CHAPTER 11

WATER QUALITY CONSIDERATIONS

11-1 **GENERAL.** The objective of this chapter is to provide an overview of water quality practices used in developed areas. The purpose of a best management practice (BMP) is to mitigate the adverse impacts of development activity. BMPs can be employed for storm water control benefits and/or pollutant removal capabilities. Several BMP options are available and should be considered carefully based on site-specific conditions and the overall management objectives of the watershed. Regulatory control for water quality practices is driven by National Pollution Discharge Elimination System (NPDES) requirements under such programs as the Clean Water Act. These requirements were addressed in Chapter 1 of this UFC. Water quality practices may not be required depending on local ordinances and regulations in specific project locations.

This chapter provides a brief introduction to the kinds of BMPs that have been used historically to provide water quality benefits. Tables 11-1 and 11-2 provide brief information on the selection criteria and the pollutant removal capabilities of the various BMP options. It is beyond the scope of this document to provide procedures for estimating pollutant loading or for the detailed design of the BMPs. Section 11-11 includes information and references for developing technologies referred to as "Ultra-Urban" technologies. For more information about the design of the BMPs, refer to HEC-22.

11-2 GENERAL BMP SELECTION GUIDANCE

11-2.1 Several factors are involved in determining the suitability of a particular BMP. They include physical conditions at the site, the watershed area served, and storm water and water quality objectives. Table 11-1 presents a matrix that shows site selection criteria for BMPs. A dot indicates that a BMP is feasible. The site selection restrictions for each BMP are also indicated. Be aware that the “Area Served” criteria presented in Table 11-1, and at other locations throughout this chapter, should not be taken as a strict limitation. They are suggested rules of thumb based primarily on pollutant removal effectiveness and cost effectiveness of typical facilities as reported in the literature. In terms of water quality benefit, Table 11-2 provides a comparative analysis of pollutant removal for various BMP designs. Generally, BMPs provide high pollutant removal for non-soluble particulate pollutants, such as suspended sediment and trace metals. Much lower rates are achieved for soluble pollutants such as phosphorus and nitrogen.

11-2.2 An important parameter in BMP design is the runoff volume treated. This volume is often referred to as the first-flush volume or the water quality volume (WQV). This initial flush of runoff is known to carry the most significant non-point pollutant loads. Definitions for this first flush or WQV vary. The most common definitions are (a) the first 0.5 in. of runoff per acre of impervious area, (b) the first 0.5 in. of runoff per acre of catchment area, and (c) the first 1.0 in. of runoff per acre of catchment area.

Table 11-1. BMP Selection Criteria*

Best Management Practices (BMPs)	Area Served (ha)					Soil Type and Minimum Infiltration Rate (mm/hr)											Other Restrictions			
						Sand 210	Loamy Sand 61	Sandy Loam 26	Loam 13	Silt Loam 7	Sandy Clay Loam 4	Clay Loam 2	Silty Clay Loam 1	Sandy Clay 1	Silty Clay 1	Clay 0.5	Ground-water Table (m)	Slope (%)	Prox. to Wells (m)	Normal Depth Range (m)
	0-2	2-4	4-12	12-20	20+	A	A	B	B	C	C	D	D	D	D	D				
Biofiltration	•	•						•	•	•	•	•	•				0.3 - 0.6	<4		
Infiltration Trench	•	•				•	•	•	•								0.6 - 1.2	< 20	> 30	0.6 - 1.8
Infiltration Basin		•	•	•		•	•	•	•								0.6 - 1.2	< 20	> 30	0.6 - 1.8
Grassed Swales (with Check Dams)	•	•	•			•	•	•	•	•	•						0.3 - 0.6	< 5		0.15 - 0.6
Filter Strips	•					•	•	•	•	•	•						0.3 - 0.6	< 20		
Water Quality Inlet	•					•	•	•	•	•	•	•	•	•	•	•				
Detention Ponds			•	•	•	•	•	•	•	•	•	•	•	•						
Retention Ponds			•	•	•				•	•	•	•	•	•	•	•				
Extended Detention/ Retention Ponds			•	•	•	•	•	•	•	•	•	•	•	•						
Detention/Retention With Wetland Bottoms			•	•	•	•	•	•	•	•	•	•	•							

*** Source: HEC-22**

Table 11-2. Pollutant Removal Comparison for Various Urban BMP Designs*

BMP/design		Pollutant removal efficiency (%)						
		Suspended Sediment	Total Phosphorus	Total Nitrogen	Oxygen Demand	Trace Metals	Bacteria	Overall Removal Capability
Extended detention pond	Design 1	60 - 80	20 - 40	20 - 40	20 - 40	40 - 60	Unknown	Moderate
	Design 2	80 - 100	40 - 60	20 - 40	40 - 60	60 - 80	Unknown	Moderate
	Design 3	80 - 100	60 - 80	40 - 60	40 - 60	60 - 80	Unknown	High
Wet pond	Design 4	60 - 80	40 - 60	20 - 40	20 - 40	20 - 40	Unknown	Moderate
	Design 5	60 - 80	40 - 60	20 - 40	20 - 40	60 - 80	Unknown	Moderate
	Design 6	80 - 100	60 - 80	40 - 60	40 - 60	60 - 80	Unknown	High
Infiltration trench	Design 7	60 - 80	40 - 60	40 - 60	60 - 80	60 - 80	60 - 80	Moderate
	Design 8	80 - 100	40 - 60	40 - 60	60 - 80	80 - 100	60 - 80	High
	Design 9	80 - 100	60 - 80	60 - 80	80 - 100	80 - 100	80 - 100	High
Infiltration basin	Design 7	60 - 80	40 - 60	40 - 60	60 - 80	40 - 60	60 - 80	Moderate
	Design 8	80 - 100	40 - 60	40 - 60	60 - 80	80 - 100	60 - 80	High
	Design 9	80 - 100	60 - 80	60 - 80	80 - 100	80 - 100	80 - 100	High
Porous pavement	Design 7	40 - 60	60 - 80	40 - 60	60 - 80	40 - 60	60 - 80	Moderate
	Design 8	80 - 100	60 - 80	60 - 80	60 - 80	80 - 100	80 - 100	High
	Design 9	80 - 100	60 - 80	60 - 80	80 - 100	80 - 100	80 - 100	High
Water quality inlet	Design 10	0 - 20	Unknown	Unknown	Unknown	Unknown	Unknown	Low
Filter strip	Design 11	20 - 40	0 - 20	0 - 20	0 - 20	20 - 40	Unknown	Low
	Design 12	80 - 100	40 - 60	40 - 60	40 - 60	80 - 100	Unknown	Moderate
Grassed swale	Design 13	0 - 20	0 - 20	0 - 20	0 - 20	0 - 20	Unknown	Low
	Design 14	20 - 40	20 - 40	20 - 40	20 - 40	0 - 20	Unknown	Low

Design 1: First-flush runoff volume detained for 6-12 h. **Design 2**: Runoff volume produced by 25 mm (1.0 in), detained 24 h. **Design 3**: As in Design 2, but with shallow marsh in bottom stage. **Design 4**: Permanent pool equal to 13 mm (0.5 in) storage per impervious hectare (acre). **Design 5**: Permanent pool equal to 2.5 (Vr); where Vr = mean storm runoff. **Design 6**: Permanent pool equal to 4.0 (Vr); approx. 2 weeks retention. **Design 7**: Facility exfiltrates first-flush; 13 mm (0.5 in) runoff/imper. hectare (acre). **Design 8**: Facility exfiltrates 25-mm (1-in) runoff volume per imper.hectare (acre). **Design 9**: Facility exfiltrates all runoff, up to the 2-yr design storm. **Design 10**: 11 m^3 (400 ft^3) wet storage per imper. hectare (acre). **Design 11**: 6-m (20-ft) wide turf strip. **Design 12**: 30-m (100-ft) wide forested strip, with level spreader. **Design 13**: High-slope swales with no check dams. **Design 14**: Low-gradient swales with check dams.

*** Source: HEC-22**

In general terms, the greater the volume treated, the better the pollutant removal efficiency; however, treating volumes in excess of 1.0 in. per acre of catchment area results in only minor improvements in pollutant removal efficiency.

11-3 ESTIMATING POLLUTANT LOADS

11-3.1 To predict the impact of development activities in a watershed, pollutant loadings can be estimated for both pre- and post-development scenarios. Several methods and models are currently available that employ algorithms for pollutant loading estimation. The Simple Method is an aptly named empirical method that is intended for use on sites of less than 1 mi^2. It assumes that an average pollutant concentration is multiplied by the average runoff to yield an average loading estimate.

11-3.2 The FHWA has developed a computer model that deals with the characterization of storm water runoff pollutant loads from highways. Impacts to receiving water, specifically lakes and streams, are predicted from the estimated loadings. More detail on the estimating procedures can be found in the 4-volume FHWA report, *Pollutant Loadings and Impacts from Highway Stormwater Runoff*.

11-3.3 Several other comprehensive storm water management models have the ability to generate pollutant loads and the fate and transport of the pollutants:

- Storm Water Management Model (SWMM)
- Storage, Treatment, Overflow, Runoff Model (STORM)
- Hydrologic Simulation Program, Fortran (HSPF)
- Virginia Storm Model (VAST)

11-4 **EXTENDED DETENTION DRY PONDS.** Extended detention dry ponds are depressed basins that temporarily store a portion of storm water runoff following a storm event. Water is typically stored for up to 48 hours following a storm by means of a hydraulic control structure to restrict outlet discharge. The extended detention of the storm water provides an opportunity for urban pollutants carried by the flow to settle out.

11-5 **WET PONDS.** A wet pond, or retention pond, serves the dual purpose of controlling the volume of storm water runoff and treating the runoff for pollutant removal. Wet ponds are designed to store a permanent pool during dry weather. These ponds are an attractive BMP alternative because the permanent pool can have aesthetic value and can be used for recreational purposes and as an emergency water supply. Pollutant removal in wet ponds is accomplished through gravity settling, biological stabilization of solubles, and infiltration.

11-6 **INFILTRATION/EXFILTRATION TRENCHES.** Infiltration trenches are shallow excavations that have been backfilled with a coarse stone media. An infiltration trench forms an underground reservoir that collects runoff and either exfiltrates it to the subsoil or diverts it to an outflow facility. The trenches primarily serve as a BMP that provides moderate to high removal of fine particulates and soluble pollutants, but also are employed to reduce peak flows to pre-development levels. Use of an infiltration trench is feasible only when soils are permeable and the seasonal groundwater table is below the bottom of the trench.

11-7 **INFILTRATION BASINS.** An infiltration basin is an excavated area that impounds storm water flow and gradually exfiltrates it through the basin floor. Infiltration basins are similar in appearance and construction to conventional dry ponds; however, the detained runoff is exfiltrated though permeable soils beneath the basin, removing both fine and soluble pollutants. Infiltration basins can be designed as combined exfiltration/detention facilities or as simple infiltration basins.

11-8 **SAND FILTERS.** Sand filters provide storm water treatment for first flush runoff. The runoff is filtered through a sand bed before being returned to a stream or channel. Sand filters are generally used in urban areas and are particularly useful for groundwater protection where infiltration into soils is not feasible.

11-9 **WATER QUALITY INLETS.** Water quality inlets are pre-cast storm drain inlets that remove sediment, oil and grease, and large particulates from parking lot runoff before it reaches storm drainage systems or infiltration BMPs. As three-stage underground retention systems designed to settle out grit and absorbed hydrocarbons, they are commonly known as oil and grit separators. Water quality inlets typically serve highway storm drainage facilities adjacent to commercial sites where large amounts of vehicle wastes are generated, such as gas stations, vehicle repair facilities, and loading areas. These inlets may be used to pretreat runoff before it enters an underground filter system.

11-10 **VEGETATIVE PRACTICES.** Several types of vegetative BMPs can be applied to convey and filter runoff:

- Grassed swales
- Filter strips
- Wetlands

Vegetative practices are non-structural BMPs and are significantly less costly than structural controls. They are commonly used in conjunction with structural BMPs, particularly as a means of pre-treating runoff before it is transferred to a location for retention, detention, storage, or discharge.

11-11 **ULTRA-URBAN BMPs**

11-11.1 The relative merits of traditional storm water control measures in the context of existing developed communities have become an important issue. The EPA Phase II storm water regulations (National Pollutant Discharge Elimination System Stormwater Program), the safety of public water supplies, and the threat to endangered aquatic species have intensified interest in identifying innovative approaches for protecting source and receiving water quality. Also, additional drivers for innovation are the implementation of Section 6217g of the Coastal Zone Act Reauthorization Amendments (CZARA), state coastal nonpoint source management programs, and the desire of many local watershed committees to improve and restore degraded streams as part of their watershed restoration priorities submitted to EPA by states as requested by the Clean Water Action Plan. Comprehensive storm water regulations, space limitations, hardened infrastructure, high urban land values, limitations of traditional BMPs, and the increase in urban runoff pollutant loads over the last decade have spurred the development of a new class of products and technologies. These non-traditional methods of capturing runoff contaminants before they reach surface and groundwater have been labeled in many circles as "ultra-urban" technologies.

11-11.2 Ultra-urban storm water technologies have an appeal that historical methods of storm water management do not have in developed areas. They are particularly suited to retrofit applications in the normal course of urban renewal, community revitalization, and redevelopment, as well as new urban development. These engineered devices are typically structural and are made on a production line in a factory. They may be designed to handle a range of pollutant and water quality conditions in highly urbanized areas. Some ultra-urban storm water controls have small footprints and may be literally dropped into the urban infrastructure or integrated into the streetscape of both private and public sector property. Others may be installed beneath parking lots and garages or on rooftops. Still others are designed to remove pollutants before they are flushed into urban runoff collection systems.

11-11.3 The Civil Engineering Research Foundation's (CERF) Environmental Technology Evaluation Center (EvTEC) has developed a Web site focusing on new and innovative storm water control technologies: http://www.cerf.org

These are two of EvTEC's ongoing evaluations:

- Stormwater Best Management Practices (BMPs) Verification Program: http://www.cerf.org/evtec/eval/wsdot2.htm
- Low-Cost Stormwater BMP Study

11-12 **TEMPORARY EROSION AND SEDIMENT CONTROL PRACTICES.** Most states have erosion and sedimentation (E&S) control regulations for land disturbance activities. The purpose of E&S measures is to reduce erosive runoff velocity and to filter the sediment created by the land disturbance. Temporary E&S controls are applied during the construction process and consist of structural and/or vegetative practices. The control measures are usually removed after final site stabilization unless they prove to be necessary for permanent stabilization. A few of these practices are listed here (for more information on these practices, see HEC-22):

- Mulching
- Temporary/permanent seeding
- Sediment basins
- Check dams
- Silt fence
- Brush barrier
- Diversion dike
- Temporary slope drain

CHAPTER 12

DESIGN COMPUTER PROGRAMS

12-1 **STORM WATER MANAGEMENT PROGRAMS**. In developed areas, planners, designers, and operators of storm water drainage systems are often required to determine quantities of storm water runoff and evaluate its quality as an important component in the overall condition of an area or watershed. Two computer models designed principally for urban areas are available. These are STORM, developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers, and SWMM, developed for the EPA.

12-2 **DRIP (DRAINAGE REQUIREMENT IN PAVEMENTS)**. DRIP is a Windows® computer program developed by the FHWA for pavement subsurface drainage design.

12-3 **CANDE-89 (CULVERT ANALYSIS AND DESIGN)**. CANDE-89 is a software program used for the structural analysis and design of buried culverts and other soil-structure systems. A variety of buried structures are considered, including corrugated steel and aluminum pipes, long span metal structures, reinforced concrete pipe, concrete box culverts, and structural plastic pipes. The CANDE methodology incorporates the soil mass with the structure into an incremental static, plane-strain boundary value problem. The program is available from the Center for Microcomputers in Transportation (Mc*Trans*) Web site:

http://www-mctrans.ce.ufl.edu

12-4 **MODBERG.** ModBerg calculates the maximum depth of frost penetration for a given location. This program is available from the PCASE Downloads Page of the Tri-Service Transportation Technology Transfer Website Portal:

https://transportation.wes.army.mil/triservice/pcase//downloads.aspx

12-5 **DDSOFT (DRAINAGE DESIGN SOFTWARE)**. Based on the Rational Formula and Manning's equation, DDSoft determines the size and bed slope of a drainage channel or storm sewer. The program works with channels of 4 different shapes (i.e., vertical curb, triangular, rectangular, and trapezoidal) and 1 sewer shape (i.e., circular). The program is available from this Web site:

http://www.ntu.edu.sg/home/cswwong/software.htm

12-6 **NDSOFT (NORMAL DEPTH SOFTWARE)**. Based on Manning's equation, NDSoft determines the normal depth in a drainage channel. It works with channels of 5 different shapes (i.e., vertical curb, triangular, rectangular, trapezoidal, and circular). Further, the program can also determine the size of a circular sewer based on the normal depth under the full-flow condition. The program is available from this Web site:

http://www.ntu.edu.sg/home/cswwong/software.htm

12-7 **PIPECAR**. PIPECAR is a program for structural analysis and design of circular and horizontal reinforced concrete pipe. Load analysis includes pipe weight, soil weight, internal fluid load, LL, and internal pressures up to 50 ft of head. The program is available for download from the Hydraulics Engineering page of the Federal Highway Administration Web site:

http://www.fhwa.dot.gov/engineering/hydraulics/software/softwaredetail.cfm

12-8 **VISUAL URBAN (HY-22) URBAN DRAINAGE DESIGN PROGRAMS**. These programs perform tasks in highway pavements drainage, open channel flow characteristics, critical depth calculations, development of stage-storage relationships, and reservoir routing. The software is available for download from the Hydraulics Engineering page of the Federal Highway Administration Web site:

http://www.fhwa.dot.gov/engineering/hydraulics/software/softwaredetail.cfm

12-9 **ADDITIONAL SOFTWARE.** Several software packages are available that provide quick and precise analysis of urban hydrology and hydraulics. The software programs reviewed in this chapter are public sector programs that incorporate many of the procedures discussed in this UFC. These modeling packages are reviewed:

- HYDRAIN
- HYDRA
- WSPRO
- HYDRO
- HY8
- HYCHL
- NFF
- HYEQT
- TR-55
- TR-20
- HMS
- HEC-RAS
- SWMM
- PSRM-QUAL
- Hydraulic Toolbox (HY-TB)
- HY22 Urban Drainage Design Programs
- DR3M

Table 12-1 presents a software versus capabilities matrix for these software packages. Some of the models have a single capability, such as hydrologic analysis, while other packages offer a variety of analysis and design options.

Table 12-1. Software vs. Capabilities Matrix

	Storm Drains	Hydrology	Water Surface Profiles	Culverts	Roadside/ Median Channels	Water Quality	Pavement Drainage	Pond Routing	BMP Evalu-ation	Metric Version
HYDRAIN	●	●	●	●	●		●	●		●
TR-55		●								
TR-20		●						●		
HMS		●						●		●
SWMM	●	●				●	●	●	●	●
PSRM-QUAL	●	●				●	●	●	*	
DR3M	●	●					●	●		
HY-TB	●				●		●			
Urban Drainage	●				●		●	●		●
Evaluation of Water Quality						●			●	

*To be added in a future update.

Many private and public domain software products are available for the analysis and design of various components of storm drain systems. These products range from simple computational tools for specific components of the storm drain system to complex programs that can analyze complete storm drain systems using interactive graphical interfaces. The computer hardware and software industry is a rapidly changing industry in which new and more advanced applications software is developed each year. This chapter is limited to a review of public sector software. For public sector software, user support is minimal or nonexistent if the software is obtained directly from the Government. Private vendors sell many of these packages and may offer user support.

12-9.1 **HYDRAIN.** HYDRAIN is an integrated computer software system consisting of hydraulic and hydrologic analysis programs. The system manages engineering computations and data associated with these subprograms:

- HYDRA - Storm Drain and Sanitary Sewer Design and Analysis
- WSPRO - Open Channel Water Surface Analysis, Bridge Hydraulics, Scour
- HYDRO - Design Event versus Return Period Hydrology
- HYCLV - Culvert Design and Analysis
- HY8 - FHWA Culvert Analysis and Design
- HYCHL - Flexible and Rigid Channel Lining Design and Analysis
- HYEQT - Equation Program
- NFF - USGS National Flood Frequency Program

12-9.1.1 HYDRAIN is a versatile hydrologic and hydraulic software package. The subprograms within the system offer a variety of analysis and design option tools. The HYDRAIN programs are embedded within a system shell that allows for quick and easy access to each module. File operations, access to program editors, and other Disk Operating System (DOS) utilities can be performed through the input shell.

12-9.1.2 Data entry for most programs within the system is done through the command line editor. The editor is equipped with short and long helps to aid the user. The user supplies the input data for the subprogram within one input file. If the subprogram is run from within the HYDRAIN environment, the input file may be modified without leaving HYDRAIN by using the built-in editor. This feature minimizes the time required for data modification and job resubmission.

12-9.1.3 HY8 and HYCHL are interactive programs. In other words, these programs access a series of menus that ask the user for specific input.

12-9.1.4 HYDRAIN can handle almost all aspects of storm drain design in a highway context. It is applicable to analysis of simple hydrologic situations and design or analysis of simple and complex hydraulic systems. HYDRAIN is easy to use, providing a full screen input editor and extensive help messages.

12-9.2 **HYDRA**. HYDRA (HighwaY Storm DRAinage) is a storm drain and sanitary sewer analysis and design program. Originally developed in 1975, the program ran on mainframe computer systems. HYDRA provides hydraulic engineers a means of accurately, easily, and quickly designing and analyzing storm, sanitary, or combined collection systems. Of HYDRA's many features, these are particularly useful:

12-9.2.1 **Operational Modes**. HYDRA operates in two modes: design and analysis. In the analysis mode, HYDRA analyzes a drainage system given user-supplied specifications. In the design mode, HYDRA can "free design" its own drainage system based on design criteria supplied by the user.

12-9.2.2 **System Types**. In either the design or the analysis mode, HYDRA can work with 3 possible types of systems: (1) storm drain systems, (2) sanitary (sewer) systems, and (3) combined (storm and sanitary) sewer systems.

12-9.2.3 **Hydraulic Analysis Features**. Two options are available to HYDRA users: the calculation of the HGL through a system and the simulation of a system under pressurized (surcharged) flow conditions.

12-9.2.4 **Storm Flow Simulation Methods**. HYDRA is capable of simulating storm flow based on either the Rational Method for peak flow simulation or user-supplied hydrographic simulation.

12-9.2.5 **Detention Basin Routing**. HYDRA will design or analyze a detention pond by routing a hydrograph with the storage-indication method.

12-9.2.6 **Planning**. HYDRA can be used for determining the most practical alternatives for unloading an existing overloaded storm drain and for formulating master plans to allow for the orderly growth of these systems.

12-9.2.7 **Drainage Systems Size**. HYDRA has a data handling algorithm especially designed to accept a drainage system of any realistically conceivable design, including complicated branching systems.

12-9.2.8 **Infiltration/Inflow Analysis**. HYDRA can account for undesirable inputs, such as infiltration in sanitary sewer systems.

12-9.2.9 **Cost Estimation**. HYDRA's cost estimation capabilities include consideration of de-watering, traffic control, sheeting, shrinkage of backfill, costs of borrow, bedding costs, surface restoration, rock excavation, pipe zone costs, and more. HYDRA is also sufficiently flexible to allow cost criteria to be varied for any segment of pipe in a system. Ground profiles, either upstream or downstream from any specified point along the system, can also be accepted for consideration in cost estimation.

12-9.3 **WSPRO**. WSPRO (Water Surface PROfile) is a water surface profile computation program originally developed by the USGS for the FHWA. Water surface profile computations are made with the standard step method in the absence of bridges. The majority of water surface profile computations are now performed by HEC-RAS, which is described in paragraph 12-10.12.

12-9.4 **HYDRO**. HYDRO is a hydrologic analysis program based on the FHWA's HDS-2. It combines existing approaches for rainfall runoff analysis into one system. HYDRO generates point estimates or a single design event. It is not a continuous simulation model. HYDRO uses the probabilistic distribution of natural events such as rainfall or stream flow as a controlling variable. HYDRO can be considered a computer-based subset of HDS-2.

12-9.4.1 HYDRO capabilities are divided into three major hydrological categories: rainfall analysis, IDF curve generation, and flow analysis. HYDRO's rainfall analysis features allow the user to investigate steady-state (rainfall intensity) and dynamic (hyetograph) rainfall conditions. Both the rainfall analysis and IDF curve generation are a function of frequency, geographic location, and duration of the storm event.

- Rainfall Analysis. HYDRO can internally calculate rainfall intensities for any site in the continental United States. This rainfall is a single peak rainfall. HYDRO can also be used to create a triangular hyetograph.

- IDF Curves. IDF curves can be created using the internal intensity databases. The curves will show, for a user-provided frequency, the duration versus intensity for any location in the continental United States. The frequency can be any whole number between 2 and 100 yr and the duration can extend from 5 min to 24 hr of rainfall duration.

- Peak Flow Methods. HYDRO implements three peak flow methods: the Rational Method; user-supplied regression equations; and the Log-Pearson Type III method. Each of these methods produces a single peak flow value or steady state of low-flow value.

- Hydrograph Method. HYDRO can combine the peak flow with the dimensionless hydrograph to handle hydrographic or dynamic flow conditions. HYDRO includes two dimensionless hydrograph methods: the USGS nationwide urban method and the semi-arid method.

12-9.5 **HY8.** HY8 is an interactive BASIC program that allows the user to investigate the hydraulic performance of a culvert system. A culvert system is composed of the actual hydraulic structure or structures as well as hydrological inputs, storage and routing considerations, and energy dissipation devices and strategies.

12-9.5.1 HY8 automates the methods presented in HDS-5, HEC-14, HDS-2, and information published by pipe manufacturers pertaining to the culvert sizes and materials.

12-9.5.2 HY8 is composed of four different program modules: Culvert Analysis and Design, Hydrograph Generation, Hydrograph Routing, and Energy Dissipation.

- Culvert Analysis and Design. Culvert hydraulics can be determined for circular, rectangular, elliptical, arch, and user-defined geometry. HY8 can analyze as many as six parallel culvert systems simultaneously, each having different inlets, inlet elevations, outlets, outlet elevations, lengths, materials, and cross-sectional shape characteristics.

- Hydrograph Generation/Routing. Storm hydrographs can be generated to be used singly or as input into culvert routing analyses. The generated hydrograph, along with the culvert data, can be used by HY8 to calculate storage and outflow hydrograph characteristics. The routing is performed by application of the storage indication (modified Puls) method.

- Energy Dissipation. HY8 can also design and analyze energy dissipation structures at the outlet of a culvert. Options include external dissipators, internal dissipators, and estimating scour hole geometry.

12-9.6 **HYCHL**. HYCHL is a channel lining analysis and design program. The basis for program algorithms are the FHWA's HEC-15 and HEC-11. The program performs several options and analyses:

12-9.6.1 **Stability Analysis**. HYCHL can analyze drainage channels for stability given design flow and channel conditions (i.e., slope, shape, and lining type).

12-9.6.2 **Maximum Discharge**. The maximum discharge a particular channel lining can convey can be calculated based on the permissible shear stress of the lining.

12-9.6.3 **Multiple Lining Types**. Depending on channel function, material availability, costs, aesthetics, and desired service life, a designer may choose from a variety of lining types, whether single or composite. HYCHL can perform analysis on rigid or flexible linings. Rigid linings in HYCHL include concrete, grouted riprap, stone masonry, soil cement, and asphalt. Flexible linings include a variety of temporary and permanent lining types. Permanent flexible linings include vegetation, riprap, and gabions. Riprap-lined channels can be designed or analyzed as irregular or regular channel shapes. Temporary linings include woven paper, jute mesh, fiberglass roving, straw with net, curled wood mat, synthetic mat, and bare soil (unlined).

12-9.6.4 **Alternative Channel Shapes**. Channel cross sections available in HYCHL include trapezoidal, parabolic, triangular, triangular with rounded bottom, and irregular (user-defined) shapes.

12-9.6.5 **Constant on Variable Channel Inflow**. HYCHL can evaluate the performance of channel linings using a design flow that is assumed to be either a constant for the entire channel length or a variable inflow. The variable lineal flow results in an increasing discharge with channel length.

12-9.7 **NFF.** The USGS, in cooperation with the FHWA and the Federal Emergency Management Agency, has compiled all the current statewide and metropolitan-wide regression equations into a microcomputer program, the National Flood Frequency (NFF) program. NFF summarizes techniques for estimating flood-peak discharges and associated flood hydrographs for a given recurrence interval or exceedence probability for unregulated rural and urban watersheds. NFF includes both the regression equations for rural watersheds in each state and the nationwide regression equations for urban watersheds, and it generates rural and urban frequency functions and hydrographs.

12-9.8 **HYEQT.** The HYDRAIN equation program (HYEQT) is an application program that allows a user to input and solve regression equations for solving peak flow (or any other formula of interest). This program can be used instead of the NFF program to allow for modification of the USGS regression equations. These equations provide estimates that engineers and hydrologists can use for planning and design applications.

12-9.9 **TR-55.** TR-55 is a hydrology program that implements SCS methods for calculating time of concentration, peak flows, hydrographs, and detention basin storage volumes. It is applicable to urban drainage situations where detailed hydrograph routing procedures are not warranted. The program, now compatible with Windows™ operating systems, incorporates the procedures outlined in Technical Release 55 (TR-55). TR-55 contains simplified procedures to calculate storm runoff volume, peak rate of discharge, hydrographs, and storage volumes required for storm water reservoirs. The procedures are applicable in small urbanizing watersheds in the United States.

TR-55 is extremely easy to use, with interactive menus that prompt the user for specific inputs. Several screens of input are normally required before an analysis can proceed. Help screens assist the user in successfully performing an analysis. These are some of the options and analyses included in TR-55:

12-9.9.1 **Estimating Runoff**. TR-55 employs the SCS Runoff Curve Number Method or the Graphical Peak Discharge Method to estimate peak discharges in a rural or urban watershed.

12-9.9.2 **Time of Concentration and Travel Time**. TR-55 computes travel time for sheet flow, shallow concentrated flow, and open-channel flow. Travel time for sheet flow is estimated using Manning's kinematic solution. Travel time in open channels is evaluated by applying Manning's equation.

12-9.9.3 **Tabular Hydrograph Method**. The Tabular Hydrograph method can develop partial composite flood hydrographs at any point in a watershed by dividing the watershed into homogeneous subareas.

12-9.9.4 **Storage Volume for Detention Basins**. TR-55 can also estimate detention basin storage volume.

12-9.10 **TR-20.** TR-20, based on SCS Technical Release 20, is a comprehensive hydrology program that implements SCS methods for generating and routing runoff hydrographs in a multibasin watershed. The program provides for hydrographic analyses of a watershed under present conditions and various combinations of land cover/use and structural or channel modifications using single rainfall events. Output consists of runoff peaks and/or flood hydrographs, their time of occurrence, and water surface elevations at any desired cross section or structure. Subarea surface runoff hydrographs are developed from storm rainfall using an SCS dimensionless unit hydrograph (UH), drainage areas, times of concentration, and SCS runoff curve numbers. Hydrographs can be developed, routed, added, stored, diverted, or divided to convey floodwater from the headwaters to the watershed outlet. TR-20 is applicable only to larger watersheds where detailed hydrograph routing is warranted. These are some of the options and analyses employed by TR-20:

12-9.10.1 **Runoff Volume**. A mass curve of runoff is developed for each subwatershed. The runoff curve number (CN), rainfall volume, and rainfall distribution are the input variables needed to determine the mass curve. CNs are determined by the user for each subwatershed based on soil, land use, and hydrologic condition information. The runoff volume is computed using the SCS runoff equation. The program can develop and route the runoff from as many as nine different rainfall distributions and ten different storms for each rainfall distribution. Runoff depths and durations will be developed and routed for a rainfall distribution defined in either dimensionless units or actual time units.

12-9.10.2 **Hydrograph Development**. An incremental UH is developed for each subwatershed. The UH time increment is calculated as a function of the time of concentration. The incremental runoff volume is determined for each time increment. The composite flood hydrograph is computed by summing the incremental hydrograph ordinates. A maximum of 300 ordinates (discharge values) can be stored for any composite flood hydrograph. The peak flow value of the composite flood hydrograph is computed by a separate routine that utilizes the Gregory-Newton forward difference formula for fitting a second degree polynomial through the 3 largest consecutive hydrograph values saved at the main time increment. In multiple peaked hydrographs, up to ten peaks may be computed.

12-9.10.3 **Reservoir Routing**. The composite flood hydrograph is routed through a reservoir using the storage indication method. The program can route a hydrograph through up to 99 structures and an unlimited number of variations for each structure.

12-9.10.4 **Reach Routing**. The composite flood hydrograph is routed through a valley reach using a modified Attenuation-Kinematic (Att-Kin) method. TR-20 can route through up to 200 stream reaches and an unlimited number of channel modifications for each reach.

12-9.11 **HMS.** HMS is a flood hydrograph package developed by the U.S. Army Corps of Engineers. The HMS model, like TR-20, is designed to simulate the surface runoff response of a river basin to precipitation by representing the basin as an interconnected system of hydrologic and hydraulic components. Each component models an aspect of the precipitation-runoff process within a portion of the basin. A component may represent a surface runoff entity, a stream channel, or a reservoir. Representation of a component requires a set of parameters that specify the particular characteristics of the component and mathematical relations that describe the physical processes. The result of the modeling process is the computation of streamflow hydrographs at desired locations in the river basin. It is applicable to only larger watersheds where detailed hydrograph routing is warranted.

Simulating a river basin as a group of subareas interconnected through channel routing reaches and confluences, HMS performs hydrologic calculations on a user-specified time step for a single storm (soil moisture recovery during dry spells is not included). HMS is used to generate discharge, not water surface elevations (although it does calculate normal depth). The HEC-RAS model is typically used in conjunction with HMS to determine water surface profiles through detailed hydraulic computations. These are the major components and characteristics of HMS:

12-9.11.1 **Precipitation**. A precipitation hyetograph is used as input for all runoff calculations. Precipitation data for an observed event can be user-supplied or synthetic storms can be used. Snowfall and snowmelt can also be considered.

12-9.11.2 **Hydrographs**. There are three synthetic UH methods in the HMS model, including the Clark UH, the Snyder UH, and the SCS dimensionless UH. User-defined UHs can be entered directly.

12-9.11.3 **Flood Routing**. Flood routing can be computed by a variety of methods, including Muskingum, Muskingum-Cunge, kinematic wave, modified Puls, working R and D, and level-pool reservoir routing.

12-9.11.4 **Flood Damage/Flood Control System Optimization**. The reservoir component of the HMS model is employed in a stream network model to simulate dam failure. HMS also has a flood control system optimization option which is used to determine optimal sizes for the flood loss mitigation measures in a river basin flood control plan.

HMS was first developed in 1968 and has undergone several revisions over the years. New capabilities of the most recent version include database management interfaces and a graphics program that allows plots of information stored in the HMS database. In addition, a user-friendly input program is available to help first-time users of HMS. The program helps the user to assemble the correct sequence of records for an HMS input file.

12-9.12 **HEC-RAS.** HEC-RAS is an integrated system of software designed for interactive use in a multi-tasking environment. The system is comprised of a graphical user interface (GUI), separate hydraulic analysis components, data storage and management capabilities, and graphics and reporting facilities.

The HEC-RAS system contains three one-dimensional hydraulic analysis components for: (1) steady flow water surface profile computations; (2) unsteady flow simulation; and (3) movable boundary sediment transport computations. A key element is that all three components will use a common geometric data representation and common geometric and hydraulic computation routines. In addition to the three hydraulic analysis components, the system contains several hydraulic design features that can be invoked once the basic water surface profiles are computed. HEC-RAS can also perform water temperature analyses in river systems.

These are HEC-RAS' current capabilities:

- Geometric Features: bridge hydraulics – extensive; culverts (nine types); multiple open (bridges & culverts); inline structures – gates and weirs; lateral structures – gates, weirs, culverts, and rating curves; pressurized conduits; storage/ponding areas; hydraulic connections between storage areas; pump stations; floating ice; levees; extensive data import and export; and GIS connections.

- Analysis Features: steady flow profiles; unsteady flow simulations; FEMA floodway encroachments; split flow optimization; sediment transport capacity and bridge scour; dam and levee breaching; navigation dam operations; channel modifications; mixed flow regime; and extensive calibration features.

- Graphical Output Capabilities: water surface profile plots; cross sections; rating curves; stage and flow hydrographs; generalized profile plot of any variable (i.e., velocity); a three dimensional view of the river system; graphical animations; and plotting of more than 250 output variables at every cross section per profile.

- Tabular Output: detailed output tables for XS and all structures; summary output tables; and user defined output.

- Documentation: extensive manuals (user's manual, hydraulic reference manual, and applications guide); online help system; and example data sets

12-9.13 **SWMM.** The Storm Water Management Model (SWMM), developed by the EPA, is a comprehensive mathematical model for simulation of urban runoff quantity and quality in storm and combined sewer systems. The model simulates all aspects of the urban hydrologic and quality cycles, including surface runoff, transport through the drainage network, storage and treatment, and receiving water effects.

12-9.13.1 SWMM simulates real storm events on the basis of rainfall (hyetograph) and other meteorological inputs and system (catchment, conveyance, storage/treatment) characterization to predict outcomes in the form of quantity and quality values. The model is structured to perform runoff computations, transport and rate functions, and water quality and cost computations.

12-9.13.2 SWMM is made up of many different components or "blocks" that perform various functions. Those blocks are: Runoff, Transport, Storage/Treatment, EXTRAN, and five other "service" blocks related to data preparation.

- Runoff Block. The runoff portion of SWMM can simulate both the quantity and quality of runoff from a drainage basin and the routing of flows and contaminants to the major sewer lines. Drainage basins are represented by an aggregate of idealized subcatchments and gutters or pipes. The program accepts an arbitrary rainfall or snowfall hyetograph and makes a step-by-step accounting of snow melt, infiltration losses, impervious areas, surface detention, overland flow, channel flow, and the constituents washed into inlets, leading to the calculation of inlet hydrographs and pollutographs.

- Transport Block. Routing is performed by SWMM in the transport "block" portion of the program. Both quantity and quality parameters are routed through a sewer system. Quantity routing follows a kinematic wave approach. Up to four contaminants can be routed. Storage routing is accomplished by the modified Puls method.

- Storage/Treatment Block. The storage/treatment block simulates the routing of flows and pollutants through a dry or wet weather storage/treatment plant containing up to five units or processes. Each unit may be modeled as having detention or non-detention characteristics, and may be linked in a variety of configurations. Sludge handling may also be modeled using one or more units.

- EXTRAN Block. EXTRAN is a hydraulic flow routing model for open channel and/or closed conduit systems. The EXTRAN block receives hydrograph input at specific nodal locations by interface file transfer from an upstream block (e.g., the Runoff Block) and/or by direct user input. The model performs dynamic routing of storm water flows throughout the major storm drainage system to the points of outfall to the receiving water system. The program will simulate branched or looped networks, backwater due to tidal or nontidal conditions, free-surface flow, pressure flow or surcharge, flow reversals, flow transfer by weirs, orifices and pumping facilities, and storage at on- or off-line facilities. Types of channels that can be simulated include circular, rectangular, trapezoidal, parabolic, natural channels, and others. Simulation output takes the form of water-surface elevations and discharge at selected system locations.

12-9.13.3 SWMM is a very complicated model with many features. Initial model setup is difficult due to extensive data requirements. Data assembly and preparation can require multiple man-months for a large catchment or urban area. The model is frequently updated, with new releases on a biannual basis (approximately). Updated user's manuals and test cases are documented in published EPA reports.

12-9.13.4 SWMM can handle almost all aspects of hydrology, runoff water quality, and hydraulics of an urban drainage system. It is applicable to only the largest and most complex storm drain systems where extremely detailed hydrology or water quality analysis is required. SWMM is very difficult to use and requires extensive input data.

12-10 **HYDRAULIC TOOLBOX (HY-TB).** Hydraulic Toolbox is a collection of four hydraulics programs written in BASIC. They are HY12, HY15, BASIN, and SCOUR. Hydraulic Toolbox evaluates gutter and inlet hydraulics, flexible channel lining design, riprap stilling basin design, and culvert outlet scour. It is applicable to analysis of any these drainage components on an individual basis but is not a tool for modeling hydraulic systems.

12-10.1 **HY12**. HY12 uses the design procedures of HEC-12. The program analyzes the flow in gutters and the interception capacity of grate inlets, curb-opening inlets, slotted drain inlets, and combination inlets on continuous grades and in sags. Both uniform and composite cross-slopes can be analyzed.

12-10.2 **HY15**. The HY15 program applies the methodologies in HEC-15. HY15 analyzes the hydraulic performance of flexible and concrete channel linings for trapezoidal or triangular channels in straight reaches. The design procedures are based on the concept of maximum permissible tractive force, where channel lining stability is determined by comparing the hydraulic forces exerted on the lining with the maximum permissible shear stress a particular lining can sustain.

12-10.3 **BASIN**. BASIN is a riprap design program that analyzes the adequacy of riprap-lined basins at the outlet of culverts.

12-10.4 **SCOUR**. The SCOUR program provides estimates of the scour at the outlet of culverts in terms of depth, width, length, and volume.

The programs in this package are simple and easy to use. Input screens prompt the user for all necessary information to perform an analysis, but there is no online user help. Although no supporting documentation exists, related references to the methodologies should provide an adequate theoretical basis for proper application.

12-11 **URBAN DRAINAGE DESIGN PROGRAMS.** The Urban Drainage Design software is a collection of three hydraulic programs written in BASIC. It includes: (1) Manning's equation for various channel shapes, (2) HEC-22 (Storm Drain Design), and (3) Stormwater Management. Urban Drainage Design software evaluates normal depth flow conditions, gutter and inlet hydraulics, and storm water management pond hydrograph routing. Like the Hydraulic Toolbox, this software is applicable to the analysis of individual drainage components, not to modeling hydraulic systems.

12-11.1 **Manning's Equation**. The Manning's equation program computes flow through circular, trapezoidal, and triangular channel shapes. Open-channel flow is solved by application of the Manning's equation. Critical depths are also computed by this program.

12-11.2 **HEC-22**. This is a pavement drainage program which applies the principles of HEC-22. The program allows for analysis of gutter flow, grates, curb openings, combination inlets, inlets in a sump, and median and side ditches. Both uniform and composite cross slopes can be analyzed.

12-11.3 **Stormwater Management**. This program provides options for computing stage-storage curves for circular pipes, trapezoidal basins, irregular basins, and rectangular basins. There is also an option for reservoir routing using the Storage Indication method. Reservoir routing is one of the main applications of this software.

The programs in this package are basic, straightforward hydraulics computation algorithms that are quick and easy to apply. The programs are menu-driven, prompting the user for all necessary data. Although no supporting documentation exists, related references to the methodologies should provide an adequate theoretical basis for proper application.

12-12 **DR3M.** The Distributed Routing Rainfall-Runoff Model (DR3M), developed by the USGS, is a watershed model for routing storm runoff through a branched system of pipes and/or natural channels. The model provides detailed simulation of storm runoff periods and a daily soil-moisture accounting between storms. Drainage basins are represented as sets of overland-flow, channel, and reservoir segments that together describe the drainage features of the basin. The kinematic wave theory is used for routing flows over contributing overland-flow areas and through channel networks. A set of model segments can be arranged into a network that will represent many complex drainage basins. The model is intended primarily for application to urban watersheds.

12-12.1 **Rainfall-Excess Components**. The rainfall-excess components of the model are more complex than the runoff methods discussed in this UFC, and include soil-moisture accounting, pervious area rainfall excess, impervious area rainfall excess, and parameter optimization. The soil-moisture accounting component determines the effect of antecedent conditions on infiltration. Soil moisture is modeled as a dual storage system, one representing the antecedent base-moisture storage, and the other representing the upper-zone storage caused by infiltration into a saturated moisture storage. Pervious-area rainfall excess is determined as a function of the point potential infiltration. In the model, point potential infiltration is computed using the Green-Ampt equation.

12-12.2 **Impervious Surfaces**. Two types of impervious surfaces are considered by the model. The first type, effective impervious surfaces, are those impervious areas that are directly connected to the channel drainage system. Roofs that drain into driveways, streets, and paved parking lots that drain onto streets are examples of effective impervious surfaces. The second type, noneffective impervious surfaces, are those impervious areas that drain to pervious areas. An example of this type would be a roof that drains onto a lawn.

12-12.3 **Routing**. DR3M has the capability to perform routing calculations through application of the kinematic wave theory. The model approximates the complex topography and geometry of a watershed as a set of segments that jointly describe the drainage features of a basin. There are four types of segments: overland-flow segments, channel segments, reservoir segments, and nodal segments.

12-12.4 **Model Versatility**. DR3M can be used for a wide variety of applications. A set of model segments can be arranged easily into a network that will represent simple or complex drainage basins. The model can be applied to drainage basins ranging from tens of hectares to several square kilometers but not to exceed 25 km^2.

12-12.5 **Urban Basin Planning**. DR3M can be used for urban basin planning purposes by its determination of the hydrologic effects of different development configurations. Examples of this type of application include assessing the effects of increased impervious cover, detention ponds, or culverts on runoff volumes and peak flows.

12-12.6 **Usability**. DR3M is a comprehensive drainage system simulation tool. It is applicable to analysis of both simple and complex hydraulic systems. DR3M has menu driven input screens and help messages available to the user through ANNIE (Interactive Hydrologic Analyses and Data Management, a USGS water resources applications program), but the model is complex and requires extensive input data. DR3M, like SWMM, should be considered only for the most complex hydrologic and hydraulic systems.

12-13 EVALUATION OF WATER QUALITY

12-13.1 The Synoptic Rainfall Data Analysis Program (SYNOP) water quality program is the computer implementation of FHWA/RD-88-006-9. This software characterizes runoff water quality and estimates impacts to streams and lakes. The user defines the site characteristics and the pollutant target concentrations. The model then determines the expected runoff concentration given a user-defined exceedence probability (50th percentile is the site median concentration that is the default setting).

The default concentrations included in the model are based on extensive monitoring data: 993 storm events at 31 highway sites in 11 states. After determining the expected runoff concentration, the model performs impact analysis for the stream (dilution modeling) or lake (Vollenweider model of phosphorus concentration only). If the computed concentration exceeds the target, the user can evaluate load reductions with these controls: grass channel, overland flow, wet ponds, and infiltration.

12-13.2 This software is simple and easy to use. Input screens prompt the user for all necessary information. Documentation for the software is adequate, while documentation for the underlying procedures is extensive (see the FHWA reports).

12-13.3 The FHWA highway pollutant loading model estimates the highway runoff load for a number of different pollutants, evaluates the impacts of pollutant load on a receiving stream or lake, and can estimate the water quality improvements with various BMPs. The model is based on a number of simplifying assumptions, but is generally applicable to water quality evaluation for all but the most environmentally sensitive highway projects.

12-14 **SOFTWARE AVAILABILITY.** Table 12-2 lists where some of the models summarized in this chapter may be obtained.

Table 12-2. Software Program Contact Information

Software Model	Contact Information
HYDRAIN	Mc*Trans* University of Florida PO Box 116585 Gainesville, Florida 32611-6585 (800) 226-1013 http://www-mctrans.ce.ufl.edu/
TR-55	Natural Resources Conservation Service National Water and Climate Center 1201 Lloyd Blvd., Suite 802 Portland, Oregon 97232-1274 (503) 414-3031 http://www.wcc.nrcs.usda.gov/hydro/
TR-20	Natural Resources Conservation Service National Water and Climate Center 1201 Lloyd Blvd., Suite 802 Portland, Oregon 97232-1274 (503) 414-3031 http://www.wcc.nrcs.usda.gov/hydro/

Software Model	Contact Information
HMS	U.S. Army Corps of Engineers Hydrologic Engineering Center 609 Second Street Davis, California 95616 (530) 756-1104 http://www.hec.usace.army.mil/
HEC-RAS	U.S. Army Corps of Engineers Hydrologic Engineering Center 609 Second Street Davis, California 95616 (530) 756-1104 http://www.hec.usace.army.mil/
SWMM	National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, Virginia 22161 (800) 553-6847 http://www.ntis.gov/index.asp Or U.S. Environmental Protection Agency Urban Watershed Management Branch 2890 Woodbridge Ave. MS104 Edison, New Jersey 08837 (732) 321-6635 http://www.epa.gov/ednnrmrl/models/swmm/index.htm
Hydraulic Toolbox	Mc*Trans* University of Florida PO Box 116585 Gainesville, Florida 32611-6585 (800) 226-1013 http://www-mctrans.ce.ufl.edu/
Urban Drainage Design	Mc*Trans* University of Florida PO Box 116585 Gainesville, Florida 32611-6585 (800) 226-1013 http://www-mctrans.ce.ufl.edu/

Software Model	Contact Information
DR3M	United States Department of the Interior U.S. Geological Survey Hydrologic Analysis Software Support Program 437 National Center Reston, Virginia 20192 http://water.usgs.gov/software/dr3m.html