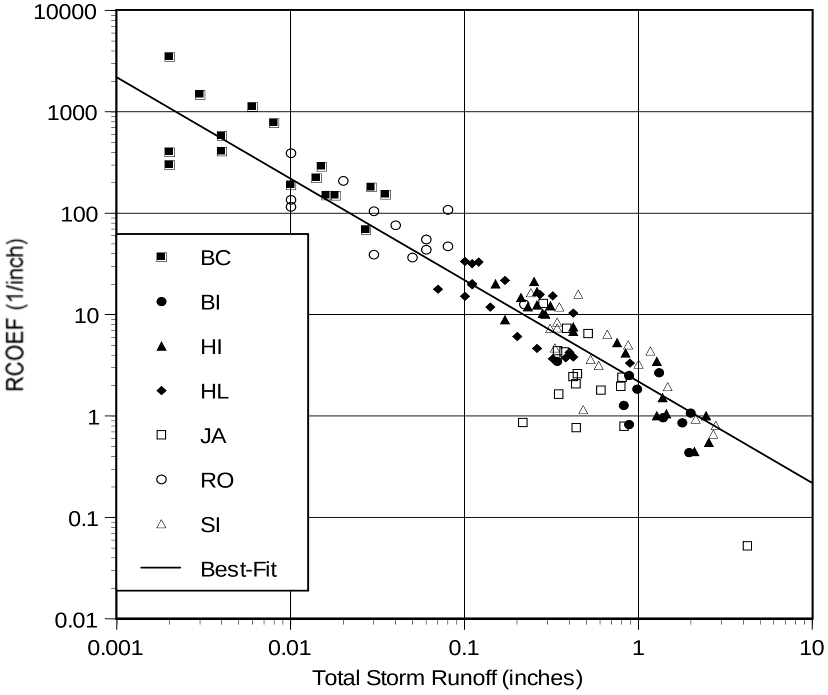


Figure 5.18 Washoff Coefficient for Single Land Use Watersheds

The relationship specified by Equation (5.14) is of some interest. If PSHED(0) is interpreted as the initial contaminant load on the watershed and LOAD is the resulting stormwater contaminant load from the event, then the ratio of LOAD to PSHED(0) is the fraction of contaminant which is removed during the runoff event. According to Equation (3.15), this fraction is expressed by

$$\left(1 - e^{-\mathrm{RCOEF} \times \mathrm{TRO}}\right) \qquad (5.15)$$

Using the relationship in Figure 5.18, Equation (5.15) may then be interpreted as stating that the fraction of the initially mobilized TSS load that is actually removed during the runoff event is

$$\left(1 - e^{-2.17565}\right) = 0.8865 \qquad (5.16)$$

According to this interpretation, the amount of TSS that is mobilized during a storm event is determined by the amount of runoff the event produces. In addition, according to Equation (5.16), roughly 90 percent of this mobilized TSS actually appears in the stormwater runoff. If the amount of runoff is small, such as that developed from the Bear Creek watershed, then RCOEF is large and the ultimate stormwater TSS load is removed with only a small volume of runoff. On the other hand, if the amount of runoff is large, then RCOEF is smaller, and the TSS load is removed more slowly with respect to runoff during the runoff event.

The RCOEF-TRO model (equation 5.14) was also fit to the total runoff data from each single-land-use watershed individually. The results are shown in Table 5.13. The estimated percent TSS removal ranges from a low of 64.3 percent for Jollyville up to 94.3 percent for Bear Creek.

Table 5.13 Percent TSS Removal During Runoff Event

Watershed	**RCOEF x TRO**	**% TSS Removal** **($1 - e^{-RCOEF*TRO}$)**
Bear Creek	2.8702	94.3
Brodie Oak	1.4733	77.1
Highwood	2.6542	93.0
Hart Lane	2.2605	89.6
Jollyville	1.0298	64.3
Rollingwood	2.7152	93.4
Barton Ck. Sq. Mall	2.6366	92.8

Combining equations (3.15), (3.19), (5.13), (5.14), and (5.16), one may estimate the initial TSS concentration as

$$C(0) = \frac{17.31\,(\text{lbs / acre / inch}) \times 2.17565}{0.8865 \times 0.226\,(\text{lb–L / acre–inch–mg})} = 188\text{ mg / L} \qquad (5.17)$$

The data in Tables 5.11 and 5.12 may be used to estimate initial TSS concentration for each single-land-use watershed individually. The results are shown in Table 5.14.

Table 5.14 Initial TSS Concentration from Single-Land-Use Watersheds

Watershed	**C(0) -- mg/L**
Bear Creek	182
Brodie Oak	123
Highwood	185
Hart Lane	280
Jollyville	230
Rollingwood	297
Barton Ck. Sq. Mall	114

5.4 Channel Erosion

Sediment accumulation and movement in the Barton Creek basin warrants further discussion due to erosion and secondary washoff processes occurring in the watershed. During periods of high flow in Barton Creek, TSS concentrations greatly exceed those evidenced in monitoring of single-land-use basins around Austin. Field visits have shown that stream bank erosion and resuspension of previous low-flow sedimentation are a primary cause. In general, storm flow monitoring in Barton Creek shows a clear correlation between flow rate and TSS concentration.

A second source of solids in runoff are construction sites and other areas of disturbed soils. Despite recent improvements in erosion and sedimentation controls, as well as improvements in technology and regulation, construction sites still contribute large amounts of solids loadings to receiving waters. Recently, construction runoff from the Highway 290/Highway 71 interchange introduced flows heavily laden with sediment to a Barton Creek tributary in spite of control measures installed by the Texas Department of Transportation and the contractor. This conclusion was reached from direct observation of silt fences and other controls being overwhelmed by runoff flows.

In order to distinguish channel erosion from other watershed sources of TSS during stormwater runoff, results from the single-land-use watershed analyses were used in conjunction with Barton Creek monitoring data for the Highway 71, Lost Creek, and Loop 360 stations. For storm events with adequate water quality data, the creek event load was calculated using the procedures described in Section 5.4. Total runoff was calculated using HYDROLOG, which integrates the area under the storm hydrograph. The total watershed TSS load was calculated using the variable model described in Section 5.4. The difference between the calculated watershed and creek loads is attributed to channel erosion. Differences in total channel erosion contributions calculated at each monitoring site were used to estimate the channel erosion load per channel length for each event.

Results calculated from four storm events are shown in Table 5.15. There were only four storm events with sufficient water quality sampling data so that means event concentrations and total loads could be estimated at Highway 71, Lost Creek, and Loop 360. The surface load was calculated using the EMCs for each land use from Table 5.11. The difference in total load and surface load (upland washoff) is attributed to the channel as a source. As stated previously, the difference in loads between Lost Creek and Highway 71, and between Loop 360 and Lost Creek, for each event gives the erosion-per-channel segment. If the channel segment erosion is divided by the length of the channel segment, the result gives the channel erosion per mile. The channel length between Lost Creek and Highway 71 is 11.84 miles, while that between Loop 360 and Lost Creek is 4.34 miles. For Highway 71, the calculated channel load is divided by the total upstream channel length for Barton Creek and Little Barton Creek, which is 35.75 miles. The slopes of channel erosion rate plotted against the runoff volume gives a normalized measure of the erosion load at these stations in units of pounds/mile/inch of runoff. Results are listed below.

• Highway 71	90,000 lbs/mile/inch
• Lost Creek Boulevard	150,000 lbs/mile/inch
• Loop 360	500,000 lbs/mile/inch

Table 5.15 Results of Barton Creek Storm Model with Erosion TSS Load

TSS	Storm Date	Event Mean Conc. (mg/l)	Runoff Volume (inch)	Total Load (lbs)	Surface Load (lbs)	Channel Load (lbs)	Segment Channel Erosion (lbs)	Surface Load Fraction	Channel Erosion per mile (lbs/mile)
Loop 360	5/3/1990	483	0.27	2.23E+06	2.86E+05	1.95E+06	4.35E+05	0.13	1.00E+05
	12/20/1991	802	6.73	9.12E+07	7.01E+06	8.42E+07	6.51E+07	0.08	1.50E+07
	3/4/1992	575	1.26	1.22E+07	1.31E+06	1.09E+07	2.52E+06	0.11	5.81E+05
	1/9/1991	666	0.29	3.32E+06	3.07E+05	3.01E+06	2.60E+06	0.09	5.98E+05
Lost Creek	5/3/1990	442	0.26	1.75E+06	2.42E+05	1.51E+06	7.89E+05	0.14	6.67E+04
	12/20/1991	367	4.01	2.29E+07	3.80E+06	1.91E+07	6.53E+06	0.17	5.51E+05
	3/4/1992	536	1.13	9.44E+06	1.07E+06	8.37E+06	5.41E+06	0.11	4.57E+05
	1/9/1991	170	0.24	6.45E+05	2.31E+05	4.14E+05	4.14E+05	0.36	3.50E+04
Hwy 71	5/3/1990	441	0.15	8.37E+05	1.14E+05	7.23E+05		0.14	2.02E+04
	12/20/1991	300	4.05	1.57E+07	3.15E+06	1.26E+07		0.20	3.52E+05
	3/4/1992	443	0.60	3.43E+06	4.64E+05	2.96E+06		0.14	8.29E+04
	1/9/1991	83	0.18	1.89E+05	1.37E+05	5.25E+04		0.72	1.47E+03

The result for Loop 360 does not include the point for the event with 6.73 inches of runoff. If this point were included, the slope would change to more than 2 million lbs/mile/inch. The increasing load factor for the downstream stations is consistent with channel morphology. The amount of alluvium along the channel increases in the downgradient direction. These results suggest that most of the TSS load during large events in Barton Creek is derived from the channel rather than stormwater runoff from the basin. The surface load fraction, which is the ratio of the surface load to the total load, is generally in the range of 0.1 to 0.2.

To evaluate the relative sensitivity of this analysis, the same procedure was applied to lead data, as shown in Table 5.16. The surface load fraction for lead is much higher than for total suspended solids, confirming that the channel is the source of most of this TSS.

Table 5.16 Results of Barton Creek Storm Model with Erosion Lead (Pb) Load

Pb	Storm Date	Event Mean Conc. (mg/l)	Runoff Volume (inch)	Total Load (lbs)	Surface Load (lbs)	Channel Load (lbs)	Segment Channel Erosion (lbs)	Surface Load Fraction	Channel Erosion per mile (lbs/mile)
Loop 360	5/3/1990	8.0E-3	2.7E-1	3.7E+1	1.6E+1	2.1E+1	1.4E+1	0.42	3.3E+0
	12/20/1991	9.4E-3	6.7E+0	1.1E+3	3.8E+2	6.8E+2	3.9E+2	0.36	9.0E+1
	3/4/1992	1.1E-2	1.3E+0	2.3E+2	7.2E+1	1.6E+2	1.7E+1	0.31	3.8E+0
	1/9/1991	2.5E-3	2.9E-1	1.3E+1	1.7E+1	-4.2E+0	-1.0E+1	1.34	-2.4E+0
Lost Creek	5/3/1990	5.0E-3	2.6E-1	2.0E+1	1.3E+1	7.2E+0	-4.8E-1	0.63	-1.1E-1
	12/20/1991	7.8E-3	4.0E+0	4.8E+2	2.0E+2	2.9E+2	7.4E+1	0.41	1.7E+1
	3/4/1992	1.1E-2	1.1E+0	2.0E+2	5.6E+1	1.4E+2	1.1E+2	0.28	2.5E+1
	1/9/1991	4.8E-3	2.4E-1	1.8E+1	1.2E+1	6.2E+0	6.2E+0	0.66	1.4E+0
Hwy 71	5/3/1990	7.2E-3	1.5E-1	1.4E+1	5.9E+0	7.7E+0		0.43	2.2E-1
	12/20/1991	7.1E-3	4.0E+0	3.7E+2	1.6E+2	2.1E+2		0.43	5.9E+0
	3/4/1992	7.1E-3	6.0E-1	5.5E+1	2.4E+1	3.1E+1		0.43	8.8E-1
	1/9/1991	5.0E-3	1.8E-1	1.1E+1	7.1E+0	4.4E+0		0.62	1.2E-1

5.5 Summary

Correlation analysis shows that BOD_5, TOC, FCOL, FSTR, TKN, TP, TSS, and TPB from runoff samples increase with flow rate, while NO_3+NO_2 is inversely related. These water quality parameters that are correlated with flow are derived from channel erosion and surface washoff. Other water quality parameters that were analyzed have a small correlation to flow rate. With the exception of NO_2+NO_3, baseflow samples show little or no correlation between flow rate and water quality.

In addition to flow rate during runoff conditions, water quality variables also are correlated with position on the hydrograph and construction period. For the most part, water quality under baseflow conditions was not impacted by the active construction in the Austin area during the period from 1983 to 1986. On the other hand, during storm flow conditions, the concentrations of many of the water quality constituents increased during this period of active construction. In particular, the TSS concentration was 550 mg/L greater. The season, location along the creek, and dryness are also important, but to a lesser degree. The correlation analyses among water quality variables also show a stronger association among pollutants in runoff than in baseflow. TSS shows a strong correlation with all variables except NO_2+NO_3, DCU, DPB, and DZN. TDS has a strong inverse correlation with all other variables, while NO_2+NO_3 has no correlation with others.

The step-wise statistical regression model of the Barton Creek watershed was shown to provide an adequate simulation of water quality constituent concentrations at the monitoring locations. Constituent concentrations may be estimated using either a measured storm hydrograph, or one that is generated through a model such as SWMM. It is recognized, however, that it is difficult to extend the statistical model to other locations, or to extrapolate the results in order to examine the impacts of land use changes on water quality.

An evaluation of single-land-use water quality data suggests that estimation of initial concentrations in storm water runoff cannot be developed through contaminant buildup models, at least for those models that are based on antecedent dry period. However, the water quality behavior of certain constituents, such as total suspended solids, does tend to follow simple washoff models. Further, it is suggested that the washoff rate coefficients are dependent on the total volume of runoff. This suggests that a relatively simple model could be developed to predict water quality for use in designing BMPs or other work. The initial constituent concentration could be taken as an average constant value representative of a given land use, or it could be treated as a stochastic parameter that is generated from an estimated probability distribution such as the log-normal distribution. Such a model could provide useful results both for single events, and for long-term simulation of storm water quality.

For large storm events, much of the sediment load in Barton Creek is derived from erosion of the channel, rather than from watershed surface stormwater runoff. The potential load from erosion increases for locations farther down the watershed.

6.0 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 Summary

Water quality in Barton Creek and Barton Springs is of significant public interest. Development within the Barton Creek watershed has the potential for adversely affecting water quality, and non-degradation has been identified as the community goal for water quality in both Barton Creek and Barton Springs. Modeling tools have been proposed for investigating the effects of land use changes on water quality, and this report describes the efforts toward application of a predictive model for water quantity and quality in Barton Creek. The general purpose of the modeling effort was to develop a tool capable of explicit representation of the physical processes governing water quantity and quality in the Barton Creek watershed.

The Barton Creek watershed is a component of the Barton Springs contributing zone which recharges the Barton Springs Edwards aquifer. In addition to Barton Creek, the contributing zone includes the drainage basins of Slaughter Creek, Williamson Creek, Onion Creek, Bear and Little Bear creeks, which drain to the 90-square-mile outcropping of Edwards Limestone. The 120-square-mile Barton Creek watershed lies on the Glen Rose Limestone over its western portion, and on the outcrop of the Edwards Limestone over the lower portion of the basin. Although the watershed consists largely of undeveloped land used primarily for ranching, the lower portion has experienced residential and commercial development.

Rainfall in the Austin area averages approximately 32.5 inches per year. While 50 percent of the rainfall events have volumes less than 0.25 inches, events of magnitude greater than 1 inch contribute half of the yearly rainfall volume, even though they represent less than 15 percent of the total number of events per year. More than 70 percent of the rainfall events over the Barton Creek watershed generate little or no runoff in Barton Creek. Total yearly potential evaporation is in excess of 70 inches, which is more than twice the average annual rainfall. Water balance studies suggest that more than 85 percent of the annual rainfall returns to the atmosphere through evapotranspiration, while less than 9 percent drains to the Colorado River after flowing over the recharge zone.

Flows in Barton Creek have been separated into baseflow volumes and direct runoff volumes. Above the recharge zone, more than three-quarters of the flow volume is baseflow. This fraction decreases over the recharge zone as flows contribute to aquifer recharge. On the basis of baseflow volume differences between the Lost Creek and Loop 360 gaging stations, it is estimated that for Lost Creek flows of less than 20 to 30 cfs, all of the flow is lost to recharge. The recharge rate remains constant at about 30 cfs for channel discharges ranging from 30 to 130 cfs. For channel flows at Lost Creek in excess of 130 cfs, the recharge rate is about 23 percent of the Lost Creek discharge. All of these estimates include only the recharge occurring between these two stations.

Stormwater quality from individual rainfall events is quite variable from storm to storm, through time for a given event, from one constituent to another, and from one site to another. The USGS/City of Austin joint monitoring program provides data for evaluating water quality along Barton Creek. In general, water quality is good. Available water quality data for three stations along Barton Creek have been analyzed. Mean values for most of the constituents are higher during storm flow conditions than for baseflow conditions. Total suspended solids (TSS), which is the most widely considered indicator of stormwater quality, has an average concentration that is two orders of magnitude larger under storm flow conditions when compared with baseflow conditions. Both the storm flow mean TSS concentration and its variability increase for downstream stations along the creek. The storm flow mean TSS concentration at Loop 360 is more than double that at the Highway 71 and Lost Creek stations, possibly reflecting the impacts of land-use changes in the lower portions of the watershed.

Of the water quality constituents that are correlated with flow, all except TPB have average concentrations greater at Loop 360 than at the other monitoring stations. One explanation of these increases is the greater amount of impervious cover at the lower end of the Barton Creek watershed. In addition, BOD_5, TOC, FCOL, FSTR, and total nitrogen have average concentrations that are one to two orders of magnitude larger during direct runoff conditions. Further, the mean TOC concentration at Loop 360 more than doubles that at Highway 71 and Lost Creek under storm flow conditions. The average TDS concentration is larger for baseflow than for storm flow conditions at all three stations, with greatest concentrations at the Lost Creek station. Correlation analysis shows that TSS, BOD_5, TOC, TKN, FCOL, FSTR, TP and TPB all increase with runoff, while only NO_2+NO_3 is inversely related to runoff. The other water quality parameters are insignificantly correlated to the runoff magnitude.

The U. S. Environmental Protection Agency's Stormwater Management Model (SWMM) was identified as having the greatest flexibility and potential for application as a stormwater quantity and quality simulation tool for the large and complex Barton Creek watershed. In the application of the SWMM model to the Barton Creek watershed, only four of the simulation model blocks are utilized: runoff, transport, statistics, and rain blocks. The Green and Ampt infiltration model is used, though it is found that the overall performance of the model is not very sensitive to this choice. The subsurface flow system is modeled as a linear reservoir, with flow rate from the saturated groundwater zone to the stream channel being based on the head difference between the aquifer and channel bottom. Use of these model features provides sufficient capabilities for simulating water quantity within the Barton Creek watershed.

The *Hydrolog* Software package that was developed as part of this research is a valuable system for hydrologic and stormwater quality analyses. This package simplifies the many analyses which are required to calibrate watershed models such as SWMM, and provides a set of tools for analysis of stormwater runoff data.

Extensive rainfall and streamflow data are available through the City of Austin and the USGS monitoring programs. These data cover single-land-use watersheds and the Barton Creek watershed at three stations. Because rainfall is not uniform over large areas, there is always uncertainty on how the recorded rainfall reflects watershed average values. Correlation analysis suggests that available records are adequate for most conditions, even over the upper reaches of the Barton Creek watershed for most of the year. Summer months may not calibrate as well due to typically localized rainfall patterns. This limits the available time periods for long-term validation using SWMM or any other watershed simulation.

Variables and parameters used for modeling flow in the Barton Creek watershed are physically based, for the most part. Most parameters are estimated before the calibration process begins. In some respects, this simplifies calibration because there are fewer model parameters to adjust in order to obtain a better fit to the observed data. The only parameters that were modified for the Barton Creek calibrations were the effective watershed width and the baseflow intensity parameter (A1). In addition, these were modified for all watersheds uniformly, so that their values were not changed for each subcatchment independently. The single-land-use watersheds do not have a subsurface flow component, so many of the flow parameters in the model are not used. There are fewer subcatchments and parameters to consider, and the effective watershed width remains a sensitive variable.

Applications show that the SWMM model can be adequately calibrated for representation of the hydrology of a single-land-use site and for the Barton Creek watershed (above the recharge zone). Both single-event and long-term periods can be simulated. The existing SWMM formulation is not able to simulate water loss from the creek over the recharge zone, so the model cannot be used to simulate flow quantity at the Loop 360 station.

The task of simulating stormwater quality has proven to be more difficult than that of simulating stormwater quantity. The buildup model used in SWMM does not lead to results that are consistent with observed data. In addition, no other model has been identified that could adequately replace those available within SWMM. This means that the model, if applied to a single-land-use watershed, or any more complex watershed, will not be able to represent the available constituent load (buildup) at the beginning of a runoff event. Thus the washoff load and concentrations will also remain uncertain. However, if the buildup could be predicted, the washoff model based on total storm runoff appears to adequately represent the monitoring data.

For large storm events, much of the sediment load in Barton Creek is derived from erosion of the channel, rather than from watershed surface stormwater runoff. The potential load from erosion increases for locations farther down the watershed.

The overall conclusion from the investigation of the single-land-use data is that a model does not exist that is able to adequately predict either the accumulated stormwater load on a watershed at the beginning of a runoff event, or the initial constituent concentration. The model does a better job of representing the washoff processes. Thus, SWMM may be a useful model for simulating single-storm events, but our understanding of the various processes that control the quality of urban runoff does not allow us to model a continuous series of events with SWMM or any other available model.

The stormwater monitoring data have provided sufficient data for statistical analysis of stormwater quality characteristics. Statistical regression analysis provides models for prediction of water quality in Barton Creek as a function of location, season, time period (construction), existing flow conditions, and antecedent flow conditions. Compared to the baseflow model, the models for storm flow conditions have greater predictive power.

Application of the statistical regression water quality model with a measured or simulated discharge hydrograph will provide useful estimates for Barton Creek water quality at the three monitoring stations, but it is difficult to extrapolate the model form to address questions associated with impacts of land-use changes on water quality. For the most part, baseflow water quality concentrations were not found to be impacted by construction activities in the Austin area during the period of 1983 to 1986. On the other hand, during storm flow conditions, the water quality concentrations in Austin-area creeks showed an increase during this period of active construction. In particular, the average TSS concentration increased by 550 mg/L.

A substantial amount of variability remains in the storm and baseflow water quality data after statistically accounting for flow rate, site, season changes, and prior flow rates. Additional research might provide further insight into the source of this variability.

6.2 Conclusions

1. There are a number of different computational tools for calculation of stormwater quantity and quality loads in urban and rural environments. These range from simple calculations using mean annual rainfall, runoff coefficients, and event mean concentrations, to complex computer-based calculations requiring significant input data and computational resources. Following a review of the available methods of stormwater computation, it is concluded that
    - SWMM and HSPF are the most generally applicable models for simulation of stormwater quantity and quality for single and multiple events.

2. The SWMM model was selected for application to stormwater modeling on the Barton Creek watershed. As part of the modeling process, SWMM was used to simulate both single and multiple stormwater events on single-land-use watersheds. Following model calibration, comparison of model simulation results with empirical measurements of stormwater loads from the monitoring program lead to the conclusion:
    - Application of SWMM to single-land-use watersheds was successful for estimation of both quantity and stormwater quality loads for single-event simulations.

3. The conclusion that SWMM could be successfully applied to estimate stormwater quantity and quality loads from single-land-use watersheds leads to the further conclusion:
    - SWMM may be applied to design and analysis of BMPs for single-land-use drainage basins. (size ~ 400 acres)

4. In the simulation of constituent concentrations for multiple events with single-land-use watersheds, a number of options are available. One may use a constant constituent EMC, a functional relationship between the flow rate and constituent concentration, or one may attempt to simulate the buildup and washoff of the constituent for the watershed. For a physically based model, the latter two options are most appealing. A review and analysis of single-event stormwater quality data has shown the following:
    - Single-land-use water quality data appear to follow the washoff process for certain constituents, including TSS. However, prediction of initial concentrations through a

constituent buildup process is not supported by the empirical data. Further, for certain constituents, their concentrations are generally greater on the rising limb of the hydrograph than on the falling limb, and a functional relationship between flow and concentration is not applicable. It is thus concluded that simulation of multiple events on single-land-use watersheds cannot be performed.

- Deterministic models such as the buildup/washoff relationships lack the capability of predicting multiple-event pollutographs.
- Prediction of total annual loads using buildup and washoff with calibration may be possible.

5. The COA/USGS stormwater monitoring program is one of the most intensive in the country in terms of the number of locations monitored and samples taken. For events on single-land-use watersheds, there are a large number of events with sufficient data to adequately characterize the pollutograph for calibration purposes. However, for the Barton Creek monitoring stations, while there are sufficient data for application of statistical methods to develop regression models for stormwater quality, there are only a small number of events with sufficient data to characterize the pollutograph for calibration purposes.
    - The stormwater monitoring program on Barton Creek has provided only a small number of storms with sufficient data for characterization of the pollutograph for model calibration purposes.

6. The SWMM model was developed with sufficient flexibility to represent many important features in the hydrologic cycle. However, channel losses such as those that occur over the recharge zone of the Edwards aquifer are not represented in a realistic fashion.
    - For the Barton Creek watershed above the recharge zone, models such as SWMM were calibrated to simulate observed creek flows both over periods of short and long duration.

7. Stormwater quality is often evaluated through measured TSS concentrations. Given the single-land-use monitoring data, one can estimate the watershed derived load from each subcatchment of the Barton Creek watershed, and thus estimate the expected load at the monitoring stations along the creek. However, the observed TSS loads greatly exceed the estimated loads because of channel-derived TSS.
    - TSS stormwater quality in Barton Creek cannot be derived from single-land-use washoff loads.

8. While there are few records with sufficient data to characterize the stormwater quality pollutograph for Barton Creek, sufficient data exist to apply statistical regression techniques to develop a statistical model for predicting stormwater quality. Such a model has been developed and evaluated.
   - A statistical model was developed with some predictive capabilities for stormwater quality in Barton Creek under existing land-use conditions.

9. Pollutographs from single-land-use stormwater quality monitoring were analyzed in terms of buildup and washoff models. Washoff data were used to develop predictive models for the washoff pollutograph for certain constituents, including TSS. This model met with limited success when compared with empirical data because the initial concentrations remained uncertain.
   - A model has been developed to predict washoff concentrations from single-land-use watersheds. However, prediction of initial concentrations remains uncertain, and the model cannot be used to simulate empirical data.

10. Pollutographs, EMCs, and runoff coefficients have been compared based on the single-land-use monitoring data.
    - Stormwater quality loads are more sensitive to changes in stormwater quantity than concentration. Thus, land-use changes that increase stormwater quantity (runoff) are especially significant in increasing constituent loads.
    - EMCs are less sensitive to land use than runoff coefficients.

11. Prediction of stormwater quality remains an approximate science because of the myriad of processes that vary from storm to storm, and from one location to another.
    - Given the uncertainty in prediction of existing stormwater quality for the Barton Creek watershed, and the uncertainty on how the predictive parameters that control water quality vary with land-use changes, it does not appear that stormwater quality models can be used to accurately predict the effects of development on water quality in Barton Creek.

6.3 Recommendations

6.3.1 Model Applications

1. The Barton Creek SWMM Model can accurately predict flow quantities above the recharge zone. Therefore, the calibrated model can be used to develop flow inputs to the Barton Springs/Edwards aquifer groundwater model being developed under a contract between the City of Austin and The

University of Texas Center for Research in Water Resources. The calibrated SWMM model can be used to predict changes in baseflow and direct runoff quantities in Barton Creek resulting from changes in impervious cover for various development and regulatory scenarios. This will allow the prediction of the effects of urban development on water levels in the aquifer and discharge rates at Barton Springs.

2. Analysis of water quality data during the course of the study demonstrated the relative importance of channel-derived load. Much of the concern about the viability of the Barton Springs salamander is centered on the effects of increased suspended solids loads in the creek and springs. Approximately one-half of the suspended solids load in the lower segments of the creek is derived from channel scour. The Barton Creek Model could be used to predict the changes in flow rates that will accompany increased urban development in the watershed. The model can be used to assess the effects of various BMPs on flow rates during runoff events.

3. Through this modeling effort the city staff has developed a familiarity with the operation, capabilities and limitations of SWMM. Because all of the available models have unique limitations and capabilities, it is recommended that the city support the use of SWMM in the Barton Creek watershed due to its familiarity and flexibility. The recommended uses of SWMM include the evaluation of various BMPs using the storage/treatment block in addition to the four blocks used in this study. The storage/treatment block simulates the effect upon flow quantity and quality of capture and residence processes occurring in structural water quality or quantity control devices. SWMM should also be used to provide guidance in site selection and planning for single-land-use flow monitoring.

6.3.2 Regulatory and Development Review

4. City of Austin flood control regulations should be reviewed in light of the importance of channel scour documented in this study. Current regulations, which are based on limiting the peak discharge from a site to predevelopment conditions, may have unintended consequences on flow rates in creeks downstream of discharge points. Depending on the relative position of the site and other factors, stormwater detention facilities constructed to city standards may increase storm flow rates in the main creek channel downstream of the site, compared to developed conditions with no controls in place. The Barton Creek Model should be used to evaluate the effectiveness of current regulations and predict the impacts of proposed changes to these rules.

5. Infiltration practices should be promoted as an effective water quality BMP based on the following conclusions:

    - Analysis of data from single-land-use watersheds indicates that the amount of impervious cover has a greater impact on stormwater loads than land-use classification.
    - Peak flows and sustained velocities have a dominant impact on water quality due to channel scour.
    - The recreational uses of Barton Creek are dependent on the maintenance of a healthy baseflow, which will be enhanced by increasing stormwater infiltration through structural and non-structural means.
    - Promoting baseflow in Barton Creek will help maintain the quality of water recharged to the Barton Springs portion of the Edwards aquifer.

    Therefore, promoting infiltration practices through the city's water quality control standards will reduce runoff entering the channel, decrease channel scour and water quality impacts, and assure that baseflow quantity will not be reduced.

6.3.3 Data Collection

6. It is recommended that the city address the potential problems associated with channel-derived suspended solids by developing a monitoring program to document current rates of bank erosion and channel scouring. Additional empirical data on the critical stream velocity that produces erosion will be necessary for the design of stormwater controls system which will effectively protect Barton Creek.

7. The accuracy of the Barton Creek Model is limited by a lack of accurate knowledge of rainfall distribution and evaporation rates. Continuously recording rain gauges should be installed upstream of Highway 71 near the border of the city's ETJ to better document rainfall rates and volumes. It is recommended that the city install a pan evaporation monitoring site to provide a backup source of data to the National Weather Service, which has proved to be inconsistent in the past.

8. A continuous-flow gauge should be installed just upstream of Barton Springs Pool. This gauge will enable greater accuracy in measurement of recharge volumes including groundwater discharge from

the Edwards aquifer to Barton Creek during periods of high water levels in the aquifer. In addition, the gauge will provide a station for water quality measurements downstream of all development. Data from this site will be needed for model calibration if SWMM is modified to include channel losses and groundwater recharge as suggested in the recommendations for “Additional Research.”

9. To better understand the processes controlling water quality in Barton Creek, the frequency of sampling should be increased during storm events. In addition, the duration of sampling should be sufficient to define the transition from direct runoff to baseflow water quality. An automated station similar to that used in the City of Austin Storm Water Monitoring Program should be maintained in Barton Creek to obtain this high-resolution data at the least cost to the city. Additionally, the Flood Early Warning gauges in the watershed with depth-monitoring capabilities should be converted to flow rate monitoring by developing accurate rating curves. This will allow the transition to baseflow to be characterized in greater detail.

10. The monitoring of rainfall water quality as currently performed by the City of Austin should be expanded to document the possible differences between urban and rural rainfall quality. This monitoring will help establish the relationship between rainfall and runoff water quality.

6.3.4 Additional Research

11. A study should be initiated to evaluate channel stability and sediment transport in Barton Creek. The study should be supported by the ongoing Citywide Master Plan because it will complement the planned needs assessment for erosion control scheduled for non-urban watersheds within the next several years.

12. Beginning with SWMM version 4.26, the model has been modified to simulate channel losses. The newer versions should be investigated with the additional data provided by the recommended monitoring gauge above Barton Springs to evaluate channel losses over the recharge zone.

13. The SWMM model should be modified to incorporate the predictive model for the stormwater washoff pollutograph with variable RCOEF described in Chapter 5 and combined with a stochastic generator for selection of initial concentrations to provide a tool for generating realistic multiple event stormwater loads for design and evaluation of BMPs. Such a representation would still be adequate for simulation of yearly loads, and could provide a more realistic representation for the input loads to BMPs.

14. A user interface or file linking program manager should be developed that will allow interactive operation of the various models describing the hydrology of the surface and groundwater systems. Modeling tools include the main programs for surface water and groundwater quantity and quality modeling, as well as the supporting database management system, geographic information system methods for spatial parameter determination and storage, program interaction modules, and user interface to the decision support system. The development of a user interface will allow interactive operation of the main components of the models without the need for low-level programming and data operations. This will allow the decision maker to use the computational methods to immediately assess the impacts of a proposed action, thus reducing the time and effort in determining its technical validity.

15. A statistical cluster analysis should be performed using all 48 water quality constituents that are currently measured. This analysis will lead to a grouping of constituents that show similar water quality behavior. From these groups, one may select representative indicator constituents for monitoring, thereby reducing the number of analyses that must be performed on a routine basis.

16. Data analyses have shown that about 85 percent of the groundwater recharge from Barton Creek is attributed to baseflow. Therefore, the effects of development on baseflow water quality should be evaluated. Baseflow water quality should be monitored, and tools for modeling baseflow water quality should be investigated.

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