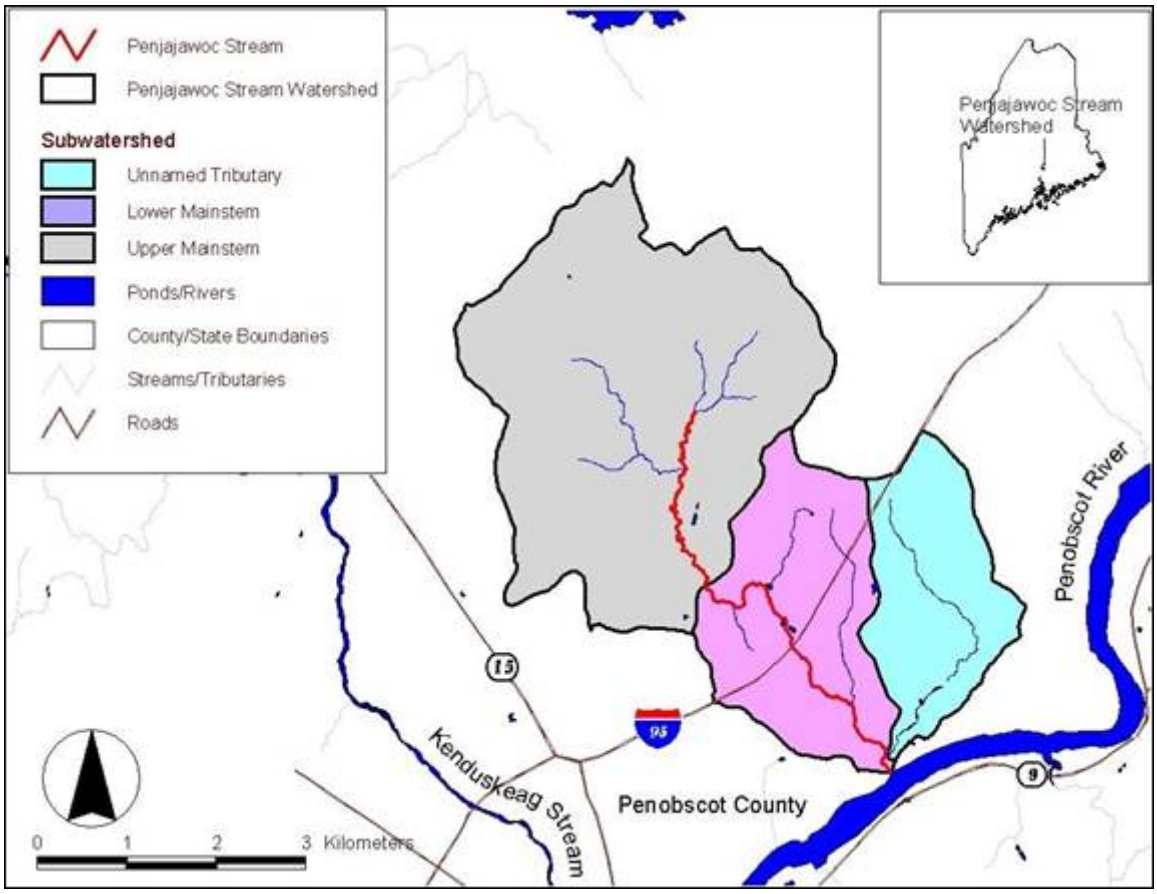
Modeling Report to Support Total Maximum Daily Load (TMDL) Development for Penjajawoc Stream (AKA Meadow Brook)

Aquatic Life Impairment



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1. Introduction

Penjajawoc stream (aka Meadow brook) is listed on the Maine 1998 303(d) list as impaired for aquatic life due to non-point sources. Penjajawoc stream is designated as a Class B water under the standards for classification of fresh surface waters. Standards for classification and associated designated uses are provided in Table 1.1.

Table 1.1 Standards for Classification of Fresh Surface Waters and Designated Uses

CLASS	DESCRIPTION	DESIGNATED USES
AA	Class AA shall be the highest classification applied to waters which are outstanding natural resources and which should be preserved because of their ecological, social, scenic or recreational importance.	- Drinking water supply after disinfection - Fishing - Recreation in and on the water - Navigation - Habitat for fish and other aquatic life* * The habitat shall be defined as free flowing and natural.
A	Class A waters shall be the second highest classification.	- Drinking water supply after disinfection - Fishing - Recreation in and on the water - Hydrologic power generation* - Navigation - Habitat for fish and other aquatic life * Except as prohibited under Title 12 Section 403.
B	Class B shall be the third highest classification.	- Drinking water supply after treatment - Fishing - Recreation in and on the water

		- Industrial Processes and Cooling water supply - Hydrologic power generation* - Navigation - Habitat for fish and other aquatic life * Except as prohibited under Title 12 Section 403.
C	Class C waters shall be the fourth highest classification.	- Drinking water supply after treatment - Fishing - Recreation in and on the water - Industrial Processes and Cooling water supply - Hydrologic power generation* - Navigation - Habitat for fish and other aquatic life * Except as prohibited under Title 12 Section 403.

Source: Maine Water Quality Standards

Total Maximum Daily Load (TMDL) development requires identification of impairment causes and the establishment of numeric endpoints that will allow for the attainment of designated uses and water quality criteria. According to Maine's 303(d) list, the probable impairment cause is non-point source runoff. No point sources were identified in the watershed. Pollutant loading associated with urban runoff was identified as the primary contributor. Therefore, a watershed model was used to estimate the urban runoff and associated pollutant loading from non-point sources under a range of conditions. These pollutants include total suspended solids (TSS), total phosphorus (TP), total kjeldahl nitrogen (TKN), copper, lead, zinc, and hydrocarbons. Maine does not have numeric water quality standards for these parameters, so numeric endpoints were developed based on an unimpaired (reference) watershed loading.

The watershed model used in this study was the P8 Urban Catchment model (Walker 1990). The P8 Urban Catchment model predicts the generation and transport of storm water pollutants in urban watersheds. It uses continuous water and mass balance calculations on a system consisting of user defined watersheds and devices (run off storage, treatment and routing components).

2. Approach and Background

A reference watershed approach was used to establish numeric endpoints for constituent loadings. The approach was based on identifying unimpaired portions of the Penjajawoc watershed where stream conditions are assumed to be representative of the conditions needed for the impaired stream to obtain its designated uses.

Urban development is largely confined to the lower portion of the Penjajawoc stream, below the Penjajawoc Marsh (Figure 2.1). The upper portion of the Penjajawoc stream as well as an unnamed tributary have significantly less urban development, and bio-monitoring data indicate that they are not impaired. Therefore, for analytical purposes the watershed was delineated into three sections: the Penjajawoc stream lower mainstem (impaired), the Penjajawoc stream upper mainstem (reference), and the unnamed tributary (reference). The three sub-watersheds are briefly described in Table 2.1 and shown in Figure 2.1.

Table 2.1 Watershed Descriptions for the sub watersheds in the Penjajawoc stream watershed

WATERSHED	DESCRIPTION
Lower (Impaired)	The lower mainstem is approximately 2.5 miles in length, extending from the outlet of the marsh to the confluence with the Penobscot River. It has a drainage area of approximately 1,337 acres.
Upper (Reference)	The Upper mainstem is approximately 1.8 miles in length. extending from the headwaters to the outlet of the Penjajawoc Marsh. It has a drainage area of approximately 3,032 acres (excluding the Penjajawoc Marsh).
Unnamed Tributary (Reference)	The Unnamed tributary is approximately 2.5 miles in length and flows southwest from its headwaters to meet the Penjajawoc near its confluence with the Penobscot River. It has a drainage area of approximately 952 acres.

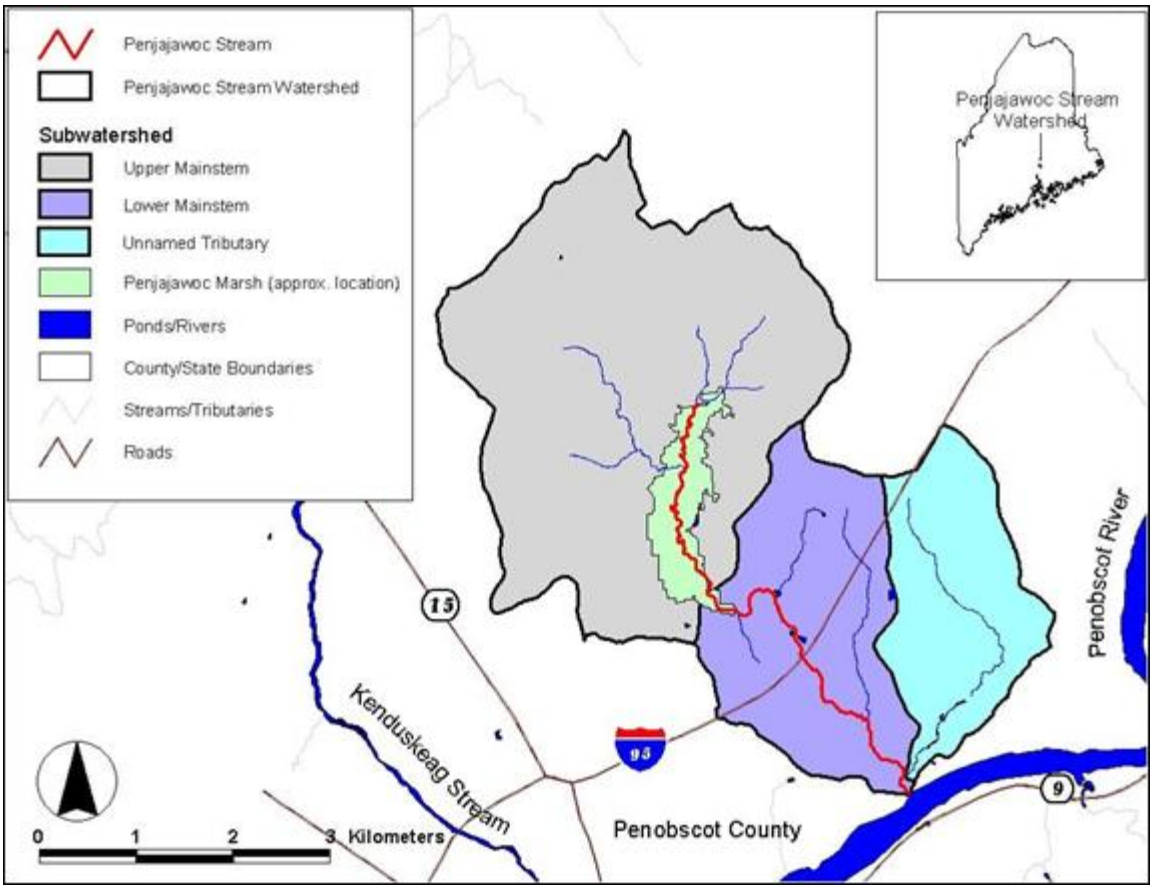

Figure 2.1 Penjajawoc Subwatersheds and Penjajawoc Marsh

2.1 Land Use / Land Cover

Land use / land cover percentages were obtained from a data layer developed as part of the Maine Gap Analysis Project by the Maine Image Analysis Laboratory at the Department of Forest Management, University of Maine, 1998 and were adjusted based on coverages provided by Maine DEP (ME DEP) (Table 2.2). The spatial distribution of land use / land cover for the Penjajawoc watershed is shown in figure 2.2. The dominant land use / land cover in the upper Penjajawoc and unnamed tributary is forested, followed by grasslands/fields. The dominant land use / land cover in the lower Penjajawoc is residential/commericial, followed by forested. In addition, the middle Penjajawoc watershed has 101 acres of highway/parking land use / land cover compared to 0 and 12 acres in the upper Penjajawoc and unnamed tributary, respectively.

Table 2.2 Land Use Percentages sub watersheds in the Penjajawoc watershed.

LAND USE	UPPER PENJAJAWOC		LOWER PENJAJAWOC*		UNNAMED TRIBUTORY	
	Area (acres)	**Percentage**	**Area (acres)**	**Percentage**	**Area (acres)**	**Percentage**
Forest	2,143	71%	228	17%	484	51%
Grasslands/Field	490	16%	154	12%	232	24%
Cropland	44	1%	6	0%	19	2%
Clear/Partial Cuts	158	5%	20	1%	28	3%
Residential/Commercial	122	4%	796	60%	142	15%
Highways/Parking	0	0%	101	8%	12	1%
Abondoned Field	21	1%	14	1%	15	2%
Scrub-shrub	30	1%	5	0%	6	1%
Wetland/Water	25	1%	14	1%	13	1%
Total	3,032		1,337		952	

* Urban areas were adjusted based on an updated parking lot coverage provided by ME DEP.

Note: The Marsh in the middle of the upper watershed is considered part of the receiving water, rather than part of the watershed (for the analytical purposes).

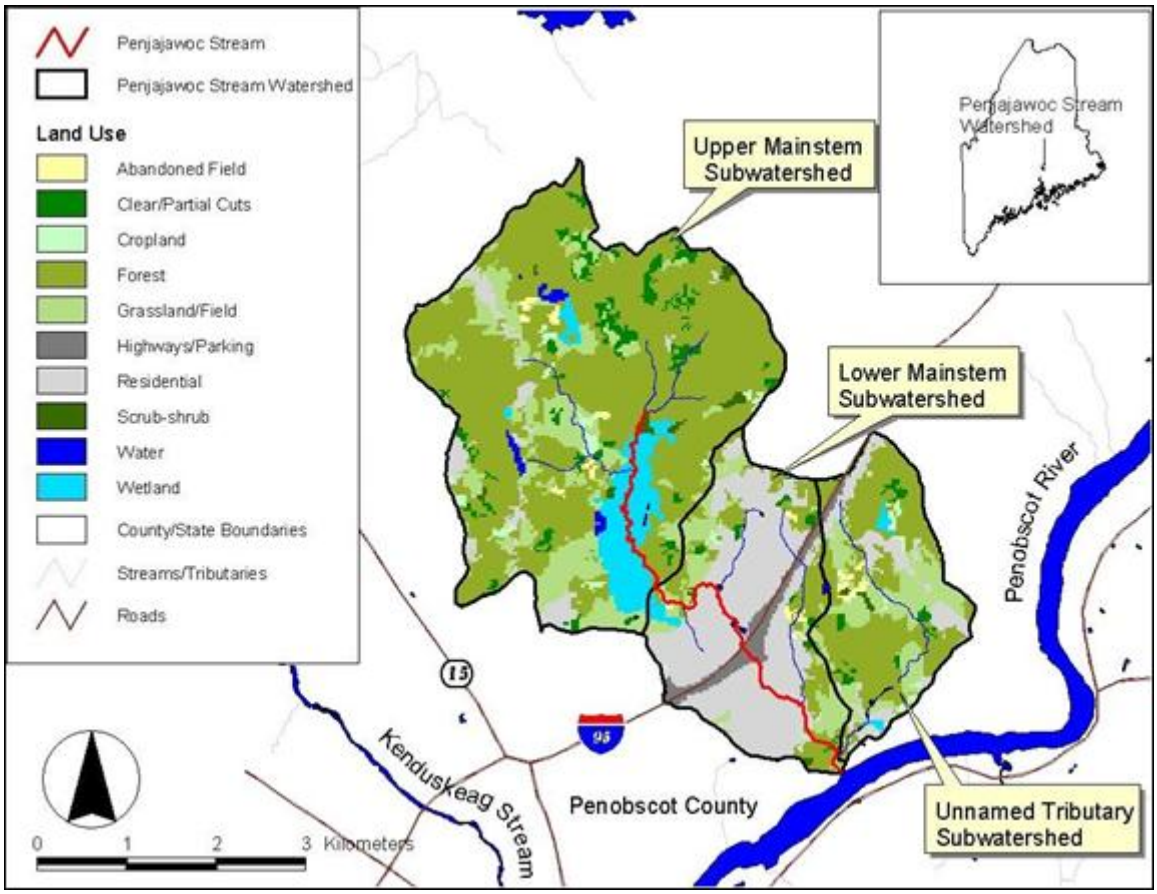

Figure 2.2 Land Use / Land Cover Areas for Penjajawoc Stream

2.2. Hydrologic Soil Groups

Soils data were obtained from the State Soil Geographic database (STATSGO) for Maine, as developed by the Natural Resources Conservation Services (NRCS). A description of the SCS soil hydrologic groups is provided in Table 2.3. All the soil types in the Penjajawoc watershed fall into the hydrologic group C.

Table 2.3 Characteristics of SCS Soil Groups

GROUP	RUNOFF POTENTIAL	INFILTRATION RATES [a]	SOIL TEXTURE AND DRAINAGE
A	Low	High	Typically deep, well-drained sands or gravels
B	Moderately low	Moderate	Typically deep, moderately well to well-drained moderately fine to coarse-textured soils
C	Moderately high	Slow	Typically poorly drained, moderately fine to fine-textured soils containing a soil layer that impedes water movement or exhibiting a moderately high water table
D	High	Extremely slow	Typically clay soils with a high water table and high swelling potential that may be underlain by impervious material, have very slow infiltration rates

3. Technical Analysis

3.1 Model Selection

Tools are often necessary to develop a Total Maximum Daily Load (TMDL). They are particularly useful in helping to understand present water quality and hydrologic conditions and in identifying appropriate conditions to attain the designated uses. Models enable us to simulate very complex watershed hydrology and water quality components and to synthesize different kinds of information. Selection of a model for this effort was based on the objective of the analysis and available data to develop and calibrate the model.

Like many developed or urbanized watersheds, the potential stressors expected to be impacting aquatic life/habitat in the Penjajawoc stream include contaminants associated with storm water runoff (e.g., sediments, nutrients, metals, etc.), hydrologic modifications (excessive and insufficient stream flow rates), riparian corridor encroachment (the area and landscaping adjacent to the stream), and channel alteration. There are many stressors that may be acting either in an individual or cumulative manner to cause the impairment. It is very difficult to determine the exact role and significance that each pollutant/stressor plays in contributing to the impairment to habitat and aquatic life, particularly in a limited data situation. However, all the stressors are associated with a common cause - storm water runoff. Therefore the model needed for the analysis should be capable of simulating quantity and quality of storm water. In addition to simulating storm water runoff in general, the model must also be capable of representing storm water control best management practices (BMP) and features like the Penjajawoc Marsh.

Considering both current and future needs and data limitations, P8 Urban Catchment Model (Walker, 1990) was selected for the analysis. The following list identifies reasons for selecting P8:

- Capability of simulating storm water quantity and quality
- Capability of simulating storm water BMPs
- Moderate requirements for data and expertise
- Established modeling history in New England region and in Maine
- Model framework is familiar to municipal engineers and planners
- Flexibility in modifying and enhancing for future changes

3.2 Model Description

P8 is a model for predicting the generation and transport of storm water pollutants in urban watersheds. Continuous water balance and mass balance calculations are performed on a user-defined system consisting of watersheds, devices (runoff storage/treatment areas, BMPs), particle classes, and water quality components. Simulations are driven by continuous hourly rainfall and daily air temperature time series data. P8 consists primarily of algorithms derived from other tested urban runoff models (SWMM, STORM, GWLF, HSPF, D3RM, and TR-20) (Palmstrom and Walker, 1990). The model simulates pollutant transport and removal in a variety of treatment devices (BMPs), including swales, buffer strips, detention ponds (dry, wet, and extended), flow splitters, and infiltration basins (offline and online), pipes, and aquifers. Water quality components include total suspended solids (TSS) (five size fractions), total phosphorus (TP), total Kjeldahl nitrogen (TKN), copper, lead, zinc, and hydrocarbons. Detailed technical documentation for the model, including simulation methods and algorithms, calibration, and testing, and limitations are provided in the P8 program documentation and user's manual (Walker, 1990). The following paragraphs in this section provide a brief overview of simulation methods in P8, as described by Palmstrom and Walker (1990).

Runoff from pervious areas is computed using the Soil Conservation Service's (SCS) curve number technique (USDA, 1964), as implemented by Haith and Shoemaker (1987) for continuous watershed simulation. Antecedent moisture conditions are adjusted based upon five-day antecedent precipitation and season. Percolation from pervious areas is estimated by water balance at the surface (percolation=precipitation–runoff-evapotranspiration). Evapotranspiration is computed from air temperature and season using Hamon's (1961) method, as implemented by Haith and Shoemaker (1987). Runoff from impervious areas starts after the cumulative storm rainfall exceeds the specified depression storage. Thereafter, runoff rate equals precipitation intensity. Both rainfall and snowmelt are considered in runoff estimations. Snow accumulation and melt are modeled using total precipitation and air temperature as implemented by Haith and Shoemaker (1987).

Particle concentrations in runoff from pervious areas are computed using a method similar to the sediment rating curve included in EPA's Stormwater Management Model (SWMM) (Huber and Dikinson, 1988). Particle loads from impervious areas are computed using either or both of two techniques: (1) particle accumulation and washoff and/or (2) fixed runoff concentration. The first method is used in default particle datasets. An exponential washoff relationship similar to that employed in SWMM is used to simulate particle buildup and washoff from impervious surfaces.

When the P8 model is executed, the watershed/device network is stored in downstream order. An elevation/volume/discharge table is calculated for each device based upon input information, including physical dimensions and outlet characteristics. The table directs flow-balance calculations using the relationship between storage volume and outflow. Continuous mass balance calculations are performed on each device and particle class, accounting for inflow, outflow, change-in-storage, and removal terms.

Depending upon device type, up to 15 mass-balance terms are considered in the simulations. Removal mechanisms include settling, first-order decay, second-order decay, and filtration. Continuous water-balance and mass-balance checks are maintained on each device and on the overall device network.

3.2 Model Simulation

Model simulation involved setting up the model with watersheds and devices, determining watershed and water quality parameters, and performing simulations to support TMDL development. This section describes the configuration and key components of the model developed for the Penjajawoc watershed.

3.2.1 Watershed and Hydrology

The P8 model for the Penjajawoc watershed was developed with three sub-watersheds, and devices (outlets, aquifers, detention pond, wetland, and routing) as presented in Figure 3.1. Watershed input data and parameters are tabulated in Table 3.1. The middle sub-watershed was further divided into two sub-watersheds in order to represent the influence of BMPs. One is the drainage area with storm water BMPs and the other is the drainage area without BMPs.

Table 3.1. Watershed input data and parameters

WATERSHED	**AREA (ACRES)**	**PERCENT IMPERVIOUS[1]**	**PERVIOUS CURVE NO.[2]**
Upper	3,032	10	73
Lower (w/ BMP)	42	60	73
Lower (w/o BMP)	1,337	37	74
Unnamed	952	5	72

1- Percent impervious was estimated by following P-8 help document based on USDA (1985).

2- SCS, USDA (1986).

The P8 model simulates the hydrology and water quality constituents in the watersheds and then simulates their movement through devices. Surface runoff from watersheds was directed to outlet devices. Outlet devices generate surface runoff hydrographs at the outlet of a watershed. Infiltration from watersheds is directed to aquifer devices that generate groundwater hydrographs with a time lag. Depending on the appropriate functions, other devices such as detention ponds, wetlands, and flow routing are introduced in the model.

For the upper watershed, the lower watershed without BMP, and the unnamed tributary watershed, surface runoff was directed to an outlet device and infiltration was directed to a ground water aquifer device. Surface runoff from the lower watershed with BMP was first directed to a detention pond and then directed to a watershed outlet device. Infiltration for both cases was directed to a ground water aquifer device. Ground water aquifer devices for each sub-watershed had different time lags (proportional to drainage area) before entering the Penjajawoc aquifer. Flow from the upper watershed was directed through a wetland device and then through a channel. Infiltration from devices also directed to the Penjajawoc aquifer are presented in Figure 3.1.

For the entire Penjajawoc watershed system, outflow from watersheds (routed surface flow) and outflow from the Penjajawoc aquifer determine total stream flow. For each sub-watershed, outflow from the watershed outlet device (surface runoff) and outflow from the respective groundwater aquifer determine the total stream flow.

3.2.2 Storm Water Best Management Practices

In this application, a single BMP representing the functions of all BMPs in the middle sub watershed was employed to simulate the effects of BMPs. Table 3.2 presents the details of selected BMPs and the single BMP used in the Penjajawoc P8 Model. The single BMP approach is appropriate as the P8 model considers a watershed as a single element, without considering the processes within the watershed. If an application requires individual performance of each BMP, the drainage area for each BMP should be separately considered as a watershed and then the flow should be directed through each BMP.

Table 3.2. Details on BMPs in the middle sub watershed of the Penjajawoc watershed

POND NUMBER	**1**	**2**	**3**	**4**	**5**	**6**	**P8- POND BMP**
Drainage Area (acres)	5.61	8.21	8.08	3.49	11.13	5.42	41.93
Impervious Area (acres)	3.36	4.60	4.85	2.09	6.68	3.09	24.67
Bottom Area (acres)	0.28	0.33	0.26	0.32	0.22	0.07	1.49
Normal Pool Area (acres)	1.03	0.80	0.60	0.53	0.47	0.40	3.83
Permanent Pool Storage (ac-ft)	1.65	1.41	1.08	1.06	0.85	0.59	6.64
Flood Pool Area (acres)	3.43	1.74	1.15	0.85	0.67	0.65	8.49
Flood Pool Storage (ac-ft)	19.49	7.77	4.58	3.81	1.99	1.64	39.28
Weir length (ft)	29.86	12.07	15.68	29.59	12.63	13.19	20.04

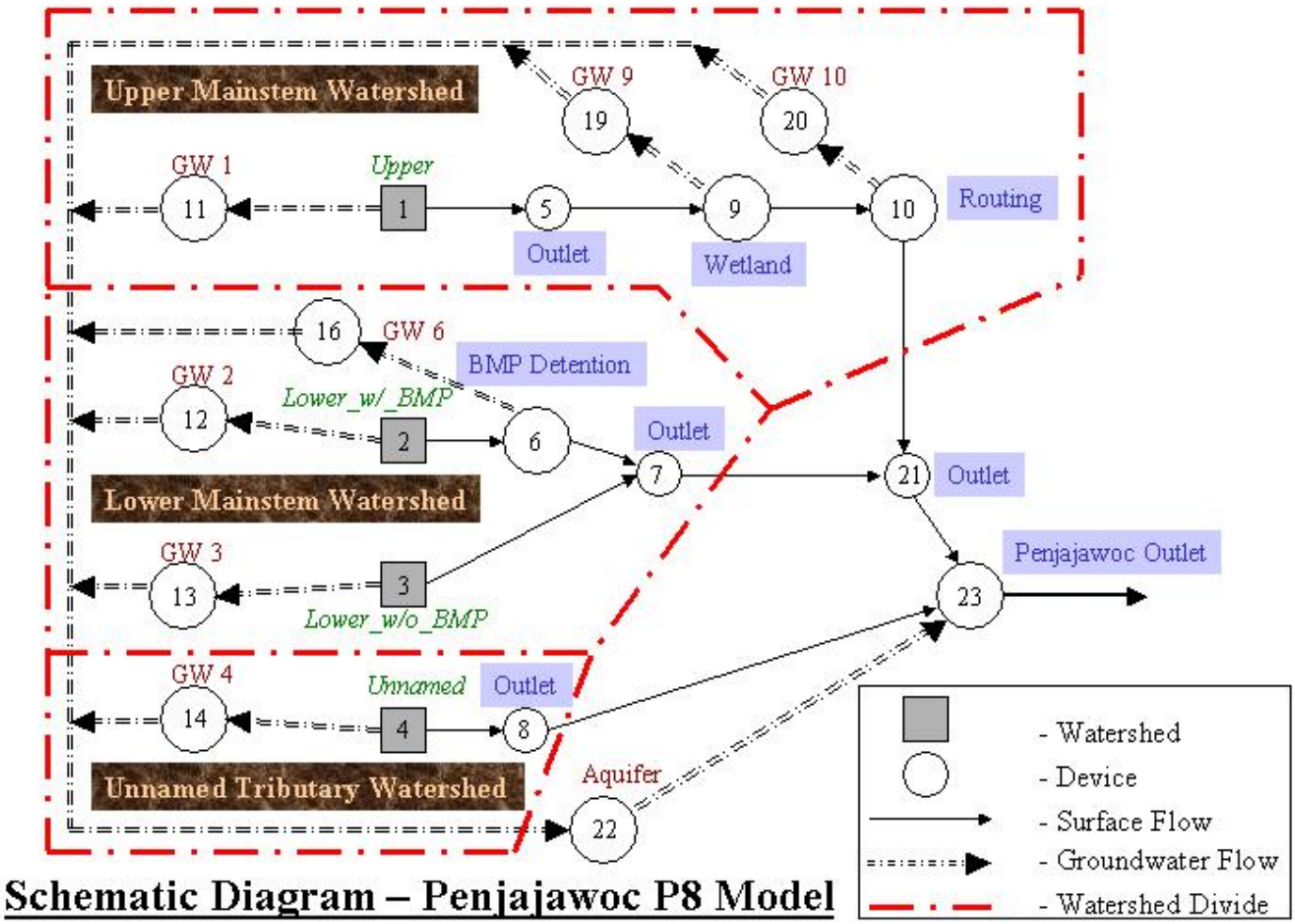

Figure 3.1. Schematic Diagram

3.2.3 Water Quality Constituents

Particle classes and water quality components were based on the Nationwide Urban Runoff Program (NURP) studies (US EPA, 1983). Component concentrations calibrated to NURP 50th percentile (median) sites were input into the model. Table 3.3 presents the input concentrations employed in this study.

Table 3.3. Event mean concentrations of water quality components

COMPONETS	EVENT MEAN CONCENTRATION (MG/L)
Total Suspended Soilds	100
Total Phosphorus	0.33
Total Kjeldahl Nitrogen	1.50
Total Copper	0.034
Total Lead	0.20
Total Zinc	0.16
Hydrocarbons	2.5

3.2.4 Simulation Approach

The Penjajawoc P8 Model (Figure 3.1) was employed to simulated stream flow and pollutant load based on hourly precipitation and daily air temperature. Hourly precipitation data from Orono, ME (ME 6435) (NCDC, 2003a) and daily temperature from BANGOR-Airport (WBAN 14606) (NCDC, 2003b) were used in the simulation. Figure 3.2 presents the proximity of weather stations to the Penjajawoc watershed. Model simulation for a 30-year period (01/1972 -12/2001) was employed to evaluate the long-term hydrology and water quality. Then, simulation for a 10-year period (01/1992 – 12/2001) was employed to evaluate model results at a fine-resolution and to develop flow/load duration statistics.

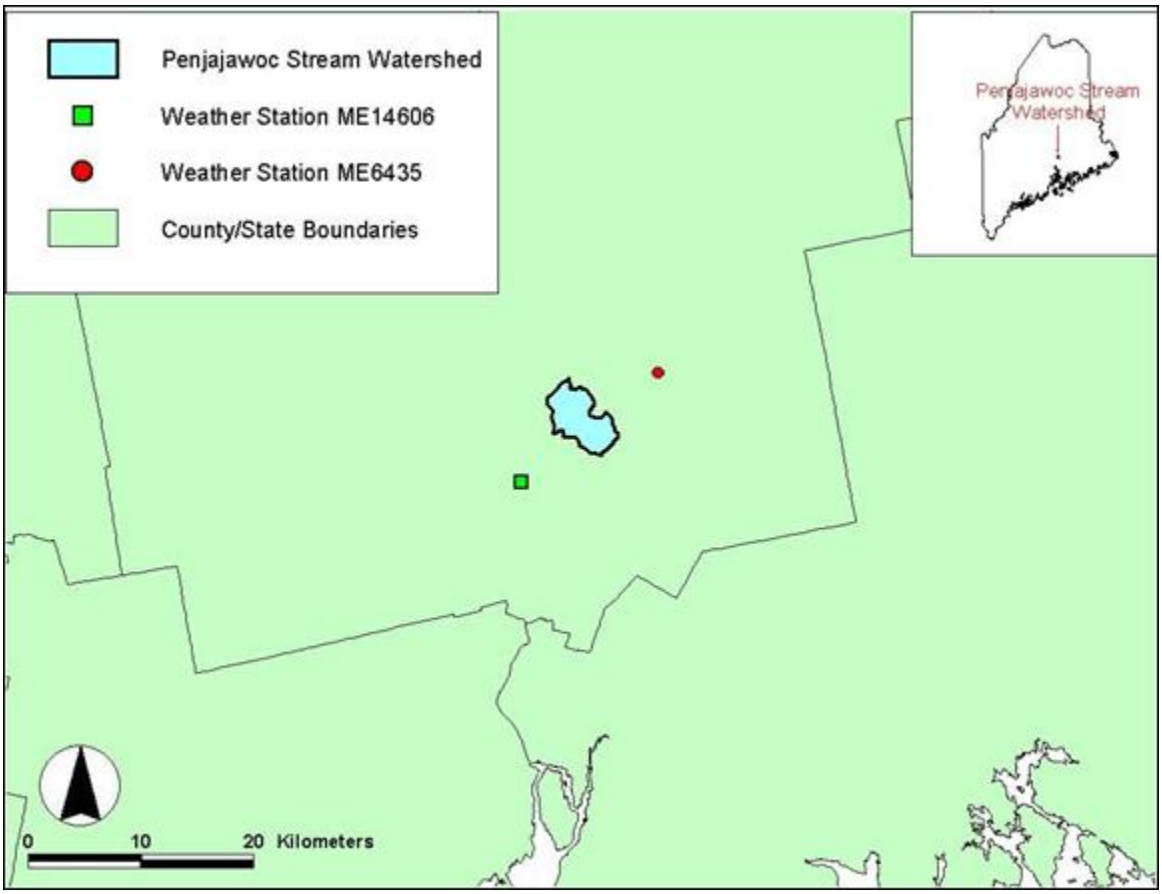

Figure 3.2 Weather Station Locations

3.3 Model Limitations

Models attempt to represent a complicated natural system using a set of mathematical equations. Therefore model applications often require calibration and validation to increase reliability in predictions. For the Penjajawoc model, stream flow data are not available, and water quality data are extremely limited for calibration or validation. Therefore, the model was employed in this analysis as a tool to evaluate relative differences between conditions. The model can, however, be readily modified or further enhanced to consider future data.

4. Results

The results are presented in the following section to enhance the understanding of aquatic life impairment and to link it with potential stressors. Section 4.1 presents the evaluation of watershed hydrology, primarily the annual average distribution of precipitation among evapotranspiration, surface runoff, and base flow, and its association with impairment. Section 4.2 presents the evaluation of the flow duration statistics that enable to understand time variation of the impairment, especially during the high flow and low flow conditions. Section 4.3 presents pollutant load and its association with impairment. Section 4.4 summaries the results to support TMDL development addressing the aquatic life impairment in the Penjajawoc stream.

4.1 Watershed Hydrology

The 30-year simulation provides insight into the system hydrology. Average annual precipitation (1972-2001) in the Penjajawoc watershed is about 44 inches. Figure 4.1 demonstrates how differently the sub-watersheds respond to the same precipitation. The average values are estimated using the monthly output of model results.

The upper and unnamed tributary watersheds show similar distribution of precipitation trends. The lower watershed, however, acts differently. The surface runoff in the lower watershed is approximately twice as high as the upper watershed and unnamed tributary watershed. Evapotranspiration and base flow in the lower watershed are also substantially lower than that of the upper watershed or unnamed tributary watershed. This difference is primarily due to the impact of urbanization in the lower watershed. The lower watershed has approximately impervious cover 38 % (combined w and w/o BMP watershed) compared to 10% and 5% of upper watershed and unnamed tributary watershed respectively. Higher imperviousness results in excess runoff in the lower watershed. The increase in surface runoff reduces the amount of infiltration into the soil and thus the storage of water in soil. As a result, evapotranspiration and base flow, groundwater contribution to stream, are substantially reduced. Overall, urbanization and the associated increase in imperviousness in the lower watershed contribute to unstable flow conditions (i.e., highly variable flow rates over short periods of time) with large volume of surface runoff and reduced groundwater recharge and stream base flow. If the lower watershed were to behave similar to that of other unimpaired sub watersheds, it would require about a 54% reduction in surface runoff.

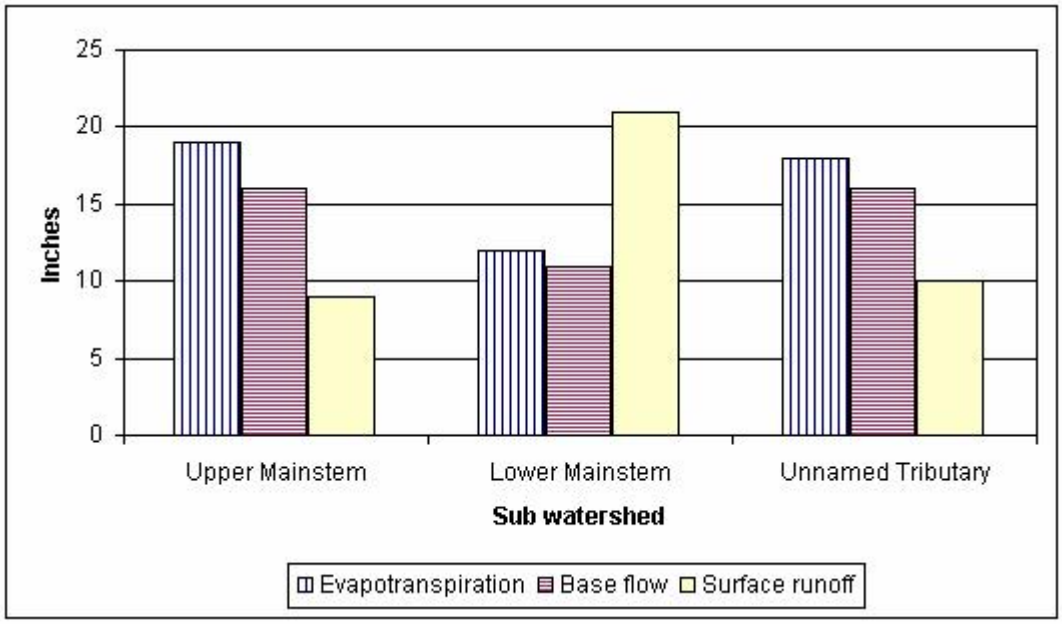

Figure 4.1. Water Balance in the sub-watersheds in the Penjajawoc. Total precipitation is 44 inches.

4.2 Flow Duration Statistic

Aquatic life impairment cannot be easily defined by a single event or an average stream condition. Typically, these types of impairments are a function of conditions that occur over an extended period of time (i.e., seasonally or annually). Aquatic life impairments in the lower watershed are believed to be due to recurring storm water discharges and associated pollutants and inadequate base flows, since it differs substantially from the upper watershed and unnamed tributary watershed. One way to enhance the understanding of habitat impairment is through a flow-duration curve. Flow duration curves show the percentage of days during a period of record that flow exceeds a certain flow value. Because actual flow rates can vary considerably among watersheds, they are normalized by the watershed area to facilitate cross-comparison from one watershed to another. The median flow is exceeded 50% of the time. The two extremes can be represented by the ninety-fifth percentile (low flow) and fifth percentile (high flow) exceedance flows.

The flow duration curve for the sub-watersheds in the Penjajawoc (Figure 4.2) was developed using the daily output of flow over a 10-year period (1992-2001) from the Penjajawoc P8 Model. A ten year period, instead of 30-year period, was selected due to the limitations of the P8 model in generating daily output of model results. Table 4.1 provides ninety-fifth, fiftieth (median) and fifth percentile exceedance flows for sub-watersheds considered in the study. The lower watershed substantially differs from the upper and unnamed tributary watersheds. The fifth percentile exceedance flow (high flow) for the lower watershed is equal to 9.11 cfs/mi^2. It is over twice that of the upper and unnamed tributary watershed

levels. In addition, it should be noted that only about twenty-two percent of the time the lower watershed yields higher flow than that of the upper mainstem and unnamed tributary. Otherwise, the lower watershed yields lower flow than that of the others. Based on these results, we expect habitat and, consequently, biological communities of the Penjajawoc stream to be impaired due to hydromodification and the increased pollutant load associated with excess storm water runoff from the lower watershed. If the lower watershed were to behave similarly to that of other unimpaired sub watersheds, it would require about a 53% reduction in fifth percentile (high flow or flood flow) exceedance flow and also a 37% increase in ninety-fifth percentile (low flow or base flow) exceedance flow.

Table 4.1. Major components of flow duration curve

WATERSHED	UPPER (REF.)	LOWER (IMPAIRED)	UNNAMED (REF.)
95% exceedance flow (cfs/mi^2) – Low Flow	0.26	0.19	0.26
50% exceedance flow (cfs/mi^2) – Median Flow	1.06	0.80	1.08
5% exceedance flow (cfs/mi^2) – High Flow	4.12	9.11	4.37

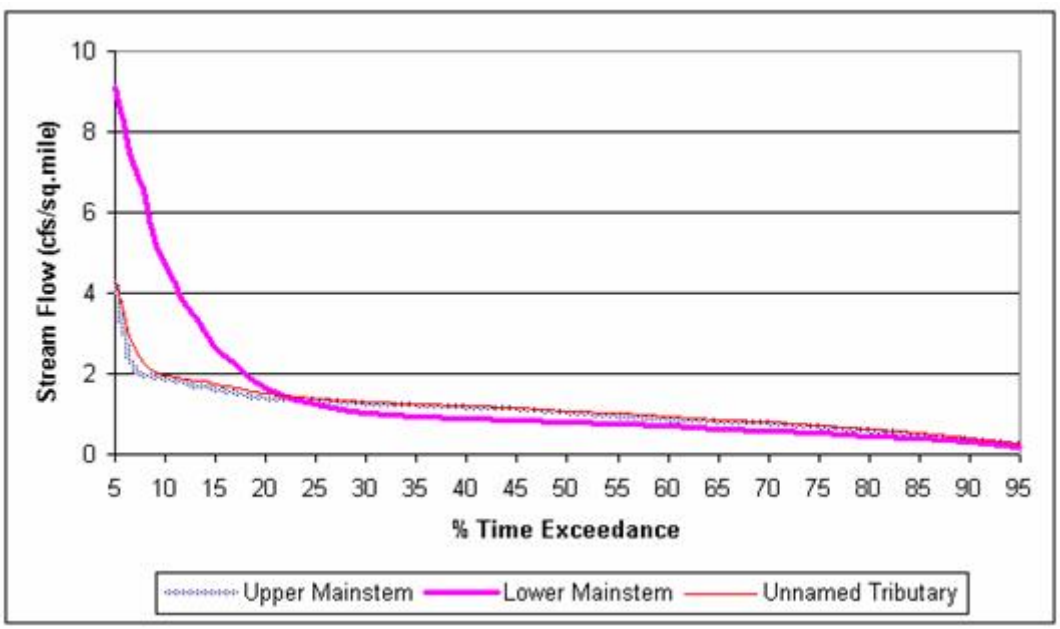

Figure 4.2. Flow duration curve generated by P8 model for the sub-watersheds in the Penjajawoc.

4.3 Water Quality

In addition to hydrological analysis, the P8 model was employed to simulate monthly pollutant load, for typical urban pollutants associated with storm water (TSS, TP, TKN, Cu, Pb, Zn, & Hydrocarbons), during the 30-year period. As an example, figures 4.3 and 4.4 present the total suspended solids (TSS) load transported from the sub-watersheds in the Penjajawoc watershed. In order to make a cross comparison, the load was normalized by watershed area. TSS load from the lower watershed was always substantially higher than that of the upper and unnamed tributary. On average, the lower watershed delivers 27 lbs/acre/month, compared to 9 and 10 lbs/acre/month for the upper and unnamed tributary watershed, respectively. Pollutants are transported from their sources in the watershed to the streams by surface runoff. Therefore, one can infer a similar trend for the other storm water-related pollutants. Table 4.2 presents all the pollutant loads simulated in this study.

Table 4.2. Unit area annual pollutant loads

WATERSHED	**UPPER (REF.)**	**LOWER (IMPAIRED)**	**UNNAMED (REF.)**	**PERCENT REDUCTION[1]**
TSS (tons/acre/year)	0.048	0.148	0.057	64%
TKN (lb/acre/year)	2.150	5.786	2.480	60%
TP (lb/acre/year)	0.441	1.223	0.512	61%
Cu (lb/acre/year)	0.049	0.131	0.056	60%
Pb (lb/acre/year)	0.023	0.068	0.027	63%
Zn (lb/acre/year)	0.229	0.617	0.265	60%
Hydrocarbons (lb/acre/year)	2.856	8.504	3.373	63%

[1] Percent reduction is based on the target set as the average of the upper and unnamed tributary watersheds.

4.4 Summary

In summary, the results revealed that the lower watershed is expected to generate excessive surface runoff and pollutant loads due to urbanization. Increased surface runoff and associated pollutants washed from impervious surfaces are the causes contributing to the aquatic life impairments in the Penjajawoc. The objective of TMDL development is to specify reductions in storm water pollutant loads and other associated stressors that result in the aquatic life uses being met. Based on the model results, the lower mainstem watershed requires approximately 60 –65% (Table 4.2) reduction in storm related urban pollutants. As previously mentioned, this pollutant reduction is directly associated with a storm water

control of about 53% reduction in surface runoff or high flow and about 37% increase in base flow or low flow (based on P8 modeling). Storm water Best Management Practices (BMPs) and/or integrated management practices (IMPs) designed to reduce high storm water flows and pollutant loads and enhance ground water recharge in the Penjajawoc watershed are expected to result in meeting the conditions that reflect maintenance of healthy aquatic life in the Penjajawoc stream.

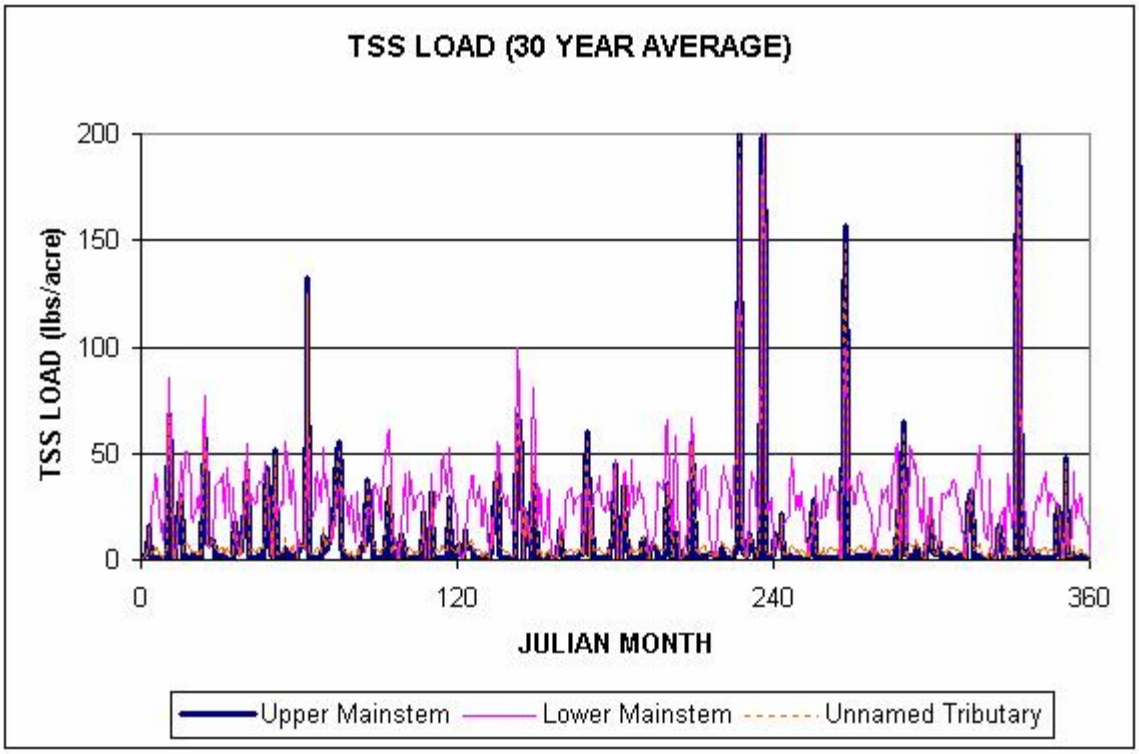

Figure 4.3. Monthly TSS load simulated by P8 model.

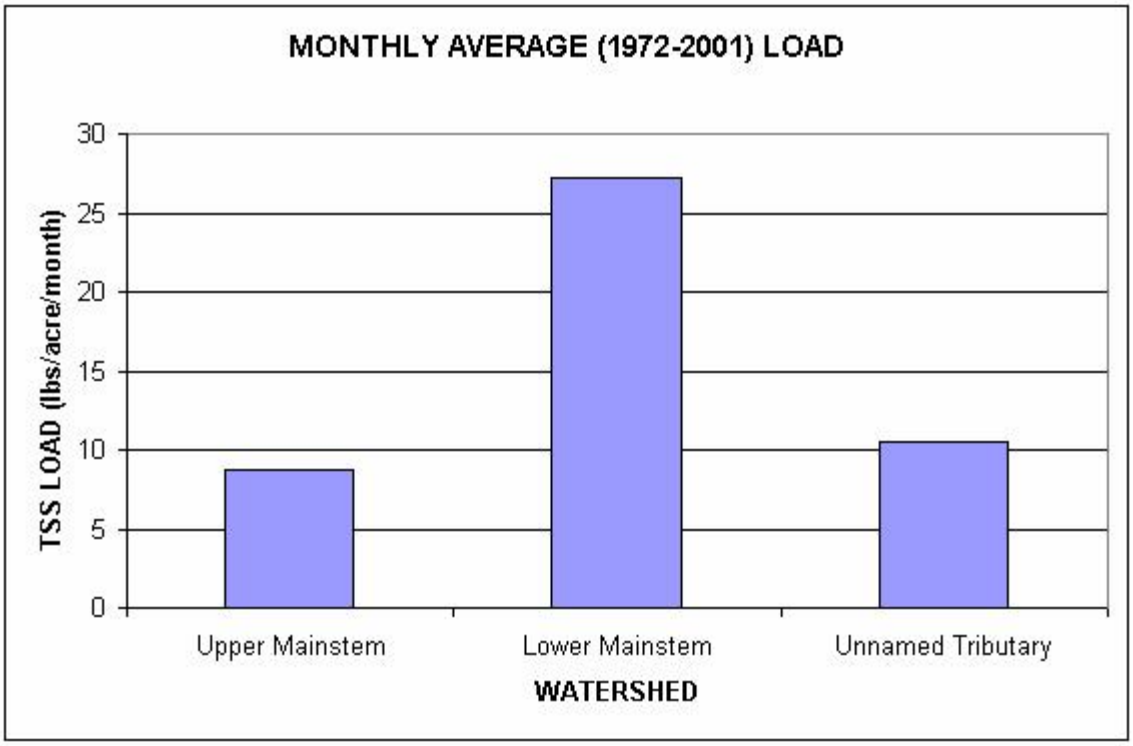

Figure 4.4. 30-year average monthly TSS load.

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