The P8 Urban Catchment Model for Evaluating Nonpoint Source Controls at the Local Level

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ABSTRACT

P8 is a model for predicting the generation and transport of stormwater runoff pollutants in urban watersheds. Continuous water balance and mass balance calculations are performed on a user-defined system consisting of the following elements: watersheds (nonpoint source areas); devices (runoff storage/treatment areas, BMPs); particle classes; and water quality components. Simulations are driven by a continuous hourly rainfall and daily air temperature time series. The model was developed for engineers and planners involved in designing and evaluating runoff treatment schemes for existing or proposed urban developments. The model is initially calibrated to predict runoff quality typical of that measured under the U.S. Environmental Protection Agency's Nationwide Urban Runoff Program for Rhode Island rainfall patterns. Predicted water quality components include total suspended solids (five size fractions), total phosphorus, total Kjeldahl nitrogen, copper, lead, zinc, and hydrocarbons. Inputs are structured in terms that should be familiar to planners and engineers involved in hydrologic evaluation. Several tabular and gr[illegible] output formats are provided. The computer runs on IBM PC-compatible microcomputers.

Introduction

Residential and commercial developments have appeared in increasing numbers in recent years throughout Rhode Island (RI Dep. Environ. Manage. 1988). This increase in development affects the surrounding environment in a number of ways. In particular, as open or forested land is developed, the area containing impervious surfaces increases dramatically, leaving fewer surfaces where precipitation can infiltrate. Increasingly, lakes, ponds, rivers, and wetlands are being affected by unmitigated stormwater runoff. Nationally, nonpoint sources of pollution account for degradation of estuaries, lakes, and rivers, about 45, 76, and 65 percent, respectively (U.S. Environ. Prot. Agency, 1989). On the other hand, municipal and industrial point source discharges degrade only 9 to 30 percent of these water resources.

Through sound land use planning and review processes, contributions of contaminants in urban runoff can be minimized and water, wetland, and wildlife resources protected. However, one of the primary constraints to implementing nonpoint source pollution controls is the lack of tools available to the local planner or engineer responsible for evaluating proposed development projects. Therefore, the P8 Urban Catchment Model, which predicts the generation and transport of stormwater runoff pollutants in urbanized catchments, was developed under a contract with the Narragansett Bay Project. The intent was to provide local and state land use planners and engineers with a tool to evaluate the effectiveness of measures for controlling urban runoff water quality, with a minimum of site-specific data.

Detailed, technical documentation for the model, including simulation methods and algorithms, calibration, testing, and limitations are provided in the P8 Urban Catchment Model Program documentation (Walker, 1990) and *P8 Urban Catchment Model User's Manual* (IEP, 1990).

Model Description

Overview

The P8 model simulates runoff and pollutant transport for a user-defined system consisting of a maximum of 24 watersheds, 24 stormwater best management devices (BMPs), 5 particle size classes, and 10 water quality components. Simulations are driven by a continuous hourly rainfall time series. P8 consists primarily of algorithms derived from other tested urban runoff models (SWMM, STORM, HSPF, D3RM, TR-20). However, P8 has been designed to require a minimum of site-specific data, which are expressed in terminology familiar to most local engineers and planners. An extensive user interface providing interactive operation, spreadsheet-like menus, help screens, and high resolution graphics facilitates model use. 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 (Fig. 1). For certain water quality components, the model is initially calibrated to predict median (50th percentile) or extreme (90th percentile) runoff concentrations measured under the U.S. Environmental Protection Agency's (EPA's) Nationwide Urban Runoff Program (NURP) (Athayde et al. 1983). Particle settling velocity distributions are also calibrated to NURP measurements.

Limitations of P8 and Other Urban Runoff Models

As with any water quality model, there are certain assumptions and inherent limitations that must be considered. A clear understanding of the assumptions and limitations is essential to the appropriate use of the model and interpretation of output. The following discussion highlights some of the primary assumptions and limitations of runoff water quality models in general, as well as those specific to P8. The program's technical documentation (Walker, 1990) provides a more detailed discussion of these limitations.

The results of the Nationwide Urban Runoff Program indicate that runoff quality is highly variable from site to site and from storm to storm at a given site (Athayde et al. 1983). The availability of calibration data limits the accuracy and use of urban runoff water quality models (Huber, 1986). Site-specific data sufficient for calibration are generally not available to the engineer and planner, particularly for future developments. The reliance of the P8 model on a generalized data source (NURP) does not solve the data availability problem but does provide a reasonable starting point for calibration and a consistent frame of reference for evaluating proposed developments.

Another important concept is that runoff model predictions are more accurate in a relative sense than in an absolute sense (Huber, 1986). For example, because it is independent of assumed runoff concentrations, prediction of suspended solids removal efficiency in a detention pond is likely to be more accurate than predictions of inflow or outflow concentrations of suspended solids. Pollutant removal is estimated by the P8 model based on particle characteristics (settling velocities or decay rates) of the runoff in relation to hydraulic characteristics of treatment device (area, depth, overflow rate, and residence time). These relationships are simulated by a physically based model. Removal efficiencies are independent of assumed inflow concentrations, which are highly variable from site to site.

A key assumption of the P8 model, as well as other physically based water quality models, is that urban runoff contaminants are largely associated with suspended solids. P8 is designed to evaluate the adequacy of treatment systems for a proposed development with respect to a target removal efficiency for total suspended solids, a specific particle class, or a specific water quality component.

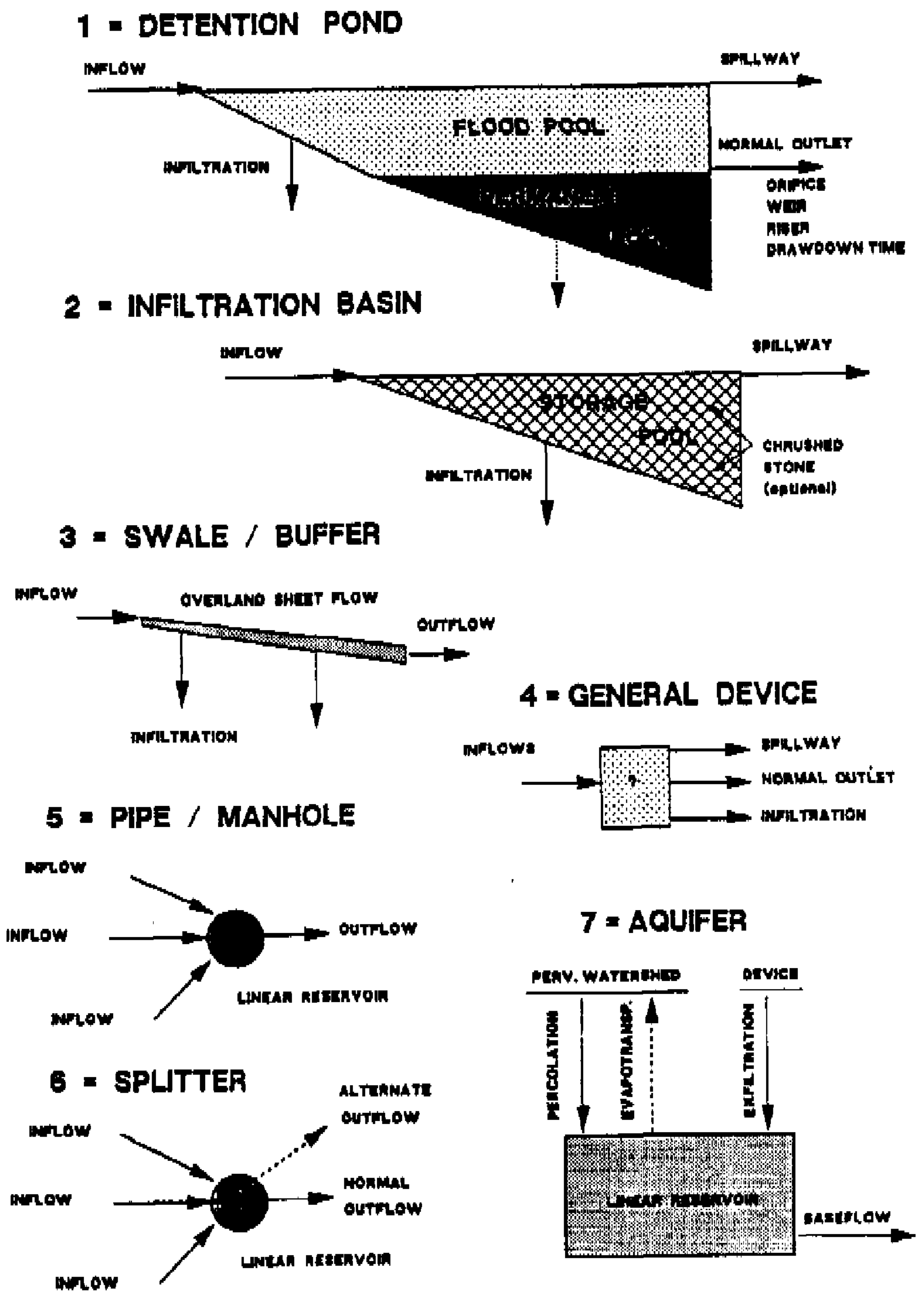

Figure 1.—P8 device types.

The generation, transport, and removal of water quality components (phosphorus, metals, petroleum hydrocarbons) are simulated by assigning contaminant components (mg/kg) to particle fractions.

The only removal mechanisms directly simulated by the model are sedimentation and filtration. Biological and chemical mechanisms of contaminant removal in treatment devices are not directly considered. Dissolved substances can be simulated with user-supplied estimates of kinetic parameters.

The primary intended uses of the model include:

- Evaluating site (development) plans for compliance with a treatment objective, expressed in terms of removal efficiency for total suspended solids or a single particle class (for example, 70 percent or 85 percent total suspended solids removal) (RI Dep. Environ. Manage. 1988).

- In a design mode, selecting and sizing BMPs to achieve a given treatment objective. The program automatically scales BMPs to match user-defined watersheds, storm time series, target particle class, and target removal efficiency.

P8 can also be used for predicting concentrations or loads from urban sites or whole watersheds. In the absence of site-specific calibration data, however, such predictions are subject to greater uncertainty because of random site-to-site variability in runoff concentrations.

Simulation Methods

Figure 2 provides a conceptual illustration of processes simulated by the P8 model. Runoff from pervious areas is computed using the Soil Conservation Service's (SCS) curve number technique (U.S. Dep. Agric. 1964), as implemented by Haith and Schoemaker (1987) for continuous watershed simulations. Antecedent moisture conditions are adjusted based upon five-day antecedent precipitation and season. Percolation from pervious areas is estimated by difference (rainfall–runoff–evapotranspiration). Evapotranspiration is computed from air temperature and season using Hamon's (1961) method, as implemented by Haith and Schoemaker (1987). Runoff from impervious areas starts after the cumulative storm rainfall exceeds the specified depression storage. Thereafter, runoff rate equals rainfall intensity. All precipitation is assumed to be rainfall.

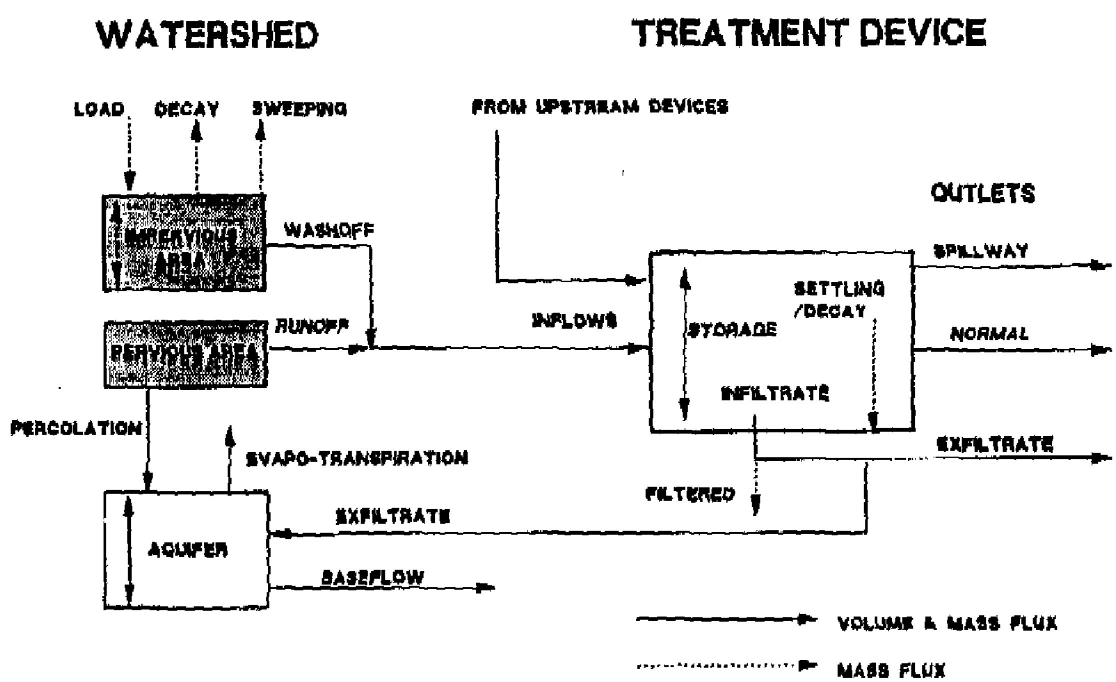

Figure 2.—P8 mass-balance schematic.

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 (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. Results are totaled. The first method is used in default particle data sets. An exponential washoff relationship similar to that employed in EPA's stormwater management model (Huber and Dikinson, 1988) is used to simulate particle buildup and washoff from impervious surfaces.

When the model is executed, the watershed/device network is sorted 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, as identified in Table 1. 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.

Table 1.—Mass balance terms.

TERM	DESCRIPTION
01 Watershed Inflows	Inflow from watershed linked to device via surface runoff or percolation (aquifer)
02 Upstream Device	Inflow from upstream devices
03 Infiltrate	Outflow passing through bottom/sides of device through Outlet 1
04 Exfiltrate	Equals Infiltrate(03) minus filtered(05)
05 Filtered	Mass removed during infiltration (trapped in soil)
06 Normal Outlet	Ouflow passing through Outlet 2
07 Spillway	Outflow through Outlet 3, used as a "relief" when device is full
08 Sedim. + Decay	Mass removed via sedimentation and/or decay
09 Total Inflow	Sum of inflows from watershed and upstream devices
10 Surface Overflow	Sum of Outlets 2 and 3; also includes Outlet 1 if its device number > 0
11 Groundw. Outflow	Outflow through Outlet 1 if its device number = 0
12 Total Outflow	Sum of surface and groundwater outflows
13 Total Trapped	Sum of sedimentation, decay, and filtration
14 Storage Increase	Increase in storage volume (or mass)
15 Mass Bal. Check	Error term in mass-balance equation; should be small in relation to total inflows if appropriate time steps are used

Program Mechanics

The P8 model operates on an IBM PC or compatible computer system (preferably an AT-class or higher with a numeric co-processor and hard disk). The P8 installation diskette contains more than 90 disk files, including sample case files and input data files. Sample case files may be used for instructional purposes or as templates for building a new case file. Input data files provided on the distribution diskette include particle/water quality component files and precipitation air temperature files for Providence (Rhode Island) Airport. Both a technical program documentation and user's manual are available for the P8 model (Walker, 1990; IEP, 1990).

The menu operates like a spreadsheet and provides access to up to four tiers of program options or functions. The primary menu options allow the user to enter, edit, or save a case file, execute the model, list or plot the output, access supplementary program functions, and access on-line help documentation. Two user modes (NOVICE and ADVANCED) are provided to facilitate user training.

Model Applications

Site Design Application

The stormwater management system for a large commercial shopping mall provides an illustrative example of the P8's simulation capabilities. The mall site is divided into two separate drainage areas (Fig. 3). Only the upper drainage area and treatment system will be discussed.

Runoff from the drainage areas is collected and routed through a treatment train that includes a sedimentation basin followed by three created wetland cells (Fig. 4). Oil and grease separators and regular sweeping of paved surfaces also provide stormwater treatment but were not considered in the P8 simulations.

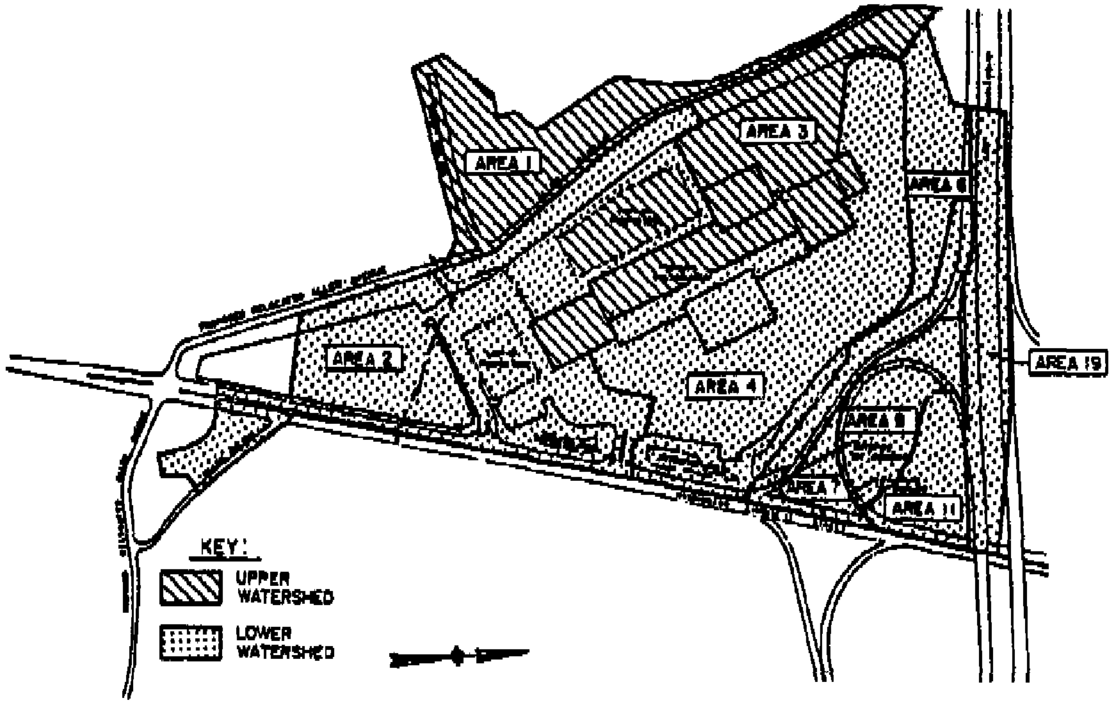

Figure 3.—Emerald Square Mall drainage areas.

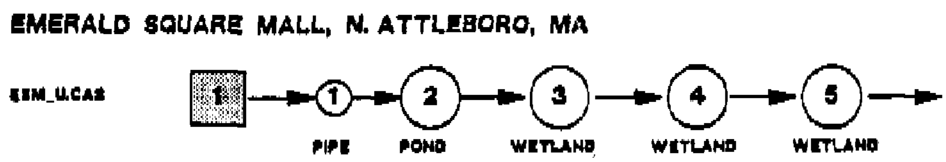

Figure 4.—Emerald Square Mall upper watershed schematic.

A water quality sampling program has been in place since June 1989 at the mall. This program includes the collection of a single grab sample and flow measurement at the terminal discharge point during one storm event each month. Water samples are analyzed for a series of water quality constituents, including but not limited to total suspended solids, total phosphorus, total Kjeldahl nitrogen, copper, lead, zinc, and hydrocarbons, as required for the National Pollutant Discharge Elimination System permit for stormwater discharge from the mall site. Data from the period of June 1989 to May 1990 will be used to compare the model predictions with available information. During this period, no discharge conditions occurred on 6 of the 12 sampling rounds.

The key model input variables for the simulation of stormwater runoff from the upper mall drainage area are provided in Table 2. The 1980 hourly precipitation data from Providence Airport and the NURP 50th percentile (median) default calibration were used in the P8 simulation. A statistical analysis of the 1980 precipitation record reveals that it is representative of an average year (Walker, 1990). A second simulation was completed using the NURP 90th percentile default calibration. These data as well as other precipitation and particle files are provided on a P8 distribution diskette.

Comparison of the P8 simulation results to data collected between June 1989 and June 1990 reveals that, with the exception of hydrocarbons, observed concentrations were lower than those predicted by

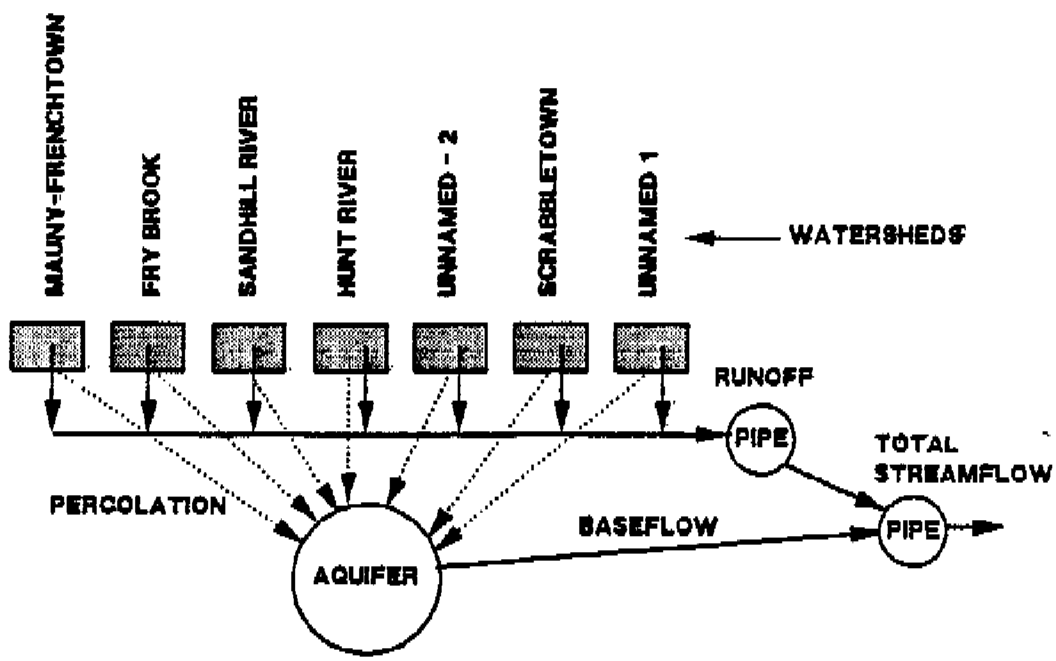

Figure 5.—Hunt-Potowomut River watershed schematic.

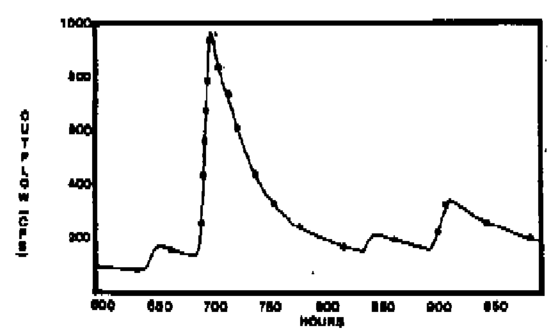

Figure 6.—Predicted instantaneous peak flow—Hunt-Potowomut River (observed peak April 11, 1983, 4:30 a.m., 968 cfs).

Results of model testing against measured daily streamflows for Water Years 1984-86 are shown in Figure 7. Observed and predicted monthly total flows (expressed in inches over entire watershed) for the entire period of flow record (Water Years 1970-86) are compared in Figure 8, while yearly moving-average flows are compared in Figure 9. The model over-predicts yearly mean flows during drought periods (1971, 1977, 1981). This may be related to errors in the prediction of evapotranspiration or to the effects of diversion from the watershed for water supply purposes (not considered in simulations). The U.S. Geological Survey (1977) reports that measured flows are affected by water supply diversions for East Greenwich, North Kingstown, Warwick, and Quonset Point (magnitudes of diversions not reported). Such diversions would tend to have greater impacts on measured streamflows during drought periods.

The comparisons support the structure and calibration of the hydrologic components of the model for predicting streamflow in this region. Calibration and testing of water quality components against site-specific data are recommended for future work.

Conclusions

The P8 Urban Catchment Model was developed for state and local planners involved in evaluating or designing stormwater management systems for proposed developments. It simulates runoff and pollutant export from watersheds and pollutant removal in treatment devices. The P8 model consists primarily of algorithms derived from other tested urban runoff models. Simulations are driven by hourly precipitation data readily available from the U.S. Weather Bureau's monitoring stations. Initial calibrations of top runoff concentrations and

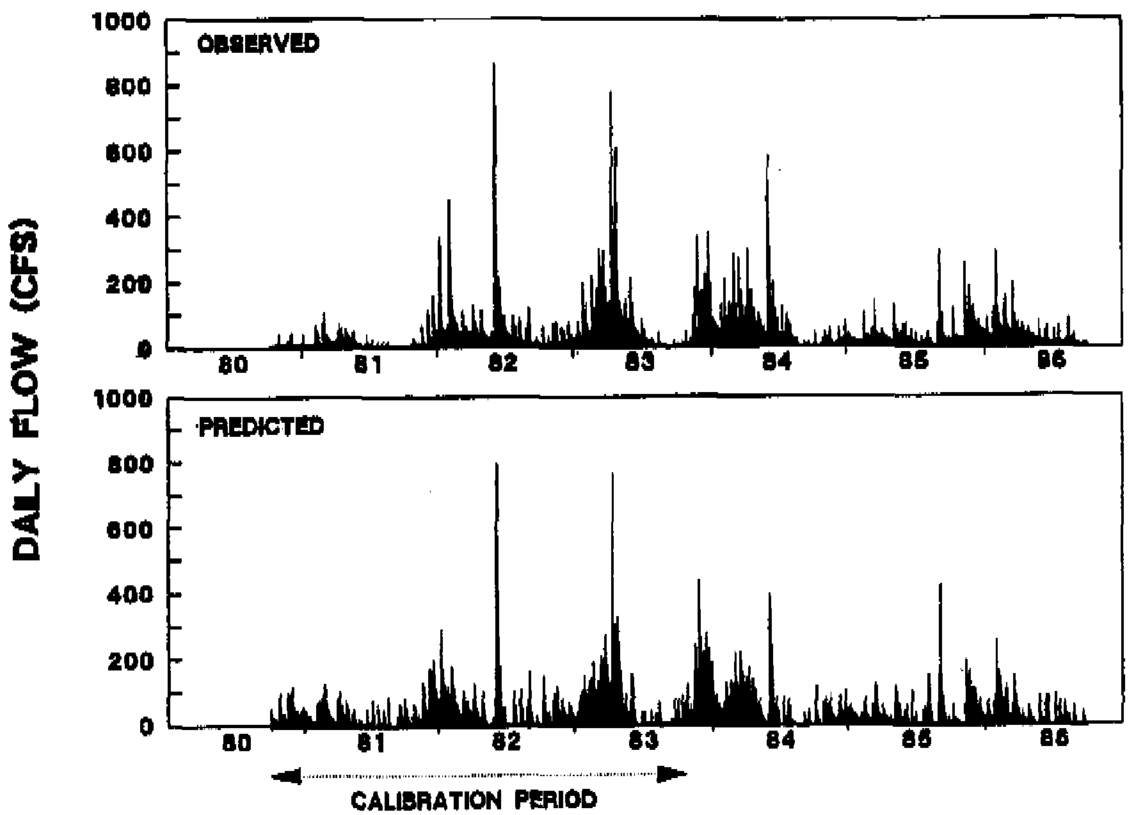

Figure 7.—Predicted versus observed daily stream flow—Hunt-Potowomut River, 1984-86.

particle settling velocities measured under the Nationwide Urban Runoff Program provide a basis for predicting pollutant removal efficiencies in runoff treatment devices for user-defined watershed/ device linkages with minimal site-specific information. If the model is to be used to predict pollutant concentrations or loads, it should be calibrated to local data sets for both water quality and discharge.

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