Using HSPF to Evaluate Stormwater Best Management Practices in the Charles River Watershed

by

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B.S., Mechanical Engineering
Columbia University, 1994

Submitted to the Department of Civil and Environmental Engineering
in partial fulfillment of the requirements for the degrees of

Master of Science in Civil and Environmental Engineering
and
Master of Science in Technology and Policy

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

February 1999

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Abstract

This thesis describes how the hydrologic computer model HSPF was used to model hydrologic and sediment transport in the Charles River Watershed and subsequently to evaluate stormwater management practices in the watershed.

The thesis briefly describes the problem of stormwater pollution. It discusses U.S. federal laws, regulations and programs that are intended to address the issue, and then focuses on the state of Massachusetts. The Massachusetts Department of Environmental Protection (DEP) has recently issued Stormwater Management Standards, which are used as guidelines by Conservation Commissions throughout the state, and which will soon become part of the Code of Massachusetts Regulations.

DEP's Stormwater Management Standards require the use of any number of Best Management Practices (BMPs) that will reduce the average annual load of total suspended solids (TSS) in stormwater by 80%. This thesis briefly describes some common BMPs and discusses the validity of using TSS as a target pollutant.

The thesis then describes in detail how the HSPF computer model was calibrated to predict sediment washoff and transport in the Charles River Watershed. It then shows how the model was used to test the effectiveness of DEP's Stormwater Management Standards. The Standards were applied to the town of Franklin in the lower part of the watershed by changing the land use in the town in order to simulate development. The solids load from this new development was then reduced by 80%. According to the model predictions, if the Standards are applied only to the part of the watershed that falls under the jurisdiction of the law, then there might be little improvement seen in the river. However, if the standards are applied wherever development occurs in the town, there may be noticeable improvement in the levels of TSS concentration in the Charles River.

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Acknowledgments

The majority of my funding during my years at graduate school was provided by a National Science Foundation Fellowship.

I would like to thank the Charles River Watershed Association for formulating this project and for providing some of my funding. Thanks in particular to Kathy Baskin and Pam Dibona.

Thank you to Professor David Marks of the MIT's Department of Civil and Environmental Engineering for helping me get my thesis organzied and for providing much of the funding.

Thank you to Tom Jobes of AQUA TERRA Consultants who helped me tremendously by answering all of my many HSPF questions.

Thank you to my advisor, Dr. E. Eric Adams of the Department of Civil and Environmental Engineering's Parsons Lab. He was consistently helpful and available, and always calm. Congratulations to him upon winning the 1998 award for graduate student advising!

Thanks to everyone in the Adams group – Brian Crounse, Amy Munson, Gordon Ruggaber, Scott Socolofsky and Ling Tang – for being so friendly and helpful. What a great group! Thanks to Scott for all of his HSPF help. Special thanks to Amy, who not only provided immeasurable help to me in my thesis work, but who was such a great companion in the Parsons basement computer lab! Thank you for all of your help, and thank you for being such a special friend.

Finally, I would like to acknowledge with love my wonderful parents, Hannah and Alex Wolf, and my amazing sister Rebecca Wolf. I can't thank them enough for being such a loving, caring and devoted family. And, last but not least, thank you to my new husband Isaac Graf, who has been a constant source of support, comfort and love during my time at MIT. I am blessed to be your partner in life. May we grow together and support each other always.

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Chapter 1

Introduction

Stormwater runoff is the water that flows over the surface of a watershed during and after a rainfall. When it rains, the precipitation will either infiltrate into the groundwater, or run off over the watershed's surface into a stream, river, or lake. How much of the precipitation will become runoff will depend on the intensity of the rainfall and its duration, the antecedent conditions (i.e. whether the rainfall was preceded by a dry period), as well as the imperviousness of the watershed. When development occurs, roads are paved and trees and vegetation are removed. These types of land use changes will result in more runoff; the precipitation that would have infiltrated into the ground or would have been intercepted by the vegetation becomes surface runoff instead.

Studies have shown that "during a 1-inch thunderstorm, one paved acre may yield the same amount of runoff as 40 to 100 acres of rangeland [44, p. 31]." Figure 1-1 shows how changes in the natural ground cover can lead to increased runoff and reduced infiltration.

Stormwater management must address both the control of water quantity and water quality, since as stormwater passes through a watershed it will collect and carry with it various types of pollutants. Traditionally, the objective of a stormwater management plan was flood prevention; only in the last two decades have town planners begun to address the water quality issues. The Netherlands, for example, introduced the concept of "integrated water management" in 1985; water quality and quantity

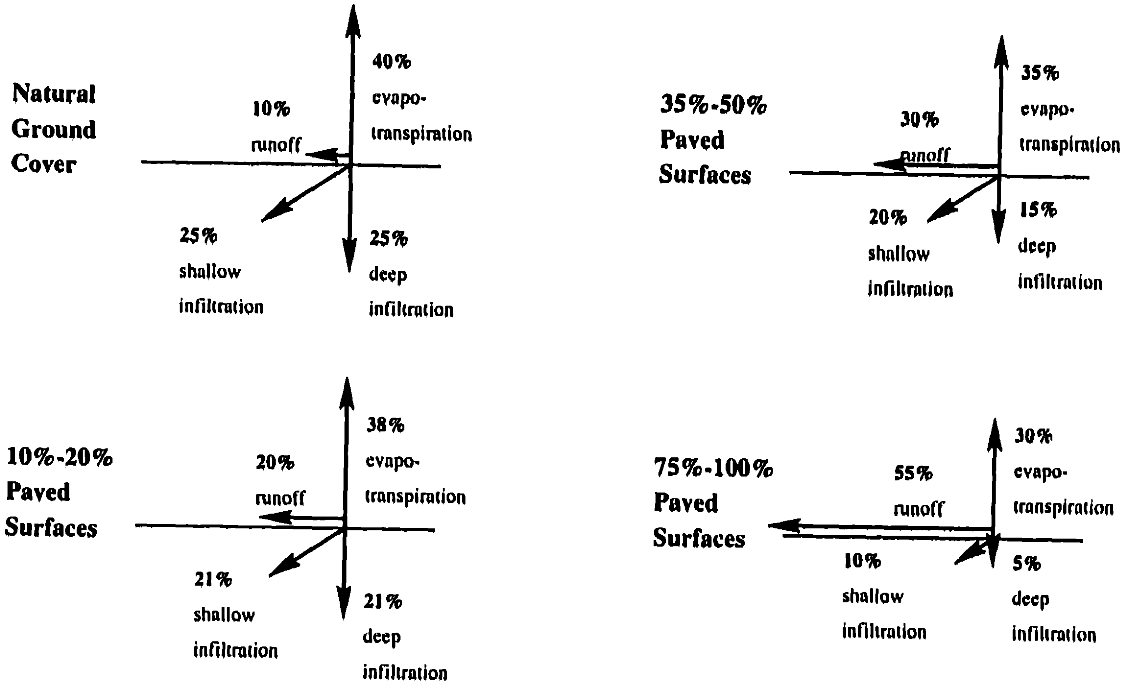

Figure 1-1: Typical changes in runoff flows resulting from paved surfaces. (Source: [51, p. 4-2]; original source: J.T. Tourbier and R. Westmacott, *Water Resources Protection Technology: A Handbook of Measures to Protect Water Resources in Land Development*, p. 3)

were to be considered as two parts of one whole/together [9, p. 7]. Often, the goals of improving stormwater runoff quality and reducing stormwater quantity are at odds with each other. For example, a detention pond that is used to detain stormwater, thereby reducing the peak flow, can also be used as a trap for settleable pollutants. However, the pollutant settling requirement of the detention pond requires a certain detention time, and the greater the detention time, the less the capacity of the basin will be to store a volume of stormwater because the water will not be released as quickly.

Modern stormwater management programs encourage management practices and infrastructure that address both aspects of the problem. There is a growing list of "Best Management Practices," or BMPs, that are being used to reduce the impacts of stormwater runoff to water quality and water quantity. Developers can effectively reduce the impacts of the change in land use on stormwater quality and quantity by utilizing these BMPs. Many of these practice can be unobtrusive and even aesthetic;

Land Use	Types of Pollutants
Residential yards	Fertilizer, pesticides, yard wastes
Streets, parking areas	Dust, heavy metals, oil and grease, particulates
Commercial, industrial areas	Various pollutants (industry dependent)
Construction sites	Sediments (due to erosion of soil)
Agricultural areas	Nutrients (N and P), sediment, pesticides, animal wastes

Table 1.1: Stormwater pollution from various land uses

for example, making use of natural vegetation, or planting additional greenways.

Many stormwater management experts recommend that structural stormwater controls should serve a dual purpose; in this way they can be successfully integrated into the community. The American Society of Civil Engineers (ASCE), for example, recommends that detention ponds (which are used to store stormwater during a storm) should have recreational uses [44, p. 32]. An example would be an athletic field which can be used as a stormwater detention basin when necessary. Of course, care must be taken to ensure public safety when the basin contains water.

1.1 Sources of Stormwater Pollution

Stormwater pollution of receiving water bodies can come from both point and non-point sources. Examples of point sources include stormwater drainage pipes and overflows from combined sewers. Examples of non-point sources include uncollected runoff from the streets, and overland runoff from construction sites and from agricultural sites. See Table 1.1 for examples of stormwater pollution resulting from different kinds of land use.

Stormwater will carry with it a number of pollutants, including suspended solids, dissolved solids, bacteria (fecal coliform is used as an indicator), nutrients, pesticides, metals, organic debris, oils and fuel. Many studies of stormwater pollution find that, by volume, suspended sediment is the most important pollutant.

The "first flush" is the stormwater that runs off the watershed at the very beginning of a storm. It can be more specifically defined in any number of ways, for example, as the first inch of rain, or as the first half inch of runoff. Usually, the first flush will contain the highest concentration of contaminants, since detached material on the land surface is readily available to be carried away by the runoff.

The water quality impacts will vary from watershed to watershed and will depend on the land use in the watershed (e.g. agricultural, industrial, commercial, residential) as well as the quality of the runoff, and the characteristics of the receiving water. Therefore, many experts recommend that rather than require a standard checklist of control measures, a stormwater control plan should be developed on a watershed by watershed basis. The United States Environmental Protection Agency (EPA) recommends that Best Management Practices, or BMPs, be put into place.

1.2 Total Suspended Solids

Total suspended solids (TSS) are considered to be important stormwater pollutants. Suspended solids suppress plant growth on stream beds, and damage the gills of fish, potentially causing suffocation. The increased turbidity in the water and the reduction in water clarity caused by suspended solids may hinder photosynthesis, because less light is able to penetrate as deep. When the solids settle (especially in slow-moving water bodies) and build up in the bed, they may change the hydraulics of the stream. In addition, the solids might cause obstructions in stormwater conveyances.

However, the primary reason for concern with total suspended solids is that the solids transport other pollutants; pesticides, nutrients, organic matter and metals adsorb to suspended sediment. Therefore, TSS can be seen as an indicator for other sorbing pollutants. According to one report, for example, 50% of the nitrogen that enters receiving waters is adsorbed to sediment [12, p. 25].

See Tables 1.2, 1.3 and 1.4 for reported values of pollutant-sediment concentrations. These results were reported in EPA publications in the early 1970s. Note that the numbers might be significantly lower today. For example, leaded gasoline is no

Pollutant	Land Use Residential (mg/kg)	Commercial (mg/kg)	Industrial (mg/kg)
BOD5	9,200	8,300	7,500
COD	20,800	19,400	35,700
Kjeldahl Nitrogen	1,700	1,100	1,400
Nitrate-Nitrogen	50	500	60
Phosphate-Phosphorus	900	800	1,200

Table 1.2: Concentrations of conventional pollutants in urban sediment (Source: [33, p.228])

Metal	Residential (mg/kg)	Commercial (mg/kg)	Industrial Light (mg/kg)	Industrial Heavy (mg/kg)	Weighted Mean (mg/kg)
Cd	3.0	4.2	4.0	3.9	3.4
Cr	192	225	288	278	211
Cu	93	133	128	107	104
Fe	20,600	23,300	21,800	28,600	22,000
Pb	1,430	3,440	2,780	1,160	1,810
Mn	392	397	490	570	418
Ni	28	48	41	37	35
Sr	21	18	27	23	21
Zn	350	520	368	317	370

Table 1.3: Concentrations of metals in urban sediment (Source: [33, p. 228])

longer used, resulting in considerably lower lead concentrations in urban sediment than were reported in 1974.

Pollutant	**Concentration** (mg/kg)
Hg	0.083
Endrin	0.0002
Dieldrin	0.028
PCB	0.770
Methoxychlor	0.500
DDT	0.076
Lindane	0.0029
Methyl Parathion	0.002
DDD	0.082

Table 1.4: Concentrations of mercury and organic compounds in urban sediment (Source: [33, p. 229])

Chapter 2

Stormwater Management Laws and Regulations

2.1 Federal Law

2.1.1 Clean Water Act: Point Sources

In 1972, the United States Congress amended the Federal Water Pollution Control Act (FWPCA); the new statute, known as the Clean Water Act, has the stated goal of eliminating "the discharge of pollutants into the navigable waters" of the United States.[1] The newly created Environmental Protection Agency (EPA) was charged with administering the Clean Water Act. EPA subsequently established water quality standards and regulations.

Under the Clean Water Act, EPA set up a National Pollutant Discharge Elimination System (NPDES) permitting program for point sources of water pollution[2]. Point sources, defined by the Clean Water Act as "any discernible, confined and discrete conveyance...from which pollutants are or may be discharged,"[3] are easier to regulate and control than non-point sources.

In many states, the state government has the authority to issue NPDES permits for

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[1] FWPCA ∮ 101(a)(1) [33 USC ∮ 1251(a)(1)]

[2] FWPCA ∮ 402 [33 USC ∮ 1342]

[3] FWPCA ∮ 502(14) [33 USC ∮ 1362(14)]

point source discharges. In those cases where the state does not have the delegated authority to issue NPDES permits, then EPA runs the NPDES program (through EPA's regional offices).

Massachusetts is one of the 10 non-delegated states. In Massachusetts, EPA runs the NPDES program and develops the permits. A joint permit from the two agencies (the federal EPA and the state DEP) is issued; these are equal yet separate permits.

2.1.2 Nationwide Urban Runoff Program

At the start of the Clean Water Act era, the Environmental Protection Agency focused on dry weather water pollution, namely, discharges from municipal and industrial wastewater pipes. However, there was a growing awareness of the potential polluting impacts of stormwater discharges. EPA realized that there was much information lacking about the water quality effects of stormwater pollution and the costs and benefits of various stormwater management systems. In order to gather more information about stormwater discharges in urban areas, EPA and the United States Geological Survey (USGS) organized the Nationwide Urban Runoff Program (NURP) to evaluate stormwater runoff in 28 cities throughout the United States. The results of this effort, which began in 1978, were published in 1983, and are widely quoted and cited, even today. See Appendix B for more information about NURP.

2.1.3 Clean Water Act: Stormwater Discharges

The 1987 Amendments to the Clean Water Act (also known as the Water Quality Act of 1987) addressed stormwater pollution, both from runoff and from point sources. The Amendments created Section 319 of the Clean Water Act, which required the states to establish Nonpoint Source Management Programs. The law was set up to help the states control nonpoint source pollution. The Section created a grant program "for the purpose of assisting the State in implementing [the] management program."[4]

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[4] FWPCA § 319(h)(1) [33 USC § 1329(h)(1)]

In addition, the Water Quality Act of 1987 required NPDES permitting of certain stormwater discharges. Section 402(p) of the statute initiated a two phase process for stormwater permitting. Phase I addressed "stormwater discharge associated with industrial activity"[5] and discharges from large and medium municipal storm sewers (MS4s). By definition, large municipal storm sewers serve more than 250,000 people, and medium MS4s serve between 100,000 and 250,000 people. Also included in Phase I of permitting is any point source that either EPA or the NPDES-authorized state "determines...contributes to a violation of a water quality standard or is a significant contributor of pollutants to waters of the United States."[6] Permits may not be required for any other discharges until October 1, 1992 (later changed to October 1, 1994).

In preparation for the second phase of NPDES stormwater permitting, which could include smaller municipalities and lighter industries, EPA was charged with conducting two studies to gather more information about these smaller types of discharges.[7]

EPA Phase I Stormwater NPDES permits

The final rule for NPDES stormwater permits, issued in November, 1990, defined which types of "industrial activity" were to be included in the first phase of stormwater permitting. These eleven industry categories include heavy and medium manufacturing activities, oil and gas facilities and hazardous waste facilities, among others. Also included in the "industrial activity" category are construction activities that disturb more than five acres of land.

EPA Phase II Stormwater NPDES permits

In December, 1997, EPA introduced proposed regulations for Phase II of the stormwater permitting process. EPA intends to finalize these regulations on March 1, 1999. According to the proposed regulations, NPDES permits will be required for small

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[5] FWPCA § 402(p)(2)(B) [33 USC § 1342(p)(2)(B)]

[6] FWPCA § 402(p)(2)(E) [33 USC § 1342(p)(2)(E)]

[7] FWPCA § 402(p)(5) [33 USC § 1342(p)(5)]

MS4s (serving fewer than 100,000 people) in urbanized areas and for construction sites that disturb less than five acres of land. Any discharges which do not fall into these Phase II categories – e.g. small MS4s in non-urban areas – may also be required to have a NPDES permit, but each case is to be evaluated separately. In addition, the new regulations will *exempt* from the permitting process those Phase I industrial sites with "no exposure" to stormwater.

These new regulations would supersede regulations currently in place, issued in August, 1995, that require most discharges to apply for a NPDES permit by August, 2001. The new regulations, which limit the Phase II requirements, will cost significantly less than the 1995 regulations, since far fewer permits will be required. At the same time, EPA believes that the regulations are focusing on those discharges that produce the greatest harm.

The regulations specifically mention those pollutants that are to be targeted in the Phase II NPDES permits. For small MS4s, the target pollutants are sediments, floatables, oil and grease "as well as other pollutants from illicit discharges." For small construction sites, the concern is sediment and erosion. The regulations encourage the use of specific Best Management Practices (BMPs).

2.1.4 Coastal Zone Management Act Reauthorization

The goal of the Coastal Zone Management Act (CZMA) of 1972 was to "preserve, protect, develop, and where possible, restore or enhance, the resources of the Nation's coastal zone"[8] and to help the states implement coastal management programs. Massachusetts is one of 29 states and territories with a Coastal Zone Management Program. In 1990, the CZMA was amended to address nonpoint source pollution of coastal waters.[9]

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[8] CZMA ∮ 303(1) [16 USC 1452]

[9] CZMA ∮ 306B(g) [16 USC 1455b(g)]

2.2 Massachusetts Laws and Regulations

2.2.1 Introduction

When a bill is passed into law by the Massachusetts State Legislature (also called the General Court), it becomes part of Massachusetts General Laws (M.G.L.). The law will often authorize a specific state agency to administer it and to develop and promulgate regulations that expand on the law. After the regulations are reviewed in a public process, they become part of the Code of Massachusetts Regulations (CMR).

The Department of Environmental Protection (DEP) is one of a number of departments and offices that are under the Executive Office of Environmental Affairs (EOEA). Watershed management and stormwater management in Massachusetts is primarily under the authority of the Department of Environmental Protection. In addition, the Coastal Zone Management (CZM) Office, also part of EOEA, is specifically responsible for protecting the coastal waters of the Commonwealth. In the case of stormwater management, DEP and CZM worked together to develop the stormwater management standards that will ultimately be developed into regulations.

Massachusetts has had a long history of waterways protection. As early as 1866, the Public Waterfront Act (Chapter 91 of the General Laws) was passed into law.

2.2.2 Conservation Commissions

The Conservation Commission Act of 1957 allows each city or town in Massachusetts to establish a Conservation Commission "for the protection and development of the natural resources and for the protection of the watershed resources of said city or town."[10] The Conservation Commissions are charged with enforcing the state's Wetlands Protection Act (described in Section 2.2.4 below) as well as any local bylaws.

According to the Massachusetts Association of Conservation Commissions (MACC), today there are 351 Conservation Commissions in the Commonwealth; every town and city in the state has a Commission.

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[10] M.G.L. c. 40 ∮ 8C

2.2.3 Clean Waters Act

The Clean Waters Act, found in Massachusetts General Laws Chapter 21, Sections 26–53, established a Division of Water Pollution Control within the Department of Environmental Protection. "It shall be the duty and responsibility of the division to enhance the quality and value of water resources and to establish a program for prevention, control, and abatement of water pollution."[11] The Clean Waters Act is intended to help the Commonwealth of Massachusetts comply with the federal Clean Water Act. As such, the Act includes a description of a point source permitting system: "No person shall discharge pollutants into waters of the commonwealth nor construct, install, modify, operate or maintain an outlet...without a currently valid permit issued by the director [of the Division of Water Pollution Control]."[12] This permitting system is parallel to the federal NPDES permitting system.

The Clean Waters Act encompasses many categories; and the Regulations for the Act include the Surface Water Discharge Permit Program, Surface Water Quality Standards, Ground Water Discharge Permit Program, and Ground Water Water Quality Standards. (310 CMR 41.00 and 314 CMR 1.00 to 15.00)

Today, the Department of Environmental Protection is organized into four Bureaus: Resource Protection, Strategic Policy and Technology, Waste Prevention and Waste Site Cleanup. The Watershed Management Division within the Bureau of Resource Protection includes four programs – Water Pollution Control (mentioned in the Clean Waters Act), Watershed Management, Drinking Water and Wetlands and Waterways.

2.2.4 Wetlands Protection Act as amended by the Rivers Act

Massachusetts General Laws (M.G.L.) Chapter 131, Section 40 is otherwise known as the Wetlands Protection Act, introduced in 1972. The statute lists certain protected areas that surround or are under water bodies. The Act regulates construction

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[11] M.G.L. c. 21 ∮ 27

[12] M.G.L. c. 21 ∮ 43(2)

activities that will "remove, fill, dredge or alter" one of these resource areas.

These areas include the following, as enumerated in DEP's Wetlands Protection Act Regulations[13]:

(a) any bank, freshwater wetland, coastal wetland, beach, dune, flat, marsh, meadow or swamp

bordering on

the ocean, or any estuary, creek, river, stream, pond or lake

(b) land under these water bodies

(c) land subject to tidal action

(d) land subject to coastal storm flowage

(e) land subject to flooding

(f) riverfront area

The sixth category, the "riverfront area", was recently added to this list of protected areas, in the 1996 Rivers Act which amended the Wetlands Protection Act.

The Wetlands Protection Act Regulations refer to these six categories either as "Areas Subject to Protection Under M.G.L. c. 131 § 40" or as "Resource Areas." In addition to these areas, the regulations created a "Buffer Zone" that is within 100 feet of the boundary of an area listed under (a) above. (None of the other resource areas have buffer zones.)

The goal of the Wetlands Protection Act is to protect certain environmental public interests. These interests are listed in the Act as: (1) protect a public or private water supply, (2) protect ground water, (3) provide flood control, (4) prevent storm damage, (5) prevent pollution, (6) protect land containing shellfish, (7) protect wildlife habitat, and (8) protect fisheries.

The Wetlands Protection Act Regulations separate the "Resource Areas" into two categories: Coastal wetlands and inland wetlands. Within these larger categories, the regulations list performance standards for each resource area.

If a party wishes to "remove, fill, dredge or alter" one of the resource areas, the party must file a "Notice of Intent" with the local Conservation Commission. The

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[13] 310 CMR 10.02(1)

Conservation Commission must then review the project and determine whether the proposed construction project will affect one of the interests specified in the Wetlands Protection Act. If a resource area will be affected, the Commission must issue an "Order of Conditions" before the project may proceed. The Wetlands Protection Act Regulations explains that "the Order of Conditions shall impose such conditions as are necessary to meet the performance standards set forth in [the regulations] for the protection of those areas found to be significant to one or more of the interests identified in M.G.L. c. 131 § 40. The Order shall prohibit any work or any portion thereof that cannot be conditioned to meet said standards."[14]

A buffer zone has similar restrictions as a resource area, although if it is unclear whether action in the buffer zone will alter an Area Subject to Protection Under MGL c. 131 § 40, a "Request for Determination of Applicability" must be submitted to the Conservation Commission. If the Commission determines that a resource area might indeed be harmed if construction is done in the buffer zone, then the applicant must subsequently file a Notice of Intent for a project within the buffer zone.

If the Conservation Commission fails to issue a Determination of Applicability or an Order of Conditions within the time period designated by the law, then the parties involved may appeal to the Department of Environmental Protection. In addition, a party may appeal to DEP to override a decision of the Conservation Commission and to issue a Superseding Determination of Applicability or a Superseding Order of Conditions. The appeal may be requested by any number of parties, including the applicant, the owner of the resource are in question, the owner of land abutting the resource area, and any ten residents of the city or town in which the project is to be done.

Rivers Act

The Rivers Act, also contained in M.G.L. c. 131 § 40, introduced a new resource area to the Wetlands Protection Act called the "riverfront area". The riverfront

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[14] 310 CMR 10.05(6)(b)

area is defined in the law as "that area of land situated between a river's mean annual high-water line and a parallel line located two hundred feet away."[15] The riverfront area extends for only twenty five feet in highly populated municipalities (more than 90,000 people), densely populated municipalities (more than 9,000 people per square mile) and 'densely developed' areas, as well as some specific areas listed by the law. The Regulations list the populated municipalities as Boston, Brockton, Cambridge, Chelsea, Everett, Fall River, Lawrence, Lowell, Malden, New Bedford, Somerville, Springfield, Winthrop and Worcester. In addition, the Regulations list another exception to the 200-foot rule: the riverfront area is only 100 feet from the river for "new agricultural and aquacultural activities."[16]

The law defines a "river" as "a natural flowing body of water that empties into any ocean, lake or other river and which flows throughout the year."[17] Thus, even a small stream will have a riverfront area surrounding it, as long as the stream is perennial. Yet, the preface to the 1997 Regulatory Revisions for the Rivers Protection Act Amendments to the Wetlands Protection Act notes that "although Massachusetts has almost 9,000 miles of rivers, the riverfront area is less than one percent of the state's total acreage."[18]

The Rivers Act lists two main criteria to be used by the Conservation Commission in evaluating a Notice of Intent. First, the proposed project should have "no significant adverse impact on the riverfront area"[19] when considering the eight environmental public interests (protecting water supply, ground water, land containing shellfish, fisheries, and wildlife habitats, providing flood control, and preventing storm damage and pollution.) Second, there must be "no practicable and substantially equivalent economic alternative to the proposed project with less adverse effects on such purposes."[20]

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[15] M.G.L. c. 131 ∮ 40 line 169
[16] 310 CMR 10.58(2)(a)(3)(c)
[17] M.G.L. c. 131 ∮ 40 line 166
[18] 310 CMR 10.00 Preface 1997 Regulatory Revisions for the Rivers Protection Act Amendments to the Wetlands Protection Act, Section I.
[19] M.G.L. c. 131 ∮ 40 line 295
[20] M.G.L. c. 131 ∮ 40 line 299

The Regulations for the Rivers Act Amendments expand on these criteria when describing the "General Performance Standards" for riverfront areas. For instance, for 200-foot riverfront areas, the Regulations limit the amount of the work that may be done to up to 10% of the riverfront area or 5,000 square feet, whichever is greater for existing lots and 10% of the riverfront area for new lots. In addition, there must be a "100 foot wide area of undisturbed vegetation"[21] in the riverfront area, preferably alongside the river. Other criteria that apply to both 200-foot and 25-foot riverfront areas require stormwater management "according to standards established by the Department [of Environmental Protection]"[22] and erosion and sedimentation controls. A final criterion requires that the work must not harm the wildlife habitats in the area.

2.3 Stormwater Management in Massachusetts

"In Massachusetts, stormwater runoff and discharges from stormwater drain pipes are the largest contributors to water quality problems in the Commonwealth's rivers, streams, and marine waters [27, p. i]."

The Stormwater Management Policy, first issued by Massachusetts DEP in 1996, introduced a list of stormwater management standards that are to be used as guidelines for reducing stormwater pollution. In the near future, these guidelines will evaluated and reworked into regulations.

When a project involves new development or redevelopment in the state's resource areas, DEP's Stormwater Management Standards are to be implemented by the Conservation Commissions of the state under the jurisdiction given to them in the Wetlands Protection Act. Since the jurisdiction involves those resource areas that are denoted in the Act, the Conservation Commissions may only apply the standards to projects and stormwater outfall pipes within the resource areas.

When an applicant submits a Notice of Intent to a Conservation Commission, the

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[21] 310 CMR 10.58(4)(d)(1)(a)

[22] 310 CMR 10.58(4)(d) (1)(b) and (2)(b)

Stormwater Management Policy requires that in addition to the Notice of Intent, a stormwater management form be submitted. The Order of Conditions issued by the Conservation Commission will require the implementation of stormwater standards in addition to the standards already listed in the Wetlands Protection Act Regulations.

For already existing stormwater discharges, the stormwater management standards note that DEP has jurisdiction under the state's Clean Waters Act.

Many towns and cities in the Commonwealth have local bylaws that provide additional protection to wetlands; in those municipalities the Conservation Commission must adhere to local laws in addition to the state (and federal) requirements. For example, in the town of Franklin in the Charles River watershed, the stormwater management standards have been incorporated into the town regulations so that even subdivisions that are not under the jurisdiction of the Conservation Commissions must meet the standards.

2.3.1 DEP's Stormwater Management Standards

Below is a summary, taken from DEP's Stormwater Policy Handbook and Stormwater Technical Handbook [27], [28], of DEP's guidelines. More information about the recommended BMPs and the procedure can be found in those sources.

Note that the standards can only be enforced in areas under the jurisdiction of the Conservation Commissions. In addition, note that they do not apply at all to subdivisions with four or fewer lots, and only "to the extent practicable" to subdivisions with nine or less lots, unless a critical area will be affected. Note as well that the standards do distinguish between discharge to a critical area (defined below) and to other receiving waters.

Nine Stormwater Management Standards

The DEP has established nine stormwater management standards that must be addressed by a developer. They are listed below, quoted directly from the Stormwater Policy Handbook [27]:

Standard 1. No new stormwater conveyances may discharge untreated stormwater (i.e. that does not follow Standards 2–9) directly to or cause erosion in wetlands or waters of the Commonwealth.

Standard 2. Stormwater management systems must be designed so that post-development peak discharge rates do not exceed pre-development peak discharge rates.

Standard 3. Loss of annual recharge to groundwater should be minimized through the use of infiltration measures to the maximum extent practicable. The annual recharge for the post-development site should approximate the annual recharge from the pre-development or existing site conditions, based on soil types.

The runoff volume to be recharged to groundwater will depend on the pre-development soil type, the hydrologic group that defines the infiltration capability of the soil. (For more information about hydrologic soil categories, see Appendix Section A.2.)

Hydrologic Group	Volume to Recharge
A	0.40 inches of runoff * total impervious area
B	0.25 inches of runoff * total impervious area
C	0.10 inches of runoff * total impervious area
D	waived

Standard 4. For new development, stormwater management systems must be designed to remove 80% of the average annual load (post-development conditions) of total suspended solids (TSS). It is presumed that this standard is met when:

(a) Suitable nonstructural practices for source control and pollution prevention are implemented, (b) Stormwater management best management practices (BMPs) are sized to capture the prescribed runoff volume, and (c) Stormwater management BMPs are maintained as designed.

The Stormwater Handbook provides a list of BMPs to chose from, and includes the accepted design TSS removal rates. The developer does not have to prove that his specific BMP actually removes TSS at the published removal rate. As long as the developer utilizes one or more of the BMPs on DEP's list, then it is assumed that

BMP List	Design Rate
Extended Detention Pond	70%
Wet Pond	70%
Constructed Wetland	80%
Water Quality Swale	70%
Infiltration Basin/Trench	80%
Dry Well	80%
Sand Filter	80%
Organic Filter	80%
Water Quality Inlet	25%
Sediment Trap (Forebay)	25%
Drainage Channel	25%
Deep Sump and Hooded Catch Basin	25%
Street Sweeping	10%

Table 2.1: DEP's Design TSS removal rates. Source: [27, p. 1-7]

the published removal rates apply. Table 2.1 lists DEP's accepted "design rate" for a list of BMPs. (A wider range of average TSS removal rates can be be found in Chapter 3, in Table 3.1; removal rates can be selected from this range if the specific BMP in question is shown to have higher or lower removal rates than DEP's official "design rate".)

It is often the case that one BMP will not be sufficient to reduce TSS by 80%. In that case, two or more BMPs may be used in series in order to comply with the 80% removal standard. The runoff from the first BMP is routed to the second BMP, which will further reduce the TSS load. For example, an extended detention pond has a published removal rate of 70%. That leaves 30% of the sediment still remaining. If the runoff is then routed to a BMP with a removal rate of 20%, then another 6% of the original TSS will be removed. This adds up to 76% removal, which falls short of the 80% standard, and yet another BMP will be needed.

Standard 5. Stormwater discharges from areas with higher potential pollutant loads require the use of specific stormwater management BMPs. The use of infiltration practices without pretreatment is prohibited.

The standards documentation lists those land uses that fall into the category of "areas with higher pollutant loads".

Standard 6. Stormwater discharges to "critical areas" must utilize certain stormwater management BMPs approved for critical areas.

Critical areas include the following: shellfish beds, swimming beaches, cold water fisheries, recharge areas for public water supplies, and "Outstanding Resource Areas" (ORWs).

Standards 4 though 6 require that BMPs be use to treat the runoff to improve water quality. The runoff volume to be treated is calculated as follows:

Location of Discharge	Calculation of Volume to be Treated by BMP
For discharges to "critical areas"	1.0 inch of runoff times the total post-development impervious area
For all other discharges	0.5 inches of runoff times the total post-development impervious area

Standard 7. Redevelopment of previously developed sites must meet the Stormwater Management Standards to the maximum extent practicable. However, if it is not practicable to meet all the Standards, new (retrofitted or expanded) stormwater management systems must be designed to improve existing conditions.

Standard 8. Erosion and sediment controls must be implemented to prevent impacts during construction or land disturbance activities.

The standards documentation list examples of these types of BMPs: staked hay bales, filter fences, hyroseeding, and phased development.

Standard 9. All stormwater management systems must have an operation and maintenance plan to ensure that systems function as designed.

This plan should identify: (a) the stormwater management system owner(s), (b) the party or parties responsible for operation and maintenance, (c) a schedule for inspection and maintenance, and (4) the routine and non-routine maintenance tasks to be undertaken.

Applicability of the Standards

DEP's stormwater management standards apply to:

"industrial, commercial, institutional, residential subdivision and roadway projects, including site preparation, construction, redevelopment, and on-going operation [27, p. 1-3]."

The standards do not apply to the following:

1. single-family house projects,
2. residential subdivisions with four or fewer lots, provided any discharge will not affect a "critical area", and
3. emergency repairs to roads or their drainage systems

The standards apply "to the extent practicable" (which means that "the applicant has made all reasonable efforts to meet the standards, including evaluation of alternative BMP designs and their locations [27, p. 1-4]." to the following:

1. residential subdivisions with four or fewer lots with a discharge potentially affecting a critical area, and
2. five to nine residential lots, providing any discharge will not affect a critical area

Chapter 3

Best Management Practices

The U.S. Environmental Protection Agency, the Massachusetts Department of Environmental Protection, and most other agencies and communities that deal with stormwater management have identified certain practices that have proven to be effective at addressing the problems associated with stormwater. These so-called Best Management Practices, or BMPs, have been categorized in a number of ways. Some are intended to target stormwater quality, and others are intended primarily to reduce stormwater volume.

There is a wide variety of BMPs from which to choose. A stormwater pollution prevention plan needs to take into account the sources of stormwater runoff and the sources and types of pollutants that are being carried to the receiving waters. Some BMPs are termed "structural" and require that some kind of infrastructure be built in the watershed to divert or intercept stormwater. Others use non-structural methods, such as street-sweeping.

Different BMPs have different objectives. Some BMPs address the issue of source control; these BMPs prevent the pollutants from coming into contact with the runoff. Other BMPs intercept already contaminated stormwater before it has a chance to enter the receiving water body.

3.1 Types of BMPs

3.1.1 Detention BMPs

Detention facilities hold stormwater for a certain amount of time, and then slowly release it. Detention basins (or ponds) were originally used for flood control; the peak flow is reduced because the stormwater is not allowed to enter the receiving water all at once. In addition, the detention BMP allows for the sedimentation of suspended solids in the stormwater.

Detention basins can be either "dry" or "wet." The mechanism for these two types are the same, although wet detention ponds have a permanent pool of water in the pond even between storm events. This design allows for the sedimentation of relatively small particles, and the wet ponds usually remove a larger percentage of TSS than do dry ponds.

Dry detention ponds are "one of the most common structural BMPs in use in the United States [45, p. 1076]." Detention ponds are designed for a certain size watershed (the DEP Standards recommend a ratio of four acres of drainage area for each acre-foot of basin storage [28, p. 3.A-2]). The design must also take into account the design storm size; it is recommended by the DEP Standards that the stormwater detention time be at least 24 hours. The longer the detention time, the more chance that solids will be able to settle. The pond must also be built with an outlet for overflow, for large storms.

3.1.2 Infiltration BMPs

Although infiltration BMPs can be very effective, they can only be used if the soil conditions are appropriate (i.e. porous). In addition, if the water table is too high, then infiltration BMPs should not be used because they may end up contaminating the groundwater. Moreover, if the stormwater that is being sent to the infiltration BMP contains a lot of suspended solids, then there is potential for clogging.

Common infiltration techniques include infiltration basins and trenches, in which stormwater is stored to eventually infiltrate into the soil. Another type of BMP is porous pavement, which is a "permeable, specially designed concrete or asphalt mix that provides an alternative to conventional pavement, allowing stormwater to percolate through the porous pavement into a deep gravel storage base area that also acts as a subsurface foundation [34, p. 184]."

3.1.3 Vegetative BMPs

Vegetative BMPs, as their name implies, use vegetation to remove pollutants, especially solids and nutrients, in stormwater. Examples of vegetative BMPs include constructed wetlands, grassy swales (channels), and vegetative filter strips, which are strips of land that act as "buffers" between the stormwater runoff and the receiving waters.

3.1.4 Source Control BMPs

Source control BMPs focus on removing pollutants at the source so that they are never exposed to the runoff in the first place. For example, when land is being developed, the soil is very susceptible to erosion. As a result, when construction is underway, the planners must ensure that the soil is as stable as possible, either by planting vegetation, providing some kind of surface cover, or by diverting the stormwater. Other examples of source control BMPs include street cleaning and hazardous waste disposal centers.

Street Sweeping

In a number of NURP studies (see Appendix B for more information about NURP), street sweeping was not found to be an effective BMP. Street sweeping removed larger solids rather than smaller ones, although "vacuum assisted" sweepers were more effective on smaller solids. Interestingly, in these studies, street sweeping did not significantly improve the water quality of the receiving waters, although it did remove "nuisance street load" [46, pp. 108-109].

BMP	TSS Removal Rates	
	US EPA	Mass DEP
[Dry] Detention Pond	–	60-80
Wet Detention Pond	50-90	60-80
Infiltration Basin/Trench	50-99	75-80
Porous Pavement	60-90	–
Constructed Wetlands	50-90	65-80
Grassed Swales	40-90	60-80
Vegetative Filter Strip	40-90	–
Street Sweeping	–	10

Table 3.1: Accepted TSS removal rates

Although the Massachusetts Stormwater Management Standards include street sweeping as a BMP, giving it a credit of 10% TSS removal, the standards state that this credit is issued "*at the discretion of the issuing authority* [28, p. 2-8]" (emphasis as in the original source).

3.2 Removal Efficiencies

Because total suspended solids (TSS) is a good indicator of other water quality problems, many BMPs are evaluated by their TSS removal efficiencies. As discussed in Section 2.3, the Massachusetts Department of Environmental Protection (DEP) will be issuing stormwater management regulations that require that "BMPs must be selected so that a total of 80% TSS removal is provided by one or more BMPs [27, p. 1-6]."

Table 3.1 lists the TSS removal rates that have been applied to various BMPs.

These numbers are debatable, and often depend on the site characteristics, including the types of pollutants produced, and the soil type. Some of the published removal rates might therefore not apply to certain sites.

3.3 TSS Removal as a Water Quality Indicator

Many states, including Massachusetts, are beginning to require that stormwater management include the use of Best Management Practices, and are using removal rates of TSS to indicate compliance. The reason for this is many-fold, as the Massachusetts DEP's Stormwater Management Standards explain:

> Total suspended solids was selected as the target pollutant constituent for a removal standard because of its widespread contribution to water quality and aquatic habitat degradation, because many other pollutant constituents including heavy metals, bacteria, and organic compounds sorb to sediment particles, and because the available data sets for BMP removal efficiency reveal that TSS has been the most frequently and consistently sampled constituent [27, p. 1-6].

All three of the reasons brought by the DEP are valid, yet at the same time arguable. Although it is true that TSS can do great damage to a receiving water water, many watershed communities are more concerned about other pollutants. For example, the Charles River Watershed Association is concerned with levels of fecal coliform in the Charles River, since high bacteria levels affect river activities such as boating and swimming.

The DEP Standards explain that the availability of TSS removal data makes TSS a useful indicator pollutant. However, one might argue that this is circular reasoning. For now, it is convenient for the Massachusetts DEP and other agencies across the country to use TSS reduction as an indicator, simply because many of the standard and proprietary (name brand) BMPs have been tested for TSS removal. However, if there are other pollutants that are or should be of greater concern to communities, then perhaps they should be the indicator pollutants. The stormwater management industry would be quick to monitor their products for these pollutants; "Technology forcing" is a common phenomenon in the policy arena.

Furthermore, it is not clear how well TSS removal correlates with the removal of other pollutants. The theory is that pollutants that sorb to the suspended solids will settle out of the water column as the solids settle. Studies have shown that the removal of certain pollutants are more correlated to the TSS removal than others.

Some experts point out that although those pollutants that are sorbed to TSS will indeed be removed by settling, there are other forms of pollutants, especially the dissolved forms, that are not sorbed to the solids. For example, dry detention basins have low removal rates for dissolved NO_2 and NO_3, and soluble phosphorus (although wet ponds have improved removal rates for these constituents) [44, p. 279]. Moreover, "the particulate forms of chemical contaminants removed in detention basins are typically not toxic [19]."

In particular, total metal concentration actually consists of different forms of the metal. Not all forms are bioavailable and toxic. Particulate forms of the metal (either sorbed or precipitated) will not be bioavailable, and only certain soluble forms of the metal will be toxic. Therefore, data which reports metal removal efficiencies (such as the NURP data) may not be useful; the removal efficiencies of the toxic metal fraction are needed.

Another issue is that BMPs which work on the settling principle often settle out the larger and heavier particles rather than the smaller and less dense ones. However, the smaller particles have a larger capacity to sorb pollutants than do the larger particles, since they have a greater total surface area. This was shown in a 1996 study by Wall et. al., which showed the connection between phosphorus and suspended sediment loads in Ontario agricultural watersheds. The researchers discovered an empirical relationship between the phosphorus-suspended solids ratio (kg/ton) and the unit area of the suspended solids load (kg/Ha/yr). The results show that the lower the suspended solids load, the greater the phosphorus-sediment ratio. This is the logical result, since, as the authors explain, "low suspended solids levels would occur only as a result of low erosion and/or sediment transport rates. In such cases, only smaller sediment particles (clays) are delivered to a watercourse [55, p. 505]." Since the smaller particles have more surface area than larger particles, there is more opportunity for the phosphorus to adsorb to the sediment, and therefore the phosphorus-sediment ratios are higher.

TSS removal in detention basins has been shown to be greatly affected by the size distribution of the incoming solids. A 1997 study of wet pond effectiveness by Greb and Bannerman concludes that "the overall efficiency of the pond appears to be influenced by the particle-size distribution of the influent...pond efficiency decreases as the proportion of clay-size particles in the influent increases [11, p. 1137]." For a pond whose overall solids efficiency was 87%, the sand, silt and clay removal efficiencies were found to be 99%, 93% and 74%, respectively. The majority of the solids that remain in the wet pond effluent were the smallest particles. Unfortunately, "because the concentration of pollutants such as metals and polynuclear aromatic hydrocarbons are typically associated with the finer fraction of the particulate materials, pollutant removal efficiency may be less than overall solids removal efficiency [11, p. 1137]."

A final comment about BMP efficiency notes that some BMPs are designed for the first flush, meaning that the only the first part of the runoff needs to be captured, because the majority of the stormwater pollution will be caused by the first flush of runoff. Stahre and Urbonas point out that not all sites will exhibit a first flush effect, which they define as situation in which the first 20% of the runoff contains 80% of the pollutants [44, p. 280]. For those sites, the BMPs might need to be redesigned.

3.4 Municipal Stormwater Management: Stormwater Utilities

Some municipalities have instituted utilities that bill property owners for their contribution to the stormwater runoff problem. The taxes collected are then used for stormwater management programs.

The stormwater taxes may be based on any one of a number of criteria, including the amount of impervious land of the property (which directly relates to the amount of runoff the property contributes), the property value, or the customer's consumption of water.

According to a case study in Manchester, New Hampshire, by Camp Dresser and

McKee, the most equitable billing system is based on each property's impervious area, or "the more you pave the more you pay [34, p.265]." Single family residences would be unfairly taxed if the payment system were based on property value or water consumption, since these do not reflect the amount of runoff the properties generate relative to other types of properties. On the other hand, parking lots and strip malls contribute a large amount of runoff, due to a large amount of paved land. Yet, a tax system based on property value or water consumption would assign these types of properties less of a financial responsibility compared to a system based on total impervious area.

Of course, of the three criteria mentioned above, impervious land area is the most difficult to quantify. Property value is already known for property tax purposes, and water consumption can be monitored with a water meter.

Chapter 4

Simulation of Sediment Transport with HSPF

4.1 Introduction to HSPF

HSPF, or the Hydrologic Simulation Program in FORTRAN, was developed in 1970 by the U.S. Environmental Protection Agency (EPA) and the U.S. Geological Survey (USGS). HSPF is widely considered to be one of the most comprehensive hydrologic models available [17], in that it can model the hydrology and water quality of both agricultural and urban watersheds.

HSPF divides a watershed into three parts: One module, called PERLND, simulates permeable land segments, defined by the HSPF User's Guide as having "the capacity to allow enough infiltration to influence the water budget [3, p. 37]." Module IMPLND simulates the impervious land segments that will not infiltrate rain and runoff. The third module, called RCHRES, simulates reaches in a river or in completely mixed reservoirs/lakes. Each of these modules can model water transport and contaminant transport. The user's control input file (more commonly called the "uci" file) contains all of the input parameters that are necessary for the model to run. The HSPF modeler can select the time step at which the model is run; the Charles River Watershed model runs on a time step of one hour.

The watershed to be modeled by HSPF is divided into any number of pervious and impervious land segments. All of the land in a given land segment has the same hydrologic characteristics. In the case of the model of the Charles River Watershed (CRW), the pervious land segments have distinct land uses. The five pervious land use types that are represented in our model of the Charles River Watershed are (1) open space, (2) wetlands, (3) forest, (4) low density residential land, and (5) high density residential land. Impervious land is considered to be land that drains directly to the river without losing any precipitation to infiltration or evaporation.

In addition to this, the watershed was split into three parts (i.e. three input files) because one file was too big. The Upper, Central and Lower Charles River Watersheds (UCRW, CCRW and LCRW, respectively) are each exposed to different meteorological conditions. Additionally, as more precipitation data became available in the Upper Charles River Watershed, it was further subdivided into another three subsections.

The modeled river and its tributaries are segmented into reaches and lakes. Each of these river segments is associated with a "subwatershed", an area of land that drains into it. Each "subwatershed" is composed of the six land uses (the five pervious land uses, and imperious land.)

In order to evaluate the water quality results of different stormwater management practices, the HSPF model of the Charles River Watershed needed to be calibrated for the sediment transport processes. However, a hydrologic calibration of the watershed must precede any water quality calibration. Before the work on the calibration of sediment transport was begun, two MIT Masters students had already discretized the Charles River and segmented the Charles River Watershed based on land use. Scott A. Socolofsky completed a hydrologic calibration of the upper third of the Charles River Watershed, and Amy D. Munson continued this work by calibrating the rest of the watershed. Their respective Master's theses provide a detailed description of the watershed discretization and the hydrologic calibration [43], [35].

During the course of the calibration, both of the hydrology and of the sediment, the modelers obtained advice from AQUA TERRA Consultants of Mountain View, California. This consulting firm is currently responsible for maintaining and modifying HSPF.

4.2 Discretization of the Charles River Watershed

Before any calibration work was begun, Scott Socolofsky discretized the entire Charles River into "reaches." The length of each reach varies, and was determined based on physical constraints (e.g. placement of lakes and tributaries), as well as flow and transport constraints. The entire river was eventually discretized into one hundred and sixty reaches, which includes twelve reaches that make up the tributaries to the Charles River.

Once the river reaches were in place, Socolofsky then evaluated the drainage area into each reach. These "subwatersheds" vary in size from 50 acres to 11,000 acres and were determined by examining topographic maps. Figure 4-1 shows the discretization of the Charles River into reaches and the division of the entire watershed into subwatersheds (drainage areas). Once the watershed was discretized, land use data from MassGIS was used to determine the land uses distribution in each subwatershed.

For more detailed information about the discretization of the watershed, refer to Socolofsky [43] or Munson [35].

4.3 Modeling Sediment Washoff from the Land

The PERLND (permeable land segment) module of HSPF contains a section called SEDMNT, which models the sediment that is produced by erosion and washed off the land during a rainstorm. Section SEDMNT models three processes: the detachment, reattachment and removal of sediment.

The SOLIDS section of the IMPLND (impermeable land segment) module of HSPF is simpler than the SEDMNT section of PERLND, since it involves only the accumulation and washoff of solids on an impervious surface; there is no detachment and reattachment on impervious land.

Figure 4-2 shows the HSPF sediment processes for a permeable land segment.

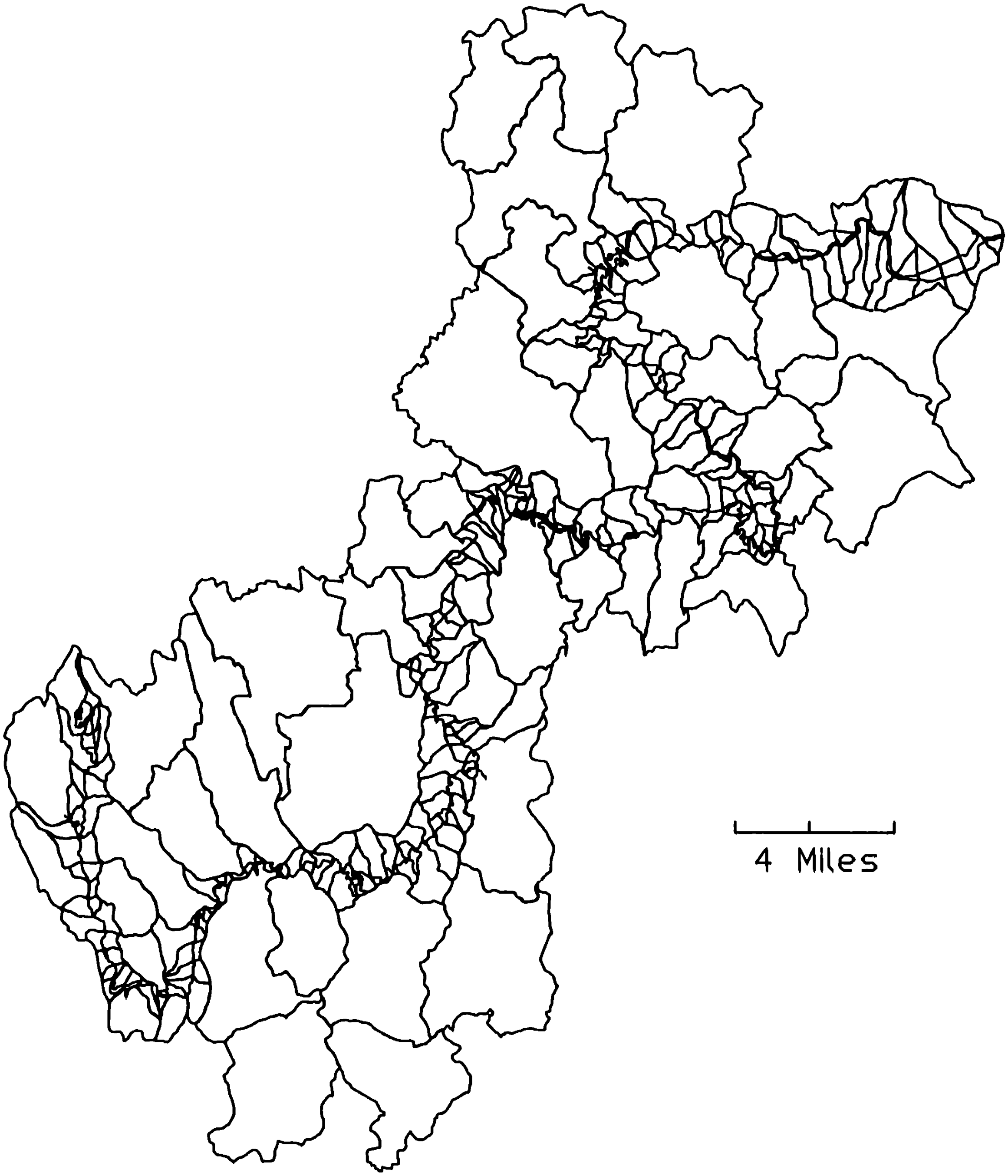


Figure 4-1: Discretization of the Charles River Watershed. Each line represents a subwatershed boundary.

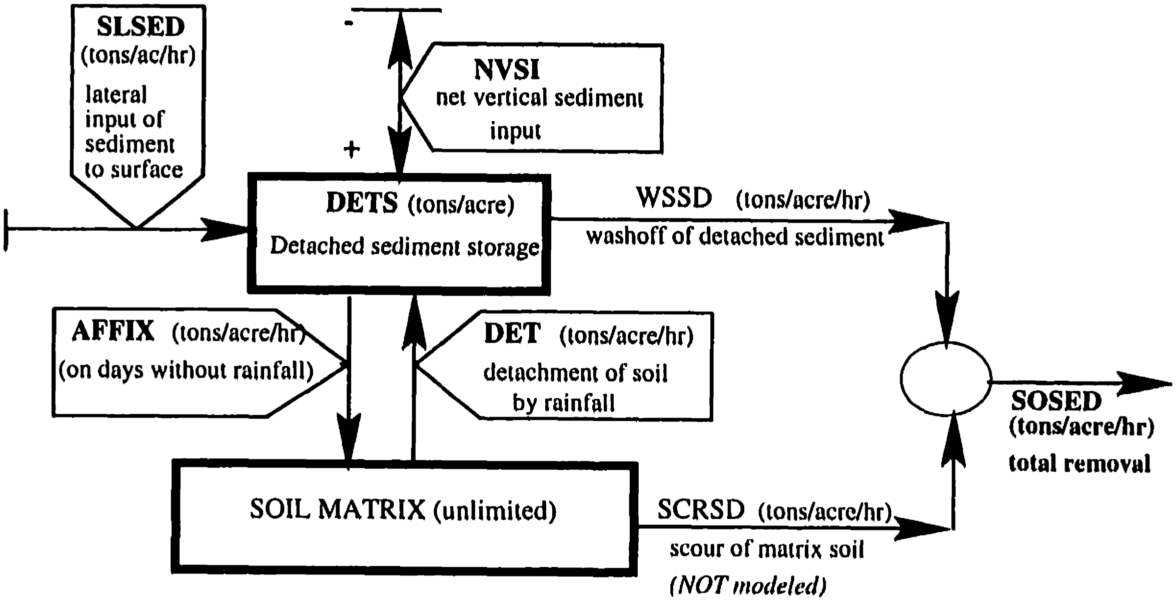


Figure 4-2: Section SEDMNT in module PERLND: The detachment and washoff of sediment from a permeable land segment. Source: [3, p. 77].

Figure 4-3 show the buildup and washoff processes on an impermeable land segment.

4.3.1 Fines Availability on a Permeable Land Segment

Soil and sediment are detached and reattached to a permeable land segment. The detached sediment storage, *DETS*, in units of tons/acre, is continually being increased (as soil is detached during a rainstorm) and decreased (as soil is reattached on a dry day or washed off the land during a storm.) The detachment and reattachment of soil is described in this section; washoff will be described in Section 4.3.3 below.

Detachment of Soil by Rainfall

The value of *DETS*, the amount of detached sediment in storage on a permeable land segment, increases when rain causes more soil to be detached, as Equation 4.1 indicates. (Note that during the storm, once the soil is detached, the total sediment in storage will subsequently be *decreased* as the soil and sediment is washed off by the stormwater.)

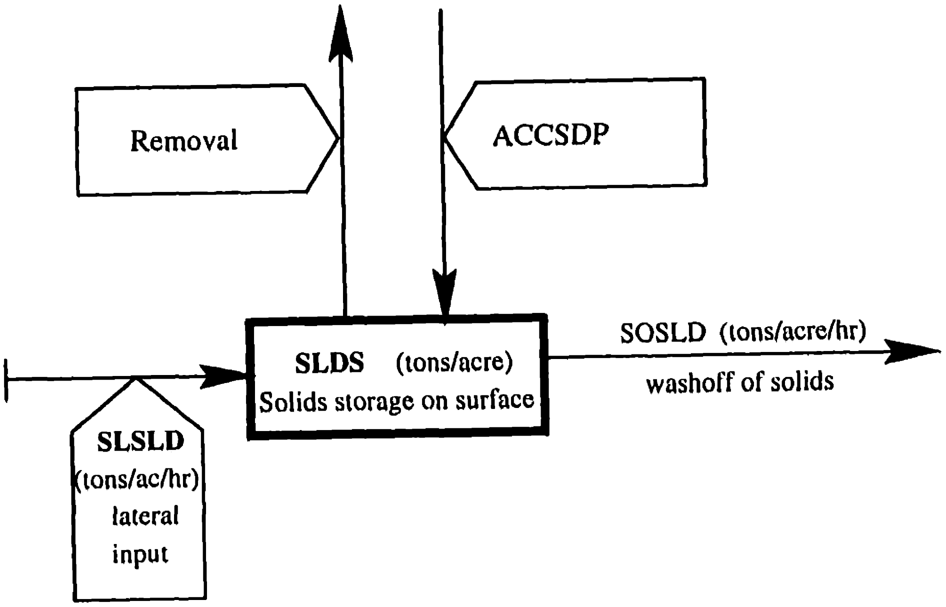


Figure 4-3: Section SOLIDS in module IMPLND: The buildup and washoff of solids on an impermeable land segment Source: [3, p. 120].

$$DETS(t) = DETS(t-1) + DET \tag{4.1}$$

Since DET is in units of tons/acre/hour (the time step is one hour), and $DETS$ is in units of tons/acre, it is implied that Equation 4.1 multiplies the DET term by the one hour time step. The value of DET is determined by Equation 4.2.

$$DET = (1 - CR) * (SMPF) * KRER * RAIN^{JRER} \tag{4.2}$$

where DET = the detachment of sediment (tons/acre/hr)

$CR = SNOW + COVER$ = fraction of land covered by snow and other cover. The snow cover ($SNOW$) is calculated by HSPF in another section of the model, while the other cover ($COVER$) is input by the user into the uci file in this section, section SEDMNT, of the model. Erosion-related $COVER$ can be input as a constant, or as a monthly changing variable. In our model, $COVER$ varies throughout the year and depends on the land use type. Table 4.1 lists the values for $COVER$ for each land use. Note that the numbers in the table represent "the fraction of land surface that is shielded from rainfall erosion (not considering snow cover) [3, p. 337]."

Land Use	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Open space	.15	.15	.20	.20	.20	.30	.30	.30	.20	.20	.10	.10
Wetland	.90	.90	.90	.92	.97	.97	.97	.97	.97	.92	.90	.90
Forest	.88	.90	.97	.97	.97	.97	.97	.97	.97	.97	.97	.90
High/Low Dens Res	.80	.80	.80	.80	.80	.80	.80	.80	.80	.80	.80	.80

Table 4.1: Fraction of land surface shielded from erosion (not including snow cover). Values are for the first day of each month; all other days are interpolated.

SMPF = the supporting management practice factor. This factor accounts for (agricultural) erosion control practices. *SMPF* corresponds to the factor P in the Universal Soil Loss Equation (USLE). See Appendix Section A.3 for more information about the USLE. For *SMPF*, we have chosen a value of 1 (which means that no erosion control practices are in effect.)

RAIN = rainfall (inches/hr)

KRER, *JRER* = detachment coefficient and exponent, input by the user. These are dependent on soil properties.

The units of *KRER* and *JRER* are given only as "complex". These units will balance Equation 4.2.

AQUA TERRA Consultants suggests in its HSPF training documentation [1] that the erodibility K factor in the Universal Soil Loss Equation is a good approximate value for *KRER*. Using the K factor data published by the Soil Survey of Norfolk and Suffolk Counties [39] and the Middlesex County Interim Soil Survey Report [50], we selected *KRER* to be 0.24 by choosing a "representative" K value.

According to a careful study of the Norfolk and Suffolk county soil maps, soil of hydrologic group type B dominates in the Norfolk and Suffolk County sections of the Charles River Watershed [57]. (Hydrologic soil groups A through D are defined in Appendix Section A.2.) According to this study, soil type B covers about 45% of the Lower and Middle Charles River Watersheds. Soil types A and C account for 25% and 20%, respectively, and soil type D is present in only about 10% of the land.

According to the Norfolk and Suffolk County Soil Survey [39], most of the soils of type B have a K value of approximately 0.23. The type A soils in the watershed have an average K value of about 0.21, and the type C soils have a K value of about 0.24. Of course, the entire Charles River Watershed consists of many types of soils with a range of erosion factors; indeed, the survey of Norfolk and Suffolk Counties documented 76 different kinds of soils [39, p. 1]. However, since the K factor is meant only to be a good starting value (and not necessarily the final calibrated value) for *KRER*, it was determined that one representative K value (0.24) would be sufficient.

JRER was selected to be 1.9 based on other previously designed uci files, and by AQUA TERRA's recommendation of a typical range for *JRER* of 1.5 to 3.0 [1].

Accumulation and Reattachment of Soil

While soil is detached due to rainfall, as Equation 4.2 shows, it is also reattached to the soil matrix during dry periods. At the start of each day that follows a day with no rainfall, the detached storage is decreased by soil compaction. This is accounted for with Equation 4.3. As the equation shows, the detached sediment is reduced by the fraction *AFFIX*. In our model, we have selected *AFFIX* to be 0.01 day^{-1}. This value is comparable to literature values values [14], [58], [7].

$$DETS(t) = DETS(t-1) * (1.0 - AFFIX) \tag{4.3}$$

Equation 4.3 implies that the constant *AFFIX*, which is in units of day^{-1}, is multiplied by a time interval of 1 day.

4.3.2 Accumulation of Solids on an Impermeable Land Segment

The solids storage on an impervious land segment is denoted by HSPF as *SLDS* and is roughly equivalent to the detached sediment storage *DETS* on a permeable land segment (discussed above in Section 4.3.1).

Since there is no detachment and reattachment to the soil matrix on an impermeable land segment, the accumulation and removal of solids from the land surface is due to other kinds of inputs (such as from the atmosphere) and removals (such as street cleaning.)

Equation 4.4 indicates how HSPF accounts for the accumulation and removal of solids only on days when there was no rainfall on the pervious day.

$$SLDS_{end-of-day} = ACCSDP + SLDS_{start-of-day} * (1.0 - REMSDP) \qquad (4.4)$$

where $SLDS$ = the solids stored on the impervious land segment (tons/acre)

$ACCSDP$ = accumulation rate of solids storage (tons/acre/day). This value must be input by the HSPF user; in the Charles River Watershed model, $ACCSDP$ = 0.04 tons/acre/day. (It is implied that $ACCSDP$ is multiplied by the time interval 1 day.)

$REMSDP$ = fraction of solids removed each day, by the wind, street cleaning, etc. In the Charles River model, $REMSDP = 0.07$ day^{-1}. (It is implied that $REMSDP$ is multiplied by the time interval 1 day.)

The value chosen for $REMSDP$ was also used in an HSPF model of an urban watershed in the San Francisco Bay area for commercial impermeable land [13]. (That same model used a value of 0.05 tons/acre/day for $ACCSDP$; the Charles River model required a lower accumulation rate so that TSS in the river would not be too high.)

Note that if there is a long period of time with no rain, then there will be no washoff of $SLDS$, and the value for $SLDS$ will reach an asymptotic limit of $\frac{ACCSDP}{REMSDP}$. In a non-dry climate such as the Charles River Watershed, this solids storage limit will not often be reached. We can confirm this by examining how $SLDS$ varies over a significant period of time. (See the third plot in Figure 4-7.) In our case, since $ACCSDP$ = 0.04 tons/acre/day and $REMSDP$ = 0.07 /day, the storage limit about 0.57 tons/acre.

4.3.3 Sediment Washoff from Permeable and Impermeable Land

Sediment is washed off a land segment during a rainfall. In order to determine how much is washed off, HSPF compares the amount of detached sediment on the surface of the land with the "sediment/solids transport capacity" of the overland flow (denoted as *STCAP*). Note that the HSPF process is the same for permeable and impermeable land segments. In the PERLND module, HSPF will compare the detached sediment, *DETS*, with the sediment transport capacity *STCAP*. In the IMPLND module, HSPF will compare the solids stored, *SLDS*, with the solids removal capacity, *STCAP*.

Thus, there are two possible conditions. In the "sediment limiting" case, the amount of detached sediment in storage is less than the transport capacity during one time step:

$$STCAP > DETS$$

or (for impermeable land):

$$STCAP > SLDS$$

In the "transport limiting" case, the transport capacity is less than the available storage during one time step:

$$STCAP < DETS$$

or (for impermeable land):

$$STCAP < SLDS$$

The limiting parameter will affect how much sediment is washed off. In theory, at the start of a big storm, the transport capacity would be the limiting parameter, and by the end of the storm, after much of the detached sediment has already been washed away, the sediment will be the limiting parameter. Of course, antecedent and storm conditions have an effect as well.

Land Use	KSER parameter
Open space	0.30
Wetland	0.10
Forest	0.05
Low density residential	0.10
High density residential and commercial	0.10

Table 4.2: Values of the KSER parameter based on land use

Permeable Land

When HSPF determines how much sediment washes off the permeable land, it will use either *DETS* or *STCAP*, depending on which is limiting. The value for detached storage, *DETS*, described in Section 4.3.1 above, is the result of detachment, reattachment and washoff of sediment. The value for the transport capacity of detached sediment is determined with Equation 4.5.

$$STCAP = KSER * (SURS + SURO)^{JSER} \tag{4.5}$$

where $STCAP$ = the transport capacity of overland flow (tons/acre/hr)

$SURS$ = surface water storage (inches). This value is calculated by HSPF in another section of the model (called PWATER).

$SURO$ = surface outflow of water (in/hr). Like *SURS*, this value is calculated by HSPF previously.

KSER and *JSER* are input by the user and can vary widely from application to application. In our model, *KSER* varies with each land use; see Table 4.2 for a list of the values used in our calibration. The value for *JSER* has been set to 2.0. (The AQUA TERRA manual suggests a range of 1.5 to 2.5 for *JSER* [1]; 2.0 is a value commonly selected for *JSER* [14], [58].) The units of *KSER* and *JSER* are given only as "complex". These units are embedded within Equation 4.5.

The washoff of soil and sediment from a permeable land segment, *WSSD*, (in units of tons/acre/hour), is given in Equation 4.6 (for the sediment limiting case) and in Equation 4.7 (for the transport limiting case).

$$WSSD = \frac{DETS * SURO}{SURS + SURO} \tag{4.6}$$

$$WSSD = \frac{STCAP * SURO}{SURS + SURO} \tag{4.7}$$

Equation 4.6 will balance if the value of *SURO* in the denominator (which is being added to *SURS*) is multiplied by the time step of 1 hour. Equation 4.7 will balance if the value of *SURS* in the denominator is divided by the time step of 1 hour.

As Figure 4-2 shows, the total amount of sediment that leaves a permeable land segment is actually equal to *WSSD* (the sediment that washes off the surface) plus *SCRSD* (the sediment that scours from the soil matrix):

$$TotalRemoval = SOSED = WSSD + SCRSD$$

However, since we are not modeling the soil scour, (as is the case in most HSPF applications) the value of *SOSED* (total removal in tons/acre per time) is equivalent to the washoff of detached sediment *WSSD* in the Charles River Watershed model.

Impermeable Land

HSPF determines how much of the stored solids are washed off the impervious land segment using the same method as for permeable land.

The value for the transport capacity of the stored solids is determined with Equation 4.8.

$$STCAP = KEIM * (SURS + SURO)^{JEIM} \tag{4.8}$$

where $STCAP$ = the capacity for removing solids (tons/acre/hr)

$SURS$ = surface water storage (inches)

$SURO$ = surface outflow of water (in/hr)

KEIM and *JEIM* are input by the user. In our model, *KEIM* has been set to 0.035 and *JEIM* is 2.0. (The AQUA TERRA training manual suggests a range of 0.1 to 5.0 for *KEIM* and a range of 1.5 to 2.5 for *JEIM* [1].) As we've explained regarding the parallel equation for permeable land (Equation 4.5), the units of *KEIM* and *JEIM* are given as "complex". The units of *KEIM* and *JEIM* are embedded within Equation 4.8 so that the formula balances.

The washoff of solids from an impermeable land segment, *SOSLD*, (in units of tons/acre/hour), is given in Equation 4.9 (for the sediment limiting case) and in Equation 4.10 (for the transport limiting case).

$$SOSLD = \frac{SLDS * SURO}{SURS + SURO} \tag{4.9}$$

$$SOSLD = \frac{STCAP * SURO}{SURS + SURO} \tag{4.10}$$

Equation 4.9 will balance if the value of *SURO* in the denominator (which is being added to *SURS*) is multiplied by the time step of 1 hour. Equation 4.10 will balance if the value of *SURS* in the denominator is divided by the time step of 1 hour.

4.4 Modeling Sediment Transport in the River

The RCHRES (river reach/well-mixed reservoir) module of HSPF contains a section called SEDTRN, which "simulate[s] the transport, deposition, and scour of inorganic sediment in free-flowing reaches and mixed reservoirs [7, p. 169]." Figure 4-4 shows the HSPF flow diagram for the transfer of sediment in a flowing river reach.

HSPF models the transport of sand, silt and clay in the river. For each constituent, HSPF performs a separate mass balance per river reach. In each reach, the Equation 4.11 must be balanced.

$$Inflow + Scour + Storage_{start} = Outflow + Deposition + Storage_{end} \tag{4.11}$$

The sediment inflow to each reach includes suspended sediment that outflows from

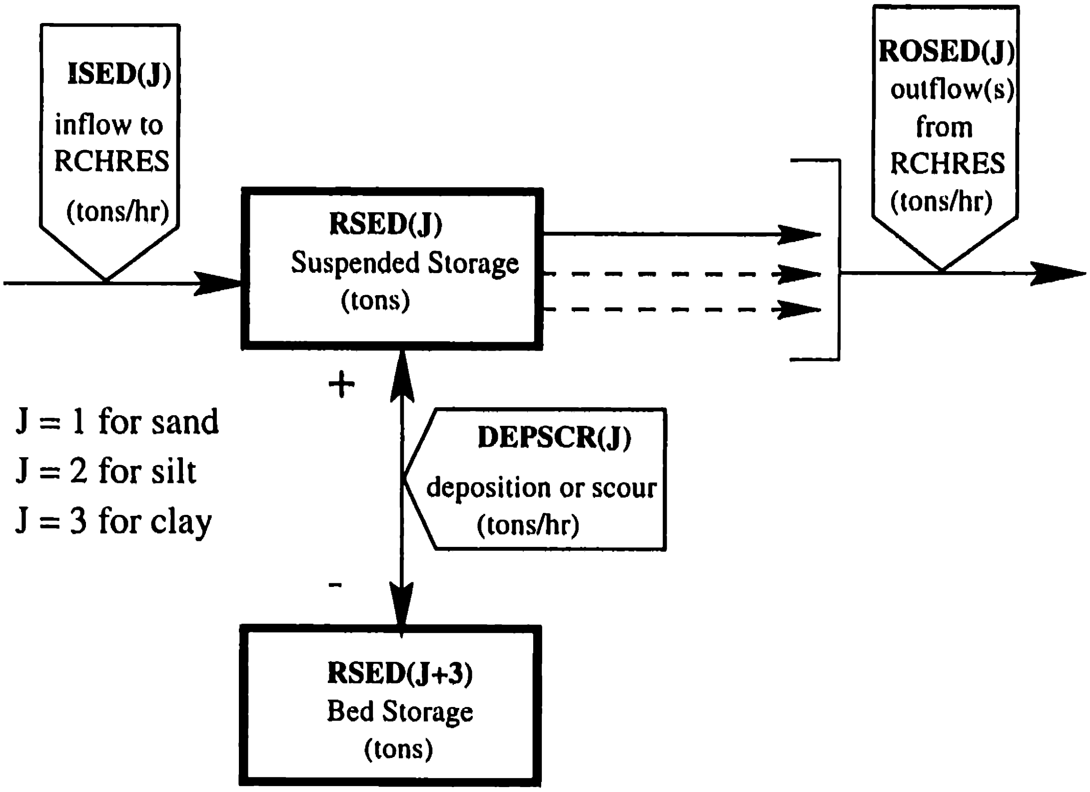


Figure 4-4: Section SEDTRN in module RCHRES: Sediment transport in the river Source: [3, p. 170].

the previous reach as well as the sediment that washes off the land, as described in Section 4.3.3 above.

As Equation 4.11 indicates, scour and deposition are two important quantities for sediment transport in the river. The transfer of cohesive sediments (silt and clay) from suspension to the river bed and vice versa is modeled differently than the transfer of noncohesive sediments (sand).

4.4.1 Sand and Gravel: Deposition, Scour and Transport of Noncohesive Sediments

HSPF allows for any one of three methods to model the flux of sand. The Charles River Watershed model uses the method described as the "power function", which is given in Equation 4.12. This equation determines *PSAND*, the sand carrying capacity of the reach. If this capacity is greater than what is actually being transported in the reach, then sand will be scoured. On the other hand, if the suspended concentration of sand is greater than PSAND, then sand will deposit.

$$PSAND = KSAND * AVVELE^{EXPSND} \tag{4.12}$$

where $PSAND$ = the potential sandload (mg/L)

$AVVELE$ = average velocity (ft/sec), calculated by HSPF in another section of the program

$KSAND$, $EXPSAND$ = the user-supplied coefficient and exponent. Based on the literature, the values $KSAND$ = 0.1 and $EXPSAND$ = 3.0 have been selected for use in the sandload suspension equation. In effect, there is rarely any sand in suspension in the model of the river. An exponent of 3.0 will result in bedload transport of sand, but the sand will not be suspended high in the water column.

AQUA TERRA documentation suggests a range of 0.05–0.5 for $KSAND$ [1]. There has been a wide range of values for $KSAND$ reported by HSPF users.

The units of $KSAND$ and $EXPSAND$ are given as "complex"; it is implied that the units of $KSAND$ and $EXPSAND$ balance Equation 4.12.

Other sand transport data are supplied in the user control file are the effective diameter of the sand particles (set to 0.014 inches in our file), the fall velocity in still water (2.5 inches/sec), and the density of the sand particles (2.65 g/cm^3). These values are comparable with those reported by other HSPF users in the literature [8], [6]. (Note that the sand particle diameter input in this section is actually not used by HSPF to calculate scour and deposition of sand; the HSPF User's Manual explains that it is "included here for consistency with the input data supplied for cohesive sediments [3, p. 532]". Rather, HSPF uses another parameter, *DB50*, the median diameter for bed sediment, which is input by the user in a different section.)

4.4.2 Silt and Clay: Deposition, Scour and Transport of Cohesive Sediments

The scour and deposition of silt and clay, cohesive sediments, are modeled differently than sand. Equation 4.13 describes the rate of deposition of silt and clay, and

Equation 4.14 describes the rate of scour (resuspension).

$$DEP = W * CONC * (1.0 - \frac{TAU}{TAUCD}) \tag{4.13}$$

where DEP = the rate of deposition (lb/ft^2/hr)

W = fall velocity of the sediment, input by the user (ft/hr; although the units for W in the input file are in/sec and are converted by HSPF)

$CONC$ = suspended concentration of the sediment (lb/ft^3)

TAU = bed shear stress, calculated by HSPF (lb/ft^2)

$TAUCD$ = critical shear stress for deposition; the stress below which sediment will begin to deposit (lb/ft^2)

$$S = M * (\frac{TAU}{TAUCS} - 1.0) \tag{4.14}$$

where S = the rate of scour (lb/ft^2/hr)

M = erodibility coefficient for the sediment, input by the user (lb/ft^2/hr; although the units for M in the input file are lb/ft^2/day and are converted by HSPF)

$TAUCS$ = critical shear stress for scour; the stress above which sediment will begin to scour (lb/ft^2)

Once the bed shear stress in the reach drops lower than the critical stress for deposition input by the user, then deposition of suspended sediment will begin at the rate indicated by Equation 4.13. Similarly, once the bed shear stress in the reach exceeds the critical stress for scour, then resuspension of bed sediment will occur at the rate indicated by Equation 4.14.

The bed shear stress, TAU, is calculated by HSPF per reach, using Equation 4.15 for a reach that is a lake, and Equation 4.16 for a river reach.

$$TAU_{lake} = GAM * (USTAR^2)/GRAV \tag{4.15}$$

where TAU_{lake} = shear stress on a lake bed (lb/ft^2)

GAM = density of water (62.4 lb/ft^3)

$USTAR$ = shear velocity (ft/s), calculated by HSPF as a function of the average flow velocity, average water depth, and the median diameter of bed material.

$GRAV$ = acceleration due to gravity (32.2 ft/sec^2)

$$TAU_{river} = SLOPE * GAM * HRAD \tag{4.16}$$

where TAU_{river} = river bed shear stress (lb/ft^2)

$SLOPE$ = slope of the river reach

$HRAD$ = hydraulic radius (ft)

Input Parameters for Silt and Clay

The uci file requires a number of input parameters for silt and clay. These include the effective diameter of the sediment particles (D), the fall velocity in still water (W), the density (RHO), the erodibility coefficient (M), the shear stress for deposition ($TAUCD$) and the shear stress for scour ($TAUCS$).

The labels "sand", "silt", and "clay" are convenient ways of classifying grain sizes. In reality, there is a continuum of grain sizes in the sediment; the categories provide an arbitrary way of placing all sediment into three major groups. HSPF requires a diameter for the silt particles and a diameter for the clay particles; this is obviously intended to be some kind of average. Since we have very little sediment data, we chose to simplify the model further by categorizing the sediment in the river into two major groups: non-cohesive sediments (sand) and cohesive sediments (silt and clay). In effect, this meant that all of the parameters that were chosen for the "silt" category were simply duplicated for the "clay" category, since HSPF still considers them two different categories.

Therefore, the diameter (D) chosen for the "cohesive sediments" category is 0.00016 inches, or 0.004 mm. According to ASCE soil classification categories listed in Appendix Section A.1, a diameter of 0.00016 inches (0.004 mm) is the lower limit for the "very fine silt" subcategory and the upper limit for the "coarse clay" subcategory. According to the USDA categorization scheme, silt ranges between 0.002 mm to 0.05 mm in diameter and clay is less than 0.002 mm; therefore, according to USDA, our representative sediment size is a fine silt particle.

The fall velocity (*W*) parameter of the silt/clay category was set to 0.0001 inches/sec. This value was selected as a reasonable value based on uci files from other HSPF models ([14], [58]) as well as values reported in the literature. Fontaine et. al. use a value of 0.007 in/sec for silt and 0.00011 in/sec for clay [8]. Chew et. al. use a value of 0.178 mm/sec (0.007 in/sec) for silt and 0.001 mm/sec (0.00004 in/sec) for clay [6].

The density (*RHO*) of the silt/clay sediment category was set to 2.10 g/cm^3. This value was selected because *RHO* values for silt and clay are commonly set to 2.20 g/cm^3 and 2.00 g/cm^3, respectively [8], [6].

The erodibility coefficient (*M*) was set to 0.05 lb/ft^2/day for most reaches. This value was selected primarily to prevent too much scour, and therefore too much TSS, in the river. In certain reaches with exceedingly high bed shear stress, the value of *M* was further lowered to 0.02 lb/ft^2/day. In two reaches which are tributaries to the river, a high shear stress resulted in very high TSS in the river and therefore *M* was reduced even further to 0.001 lb/ft^2/day. In two tributaries in the Central watershed, *M* was increased to 0.10 to allow for more TSS in that part of the river on days with high river velocity. These values are low compared with most of the literature, although at least one uci file used values as low as 0.001 lb/ft^2/day for *M* [14].

The sand, silt, and clay calibration parameters are summarized in Table 4.3, along with values found in the literature. The final two parameters, the critical shear stresses *TAUCS* and *TAUCD*, are discussed in more detail below.

Critical Shear Stress

During the course of the sediment calibration, it became clear that the critical shear stresses for scour and for deposition have a significant effect on the amount of suspended sediment in the river. Since we were calibrating the model to predict TSS, or total suspended solids, in the Charles River, critical shear stress emerged as an important calibration parameter.

The input file allows different critical stresses to be input for each reach. According to the AQUA TERRA training documentation [1], the values for *TAUCS*, critical

	D inches	W in/sec	RHO gm/cm^2	M lb/ft^2/d
Sand				
CRW	0.014	2.5	2.65	–
lit	0.014 [6], 0.01 [8], 0.005 [14], [58]	2 [6], 1.7 [8], 0.02 [14], 0.25 [58],	2.65 [6], [8], 2.5 [14], [58]	–
Silt				
CRW	0.00016	0.0001	2.10	0.05
lit	0.00063 [6], [8], 0.0004 [14], [58]	0.007 [6], 0.0071 [8], 0.0001 (riv) [14], 0.003 (lake) [14], 0.02 [58]	2.2 [6], [8], 2.2 [14], 2.4 [58]	3.0 [6], 0.6 [8] 0.005 (riv) [14], 0.001 (lake) [14], 1.0 [58], 0.0075–0.9 [1]
Clay				
CRW	0.00016	0.0001	2.10	0.05
lit	0.000055 [6], 0.000079 [8], 0.00006 [14], 0.00001 [58]	0.00004 [6], 0.00011 [8], 0.00005 (riv) [14], 0.001 (lake) [14], 0.00009 [58]	2.0 [6], [8], 2.2 [14], 2.4 [58]	6.4 [6], 0.6 [8] 0.01 (riv) [14], .001 (lake) [14], 3.0 [58], 0.01–0.9 [1]

Table 4.3: Calibration parameters for SEDTRN (sediment transport in RCHRES). Comparison of our Charles River Watershed model (CRW) with literature values

shear stress for scour, and *TAUCD*, critical shear stress for deposition, should be determined on a reach by reach basis. The bed shear stress for each reach, evaluated as a function of the slope and hydraulic radius of the reach, varies over time, as flow in the river changes. In order to determine the critical shear stresses for deposition and resuspension, the user is advised to examine the variation in bed shear stress (*TAU*) over the course of time, and to select a relatively high value to be the critical shear stress for scour and a low value to be the critical shear stress for deposition. When the bed shear stress is somewhere in between those two values, there will be neither scour nor deposition. For all reaches in the Charles River Basin (downstream of the Watertown Dam), HSPF outputs a shear stress of zero. In these reaches, there can be no critical shear stress that will induce scour.

Figure 4-5 explains the critical shear stress process as suggested by AQUA TERRA. The figure shows the variation in bed shear stress for three reaches in the river. The top figure shows a reach in the upper part of the watershed, the middle figure is for a central watershed reach, and the bottom figure is for a lower watershed reach. As can be seen from the plots, shear stress can vary widely in the river. Shear stress in the upper watershed reach, labeled as Reach 27 in the uci file, can vary from less than 0.075 lb/ft^2 to over 0.95 lb/ft^2. For demonstration purposes, critical stress for deposition *TAUCD* is drawn onto the graph as 0.15 lb/ft^2, and the critical stress for scour *TAUCS* is shown as 0.56 lb/ft^2. Reach 132 (a reach in the central watershed) has shear stresses that are an order of magnitude lower than Reach 27; suggested critical shear stresses for deposition and scour are shown on the graph. Shear stresses in Reach 77 in the Lower Charles River Watershed are similar in order of magnitude to those in Reach 27, although there is a wider range of shear stress values.

Although the AQUA TERRA procedure was followed in initial attempts at calibration of the sediment, the procedure did not produce any more successful results than did a much simpler procedure, described in the next section.

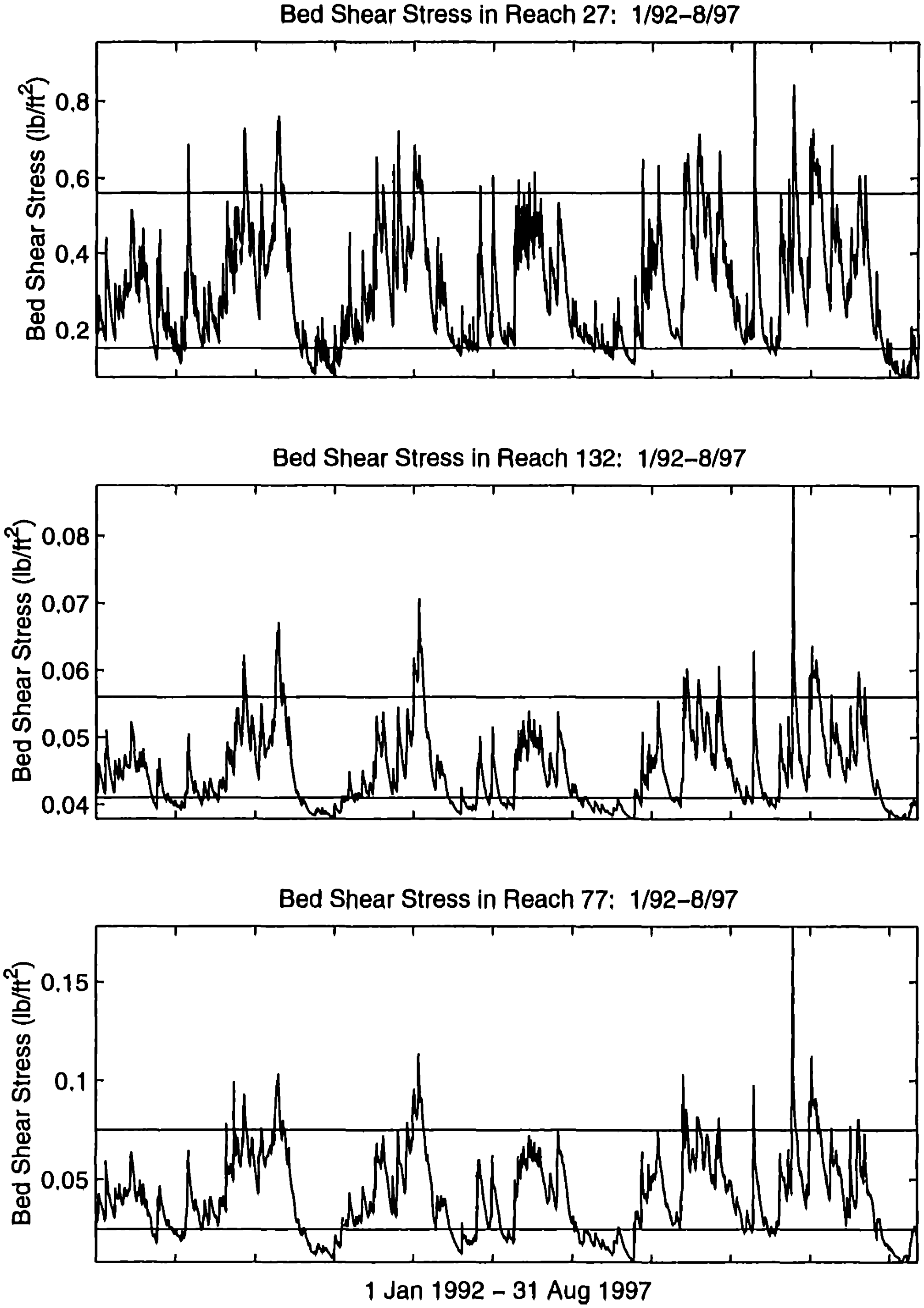


Figure 4-5: Variation in bed shear stress in three reaches; selection of critical stresses for scour and for deposition

Selection of Critical Shear Stress

Determining a critical shear stress for cohesive sediment in a river is a very difficult process, even when there is observed data about the sediment (such as median diameter and organic content) and sediment transport in the river. Although the critical shear stress for sand and gravel has been well studied and can be predicted within a reasonable margin of error (e.g. using a Shields diagram) [54], the critical shear stresses for cohesive sediments are not as predictable. Silt and clay particles that have recently been deposited, for example, are more easily disturbed than those that have been in the river bed for a long time, and they will therefore erode with a much smaller shear stress. The literature acknowledges the difficulty of predicting the erosion of cohesive sediment. Kamphuis and Hall note that "the shear stress required to erode a cohesive sediment is...significantly affected by the amount and type of clay material, microscopic and macroscopic clay properties, water content, pH and temperature of the eroding water as well as the pore water, and the thixotropy and consolidation of the clay and its resulting clay fabric [15]." Microscopic and macroscopic clay properties include "the atomic structure of clay materials, capacity of exchangeable cations (CEC), types and concentrations of the absorbed cations and organic matter, chemical additives, etc. [37]."

The values for critical shear stress in the literature are often reported for sand-gravel river beds or for coastal waters and can't necessarily be applied to our river model. The literature reports a wide range of values for critical shear stress. A recent study of suspended sediment in a supply canal in the Florida Everglades determined the critical shear stress to be 0.12 Pa, or 0.0025 lbs/ft^2 [23].

Kamphuis and Hall began their 1983 paper on erosion of cohesive material [15] by summarizing the results of a literature review of reported critical shear stresses for cohesive sediment; a wide range of values, from 72 Pa (1.5 lb/ft^2) to 0.4 Pa (0.008 lb/ft^2), have been reported. The authors then performed experiments with cohesive sediment from the MacKensie River in Canada in order to determine the critical shear stress for erosion. The mean grain size diameter D_{50} was 0.0036 mm (comparable to

Test #	Consolidation Pressure (kPa)	Critical Shear Stress				% Clay	% Silt	% Sand
		(Pa)		(lb/ft^2)				
		range	average	range	average			
A-4	191.5	11.7–12.5	12.1	0.244–0.261	0.253	60	35	5
A-5	50.3	8.6–9.6	9.1	0.180–0.200	0.190			
A-6	95.8	9.9–11	10.45	0.207–0.230	0.218			
A-7	143.6	10.7–11.9	11.3	0.223–0.248	0.236			
A-8	196.3	12.5–13.4	12.95	0.261–0.280	0.270			
A-9	191.5	15.7–15.7	15.7	0.328–0.328	0.328			
A-11	215.5	17.8–18.4	18.1	0.372–0.384	0.378			
A-12	95.8	9–9.8	9.4	0.188–0.205	0.196			
B-1	191.5	12.2–13.4	12.8	0.255–0.280	0.267	60	38	2
B-3	47.9	9.9–10.7	10.3	0.207–0.223	0.215	60	39	1
B-4	95.8	10.2–11.3	10.75	0.213–0.236	0.224	60	36	4
B-5	143.6	11.3–12.5	11.9	0.236–0.261	0.248	58	40	2
C-1	47.9	4–4.8	4.4	0.084–0.100	0.092	48	35	17
C-2	95.8	6–7.2	6.6	0.125–0.150	0.138			
C-3	191.5	7.9–8.9	8.4	0.165–0.186	0.175			
D-1	47.9	1–1.4	1.2	0.021–0.029	0.025	36	35	29
D-2	95.8	2.4–2.9	2.65	0.050–0.061	0.055			
D-3	191.5	4.6–5.4	5	0.096–0.113	0.104			
E-1	191.5	1.5–1.8	1.65	0.031–0.038	0.034	15	35	50

Table 4.4: Critical shear stresses: Experimental data from the MacKensie River (Source:[15])
Sample A was taken from a land-based location, and Sample B from the bottom of the river. Samples C, D and E were the equivalent of Sample A with reduced clay content.

our input cohesive sediment diameter of 0.00016 inches, or 0.004 mm.) They found that with increased consolidation pressure of the sediment particles, the critical shear stress increased. Additionally, the higher the clay content, the greater the critical shear stress. Their results are reported in part in Table 4.4.

In the field, the sand content of the bed sediment will reduce the critical shear stress of the sediment. However, the HSPF model treats the erosion of sand separately; the critical shear stresses input into the uci file are for silt and clay only. Therefore, we felt justified in using values for critical shear stress that might be slightly higher than most of the reported values in the literature.

Sediment	**Mean Grain Size** (mm)	**% Silt and Clay**	**Critical τ** (lb/ft^2)	
			Min	Max
1	0.022	69.0	0.48	0.49
2	0.072	35.0	0.18	0.33
3a	0.328	12.5	0.057	0.063
3b	0.319	18.0	0.057	0.083
3c	0.308	26.0	0.11	0.12
3b	0.250	44.0	0.14	0.15
4	0.078	41.0	0.19	0.28
5	0.081	31.0	0.11	0.15
6	0.038	46.0	0.30	0.33
7	0.016	78.0	0.30	0.45
8	0.015	81.0	0.40	0.41
9	0.026	56.0	0.19	0.32
10	0.014	88.0	0.43	0.48
11	0.014	95.0	0.48	0.49
12	0.139	10.0	0.053	0.053
13	0.173	5.0	0.043	0.033

Table 4.5: Observed critical shear stress for various types of sediment (Source:[54, p.109]; observed by Dunn(1959))

A value of 0.3 lbs/ft^2 was selected for critical shear stress (for scour as well as for deposition) in most of the reaches of the river. This value is consistent with data reported in the American Society of Civil Engineers (ASCE) text, *Sedimentation Engineering* [54], reproduced here as Table 4.5.

Since there is a lack of data about the Charles River sediment, we have chosen to view the parameters of TAUCS and TAUCD as calibration parameters. In other words, given the TSS data in the river, we sought to determine how we could best fit the data by changing either the critical shear stress parameter or the erodibility coefficient.

Additionally, since there is relatively little data about sediment transport in the Charles River, we decided to model the resuspension and deposition of sediment in the river using a single critical shear stress, rather than one for each reach. This critical stress was not determined based on the variability of bed shear stress in the river but by reasonable numbers obtained from the literature. Given a critical shear stress of 0.3 lb/ft^2, we concluded that there will be deposition, rather than scour, in most of the reaches in the river during most of the year. This conclusion seems reasonable, based on knowledge of the flow of the Charles River.

However, there are specific reaches in which HSPF outputs an extremely high bed shear stress (*TAU*). In those cases, for the sake of the calibration of TSS, we were forced to increase the critical shear stress to prevent the entire bed from scouring away in those reaches and to reduce the TSS during high flow periods.

4.5 Calibration of Sediment Washoff from the Land: Sediment Load

As is required by HSPF, the hydrology of the model was calibrated and verified before the water quality was calibrated. The sediment calibration can be separated into two parts. First, the sediment load that washes off the land, both annually and during a storm event, must be reasonable. Second, the suspended sediment concentrations in the river as predicted by HSPF must coincide with the measured concentrations.

The PERLND and IMPLND sections of the model determine the volume of stormwater runoff as well as the sediment load that is washed off the watershed. Certain parameters in the uci file need to be calibrated so that the model predicts reasonable values. According to the Users Manual for HSPF, "the major sediment parameters are modified to increase agreement between simulated and recorded monthly sediment loss and storm event sediment removal [7, p. 98]." Unfortunately, there is no recorded data from the Charles River Watershed for monthly sediment loss, and there is only a small amount of storm event data. This lack of data severely challenged the calibration of sediment removal from the land. In order to calibrate certain sediment parameters, reasonable values were determined from other HSPF applications for other watersheds. Of course, since land use greatly affects the calibration parameters, values did not always relate well from a purely agricultural watershed to the Charles River Watershed.

4.5.1 Buildup and Washoff of Detached Storage

As described above in Sections 4.3.1 and 4.3.2, the storage of sediment and solids on permeable land segments (*DETS*) and on impermeable land segments (*SLDS*) will vary throughout the year. Different types of land uses will have different sediment storage patterns. For example, on agricultural land (which for the most part does not exist in the Charles River Watershed), there will be an increase in detached storage during periods when the soil is being plowed. For other land uses, *DETS* might follow a cyclical pattern.

Figures 4-6 and 4-7 show the model's prediction for how the detached storage of sediment and solids vary by land use over the course of a five year period. During our calibration of the Charles River Watershed model, we selected values for the parameter *KSER* that would allow *DETS* on each of the permeable land segments to remain relatively stable. (Table 4.2 lists those values ultimately selected for *KSER* per land type.) Note that the plots in Figures 4-6 and 4-7 show only the values from the land uses in the top third of the Upper Charles River Watershed; the calibration was similarly done for the other two sections of the Upper Charles River Watershed as well as for the Central and Lower Charles River watershed.

The solids washoff from impermeable land is modeled differently, and depends on the accumulation rate of solids storage on a dry day as well as the fraction of solids removed from the land on a dry day. After a significant number of dry days, the value of *SLDS* will reach a limit. As mentioned in Section 4.3.2, in the Charles River Watershed, with its non-dry climate, the solids storage limit will rarely be exceeded. With a value of 0.04 tons/acre/day for the accumulation rate *ACCSDP* and a value of 0.07 /day for the fraction of solids removed *REMSDP*, the accumulation limit will be 0.57 tons/acre. The last plot in Figure 4-7 shows this.

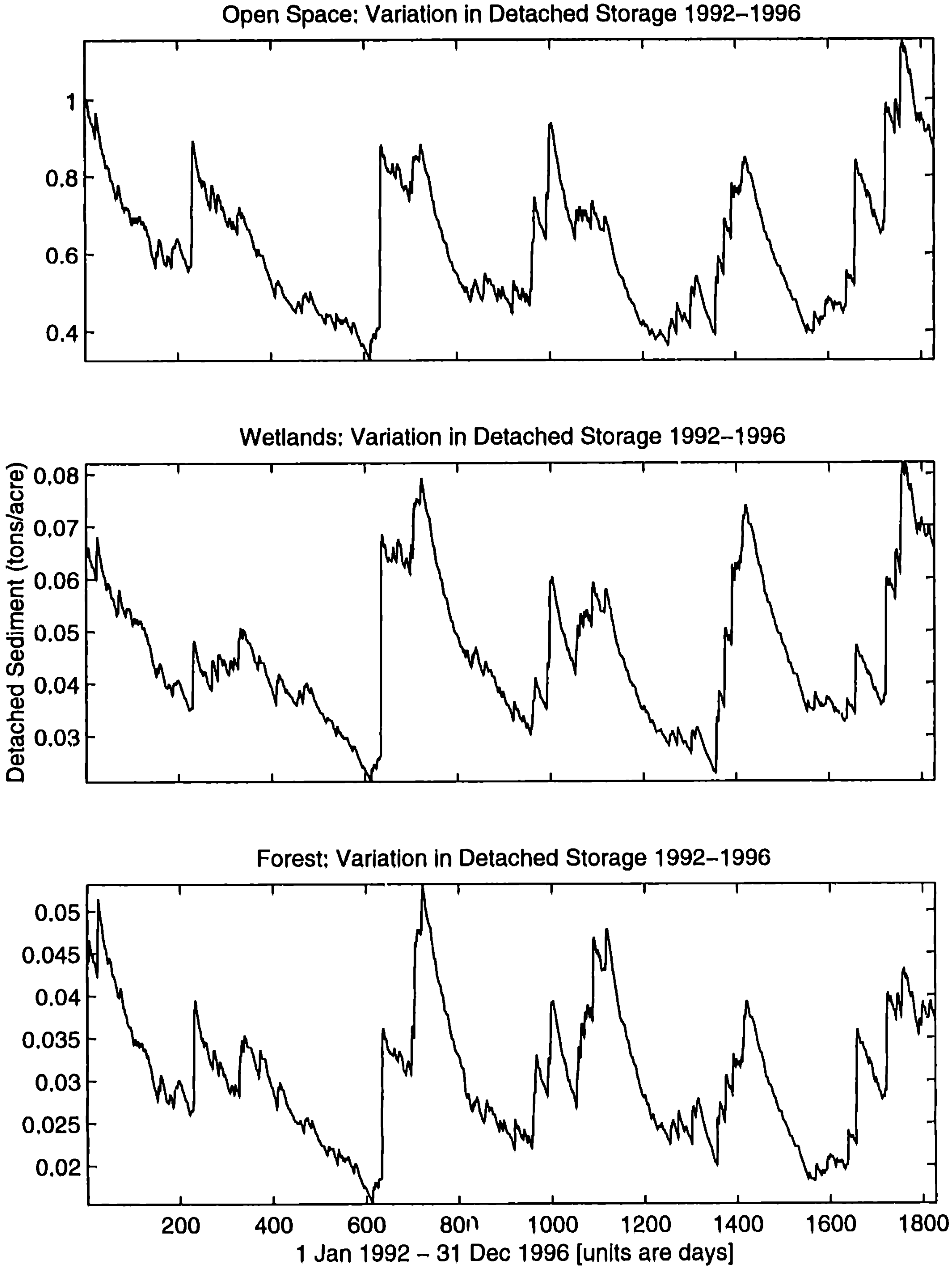


Figure 4-6: Detached sediment over a five year period: Open space, wetlands and forest

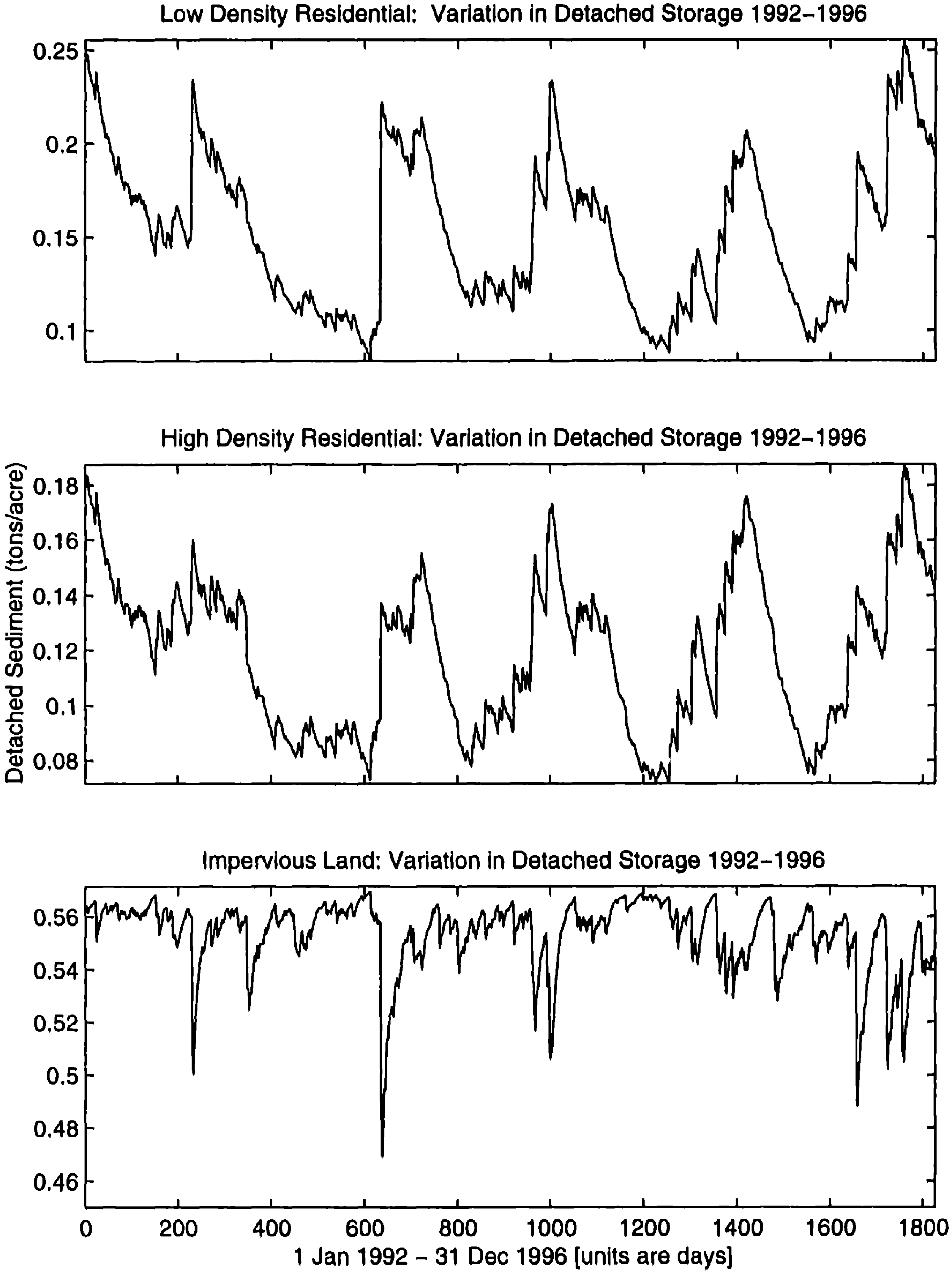


Figure 4-7: Detached sediment/solids over a five year period: Low density residential, high density residential and impervious land

4.5.2 Comparison With M&E/MWRA Data

The environmental consulting firm Metcalf & Eddy (M&E) produced a 1994 technical report for the Massachusetts Water Resources Authority (MWRA) entitled *Sub-Task 2.5.5: Final Technical Memorandum Estimation of Stormwater Flows and Loads* [32]. The report estimated stormwater flows and pollutant loads to a CSO study area. This study provides the only sediment load data that was available to calibrate the HSPF model. The study area includes a section of the Charles River Watershed from the Watertown Dam down to the end of the river. Most of the study area does not coincide with the Charles River Watershed. The report documents stormwater flows for four different storms in 1992 and 1993, and simulates pollutant loads for these storms. The pollutants included in the report are BOD, TSS, ammonia, nitrate and nitrite, TKN, phosphorus, copper, zinc and fecal coliform. Unlike our HSPF model, the M&E model assumed a constant concentration of each of these pollutants, and simply determined the pollutant load by multiplying the stormwater volume by the assumed concentration. In reality, of course, pollutant concentration varies widely between storms and is affected by the antecedent conditions as well as the storm characteristics.

The M&E/MWRA report included a discussion of a number of previous reports which had studied washoff of pollutants in stormwater in the Boston area. The report statistically analyzed five different sets of water quality data. The arithmetic mean of the pollutant concentrations from four of these five datasets was ultimately used by the M&E/MWRA report to calculate the load for each of the pollutants [32, p. 28]. Thus, based on these previous studies, the M&E/MWRA report selected a fixed concentration for TSS of 37.5 mg/L. Note that according to the M&E report, the standard deviation from the mean value is 63.1 mg/L, quite large in relation to the mean, and reported values range from 3 to 542 mg/L. (See Appendix Section E.1 for more detail about each of these studies.)

The M&E/MWRA report divided its watershed into fourteen "receiving water segments." Of these, only two segments (called "Upper Charles" and "Lower Charles") coincided with our Charles River Watershed. We overlaid a map of these two subwatersheds on top of our map of the Charles River Watershed in order to determine which of our reaches included the "Upper Charles" and "Lower Charles" segments. Some of our reaches were completely included in the M&E/MWRA subwatershed, and others were only partly included. Using this information, we divided these two M&E/MWRA segments into the six land uses. If, for example, 20% of a given HSPF reach was included in an M&E receiving water segment then it was assumed that the receiving water segment had 20% of the area of *each* of the six land uses. Tables E.2 and E.3 in Appendix Section E.2 explain how the land uses were determined for the "Upper Charles" and "Lower Charles" receiving water segments and Table E.4 shows the final division

It is important to divide the subwatersheds by land use, because HSPF outputs values for washoff of sediment and solids for each of the six land uses in units of tons/acre. Therefore, the value associated with each land use must be multiplied by the acreage of the land use in order to determine the total sediment (in tons) washed off the land. Similarly, the value for the surface water outflow is given per land use in units of inches. In order to determine the total volume of surface water leaving the land, we need to multiply the value associated with each land use by the total acreage of that land use.

Once the total acreage for each land use was determined, the values for stormwater volume and TSS load were compared with the M&E/MWRA report. Table 4.6 summarizes these results. The hydrology was calibrated such that the stormwater volume that HSPF generated was extremely close to the values reported by M&E. The sediment load predictions fit extremely well for one of the four storms. The HSPF predictions for TSS load were lower than those reported in one case and were higher in two cases. However, as mentioned above, the M&E/MWRA report did not measure TSS load; rather, it assumed a constant concentration of 37.5 mg/L. HSPF, on the other hand, simulates buildup and washoff of sediment and solids on the land, and will take the antecedent and storm conditions into account. Moreover, the selected concentration of 37.5 mg/L is a highly variable value. As mentioned above, the standard deviation for that value is 63.1 mg/L, and reported TSS values range from 3 to 542 mg/L. The TSS concentrations in the stormwater from the HSPF runs ranged from 21 mg/L in the November 1982 storm to 73 mg/L in the November 1993 storm, as shown in Table 4.7.

There are other reasons for the discrepancy between the the Charles River model results and the M&E/MWRA report. As can be seen from Table 4.8, the storm conditions simulated by HSPF are not the same as those used by the M&E model; total rainfall during the storm do not agree. Given the fact that HSPF is obviously using slightly different meteorological data than the M&E report, the final results can not be expected to coincide precisely.

Although we acknowledge the reasons for the differences between the HSPF model and M&E's model, the results predicted by HSPF are within the same order of magnitude of those reported by the M&E/MWRA report. Given this comparison between the M&E study and our models results, we can feel confident that the sediment calibration of our Charles River Watershed model provides reasonable results. Note that we are not assuming that the M&E model is more accurate than the HSPF model; we are using the model only as a basis for comparison. Had the order of magnitude between the models' results differed, then an explanation would have been required.

4.5.3 Annual Washoff of Sediment

The literature includes published values of sediment loads off of various land uses. Table 4.9 lists the total sediment load by land use off of the Charles River Watershed into the river (*WSSD*) for the years 1992–1996, as predicted by HSPF. Also included in the table is the total precipitation for each year.

The data in Table 4.9 allows for some interesting observations. Although the total amount of rainfall will have an effect on the total load, the placement and intensity of the storms can have a more important effect. Years with more rainfall do not always translate into years with a larger sediment load.

For comparison with the literature, we summarize the data in Table 4.9 into one average value for each land use. These average values are presented in Table 4.10.

	Stormwater Volume (MG)				TSS Load (lbs)			
	"Upper Charles"		"Lower Charles"		"Upper Charles"		"Lower Charles"	
Storm	HSPF	M&E	HSPF	M&E	HSPF	M&E	HSPF	M&E
3-6 Nov 1992	66	80.75	39	45.23	11,590	25,274	6,772	14,157
26-27 Sep 1993	116	117.68	68	65.39	68,161	36,831	39,757	20,466
30 Oct-1 Nov 1993	122	121.19	71	66.77	32,678	37,929	19,057	20,897
28 Nov 1993	73	74.49	42	41.90	44,509	23,312	25,474	13,113

Table 4.6: Comparison of HSPF results with M&E results for stormwater volume and TSS load

	HSPF Predicted Concentration (mg/L)	
Storm	"Upper Charles"	"Lower Charles"
3-6 Nov 1992	21.0	20.8
26-27 Sep 1993	70.3	70.0
30 Oct-1 Nov 1993	32.1	32.1
28 Nov 1993	73.0	72.6

Table 4.7: HSPF generated TSS concentration for the four M&E storms; these values compare with an M&E value of 37.45 mg/L and were determined from the results in Table 4.6.

	Rainfall (inches)	
Date	HSPF	M&E
3-6 Nov 1992	1.00	0.90
26-27 Sep 1993	1.67	0.73
30 Oct-1 Nov 1993	1.77	0.99
28 Nov 1993	0.88	0.95

Table 4.8: Comparison of HSPF precipitation data (measured at Logan Airport) with M&E reported values

Annual Sediment Loads to the Charles River By Land Use [tons/acre]

		Year					
	Land Use	1992	1993	1994	1995	1996	Oct 1996
1a	Open Space	0.0073	0.0107	0.0186	0.0158	0.1573	0.0558
	Wetlands	0.0002	0.0010	0.0010	0.0003	0.0257	0.0092
	Forest	0.0003	0.0007	0.0011	0.0005	0.0297	0.0048
	Low dens resid	0.0229	0.0200	0.0303	0.0266	0.1839	0.0732
	High dens resid	0.0425	0.0348	0.0712	0.0481	0.1639	0.0633
	Impervious	0.2695	0.2250	0.2760	0.2353	0.3766	0.0757
	Rain (inches)	47.96	45.99	50.33	41.09	58.76	8.34
1b	Open Space	0.0135	0.0011	0.0055	0.0013	0.0519	0.0381
	Wetlands	0.0007	0.0002	0.0005	0.0001	0.0090	0.0075
	Forest	0.0007	0.0002	0.0020	0.0001	0.0042	0.0033
	Low dens resid	0.0163	0.0031	0.0137	0.0025	0.0690	0.0282
	High dens resid	0.0863	0.0885	0.0783	0.0415	0.1678	0.0357
	Impervious	0.2512	0.2533	0.2842	0.2144	0.3841	0.0602
	Rain (inches)	47.21	45.11	49.92	39.19	57.23	7.76
1c	Open Space	0.0005	0.0046	0.0359	0.0060	0.1729	0.1621
	Wetlands	0.0001	0.0004	0.0095	0.0003	0.0524	0.0512
	Forest	0.0000	0.0003	0.0071	0.0001	0.0469	0.0463
	Low dens resid	0.0021	0.0095	0.0326	0.0116	0.1930	0.1676
	High dens resid	0.0326	0.0349	0.1370	0.1633	0.2705	0.1723
	Impervious	0.2492	0.1743	0.3242	0.2414	0.4481	0.1244
	Rain (inches)	46.05	43.13	51.71	36.61	57.30	7.33
2	Open Space	0.0003	0.0032	0.0005	0.0031	0.2585	0.2335
	Wetlands	0.0000	0.0003	0.0000	0.0001	0.0767	0.0744
	Forest	0.0000	0.0001	0.0001	0.0000	0.0493	0.0482
	Low dens resid	0.0008	0.0046	0.0017	0.0062	0.1781	0.1384
	High dens resid	0.0337	0.0159	0.1007	0.0523	0.2212	0.1186
	Impervious	0.2326	0.1462	0.2626	0.1735	0.3853	0.1139
	Rain (inches)	46.12	40.29	46.87	35.81	58.26	9.29
3	Open Space	0.0412	0.0131	0.0186	0.0056	0.3974	0.0701
	Wetlands	0.0049	0.0012	0.0015	0.0007	0.0700	0.0099
	Forest	0.0015	0.0005	0.0004	0.0001	0.0333	0.0021
	Low dens resid	0.0549	0.0136	0.0257	0.0128	0.2426	0.0492
	High dens resid	0.1695	0.0584	0.1458	0.0897	0.2944	0.0753
	Impervious	0.3085	0.2304	0.3554	0.2097	0.3609	0.0974
	Rain (inches)	43.72	43.21	47.62	35.10	53.805	10.15

Table 4.9: HSPF simulated sediment loads: 1992-1996 (October 1996 is included as an unusually stormy month.) 1a = Top of the Upper CRW; 1b = Middle of the Upper CRW; 1c = Bottom of the Upper CRW; 2 = Central CRW; 3 = Lower CRW.

Average Annual Sediment Loads to the Charles River 1992–1995			
	Average Annual Sediment Removal		
Land Use	tons/acre	lbs/acre	kg/hectare
Open space	0.01032	20.6	23.1
Wetlands	0.00115	2.3	2.6
Forest	0.00079	1.6	1.8
Low dens resid	0.01558	31.2	34.9
High dens resid	0.07625	152.5	170.9
Impervious	0.24585	491.7	550.9

Table 4.10: HSPF simulated average annual sediment loads by land use (Summary of Table 4.9)

Typical Annual Surface Loads of TSS	
Land Use	TSS (lbs/acre)
Low density residential	310
High density residential	290
Industrial	540
Parks, open space	9

Table 4.11: Typical annual TSS surface loads (Source: [34, p. 278]; from PLUARG studies by Marsalek, 1978)

We can compare our annual TSS loads to the literature. For example, typical annual surface loads reported in one stormwater text book are given in Table 4.11. Our HSPF predicted values are a bit lower than their values, and in some cases are one order of magnitude lower. Part of the reason for this may be due to differing definitions of the land use descriptions.

Expected Erosion Rates

AQUA TERRA Consultants, in their 1998 training documentation, provided a chart of "Typical Ranges of Expected Erosion Rates" to help HSPF modelers calibrate the sediment washoff of the land [1]. These erosion rates are estimated by the Universal Soil Loss Equation. The total erosion rate includes sediment that reattaches to the soil in addition to sediment that washes off the land. In order to relate these erosion rates to HSPF's predicted sediment washoff, we use a "delivery ratio," defined as the ratio between the sediment that washes off the land and the erosion rate, or the "percent of gross erosion" [1]. AQUA TERRA also provides a graph of "Sediment Delivery Ratio vs. Size of Drainage," reproduced from the Natural Resources Conservation Service. This log-log graph plots drainage area on the x-axis versus delivery ratio on the y-axis. Different curves on the graph represent different grain sizes. The larger the sediment size, the lower the delivery ratio, and the larger the watershed area the lower the delivery ratio.

Using the "Sediment Delivery Ratio vs. Size of Drainage" graph, and using the curve that represented the median for all grain sizes, we found a delivery ratio of approximately 6.5% for a 300 square mile drainage area.

The AQUA TERRA chart of typical ranges of erosion rates is reproduced in the first column of Table 4.12. The second column converts erosion rates to sediment washoff, using a delivery ratio of 6.5%. When we compare these values to the HSPF-predicted annual sediment washoff data (in Table 4.10) we see that HSPF predictions for various land uses align with the AQUA TERRA guidance. The HSPF prediction for sediment removal from forest land is low compared with AQUA TERRA, but if we compare our "open space" land use with the "pasture" land use in Table 4.12, we find relative agreement. Likewise, our "low density residential" and "high density residential" compare well with the "urban" category in Table 4.12. (Note that the impervious land category in HSPF yields much higher sediment removal per acre.)

4.5.4 NURP Data

One way to check whether our sediment washoff values are reasonable is to compare them with published data based on land use. The Nationwide Urban Runoff Program (NURP), which published its results in 1983, monitored runoff and stormwater pollution in cities throughout the United States. (For more information about NURP,

Typical Erosion Rates and Sediment Removal [tons/acre]		
	Typical Erosion Rates	Sediment Removal
Forest	0.05 - 0.4	0.00325 - 0.026
Pasture	0.3 - 1.5	0.0195 - 0.0975
Conventional Tillage	1.0 - 7.0	0.065 - 0.455
Conservation Tillage	0.5 - 4.0	0.0325 - 0.26
Hay	0.3 - 1.8	0.0195 - 0.117
Urban	0.2 - 1.0	0.013 - 0.065
Highly Erodible Land	> 15.0	> 0.975

Table 4.12: Typical ranges for erosion rates (provided by AQUA TERRA Consultants and sediment removal (using a delivery ratio of 6.5%). Note that there is little agricultural land in the Charles River Watershed; the agricultural land use data is included here only for completeness.

refer to Appendix B.)

NURP reported a wide range of results, and comparing our results with the NURP median or average results from sites and storms across the country proved to be difficult. Nevertheless, we used the NURP results as a indicator of whether the HSPF results are reasonable.

TSS Loads

For the most part, the NURP documentation reports the estimated mean concentrations (EMCs) of pollutants rather than the total pollutant loads, since the latter is much more dependent on the size of the storm, and therefore is not as useful for planners. However, NURP did publish a table of annual urban runoff loads, for watersheds with an average of 40 inches of rain per year. The TSS loads are shown in Table 4.13. In theory, the HSPF impervious land use category should correspond with the "Commercial" category of NURP, which has a runoff coefficient (defined as the runoff volume divided by the rainfall volume) of 0.8. It seems that the HSPF predictions for high density residential land and impervious land are a bit lower that the

Annual Urban Runoff Loads (kg/ha/yr)			
Site Mean Conc (mg/L)	Residential	Commercial	All Urban
180	550	1460	640

Table 4.13: Annual urban runoff loads as reported by NURP (Source: [51, p.6-64]). The assumed runoff coefficients are 0.3 for "Residential", 0.8 for "Commercial", and 0.35 for "All Urban"

Median Estimated Mean Concentration for All Sites TSS (mg/L)							
Residential		Mixed Uses		Commercial		Open/Non-urban	
Median	CV	Median	CV	Median	CV	Median	CV
101	0.96	67	1.14	69	0.85	70	2.92

Table 4.14: Median EMCs for TSS for all sites by land use category (Source: [51, p.6-31])

reported NURP data. However, the site mean concentration for TSS is given as 180 mg/L, which is higher than HSPF predicts, as can be seen in Table 4.16, presented in the next section.

Estimated Mean Concentrations

As mentioned above, most of the NURP report documents estimated mean concentrations (EMCs) of the monitored pollutants. Table 4.14, taken from the NURP report, summarizes the median EMCs for TSS for all sites in the program. (See Table B.2 for EMCs of all of the monitored pollutants.)

The results reported in the table are the median EMCs; when we examine the individual TSS concentrations at specific sites we find wide variation between sites and even between different sampling days at the same site.

In order to grossly evaluate the HSPF prediction for TSS concentration in stormwater, we calculated an "average" concentration per land use by summing up all of the sediment washed off the land in a given year, and dividing it by the water volume that ran off the land use in that year. As expected, the results vary widely from land use to land use and from year to year. The results are reported below in Table 4.15.

Table 4.16 averages the results reported in Table 4.15 over a four year period 1992-1995.

For a more specific depiction of how TSS concentration in stormwater varies over the year, during individual storms, see Figures 4-8 through 4-13. These are plots for the top part of the Upper Charles River Watershed, over the year 1993. To focus on a specific storm, we include Figures 4-14 through 4-19 for the month of October, 1996, during which there were two heavy storms.

4.5.5 Calibration Issues

There are a numbers of issues that must be taken into account when examining the model's output of sediment concentration into the river due to surface runoff. Since concentration is defined as the mass of solids washed off divided by the volume of water washing off, the concentration will become huge if the flow drops close to zero. This possibility must be taken into account when examining the data.

In addition, problems with the sediment data may occur because the hourly data in the upper and middle watersheds are not accurate. The precipitation gages in these subwatersheds report only daily rainfall. Since HSPF runs on an hourly timestep, these daily precipitation values needed to be divided into hourly rainfall. In order to do this, Socolofsky and Munson developed a precipitation disaggregation scheme which separated the daily rainfall into hourly rainfall [35], [43]. As a result, the hourly rainfall that HSPF uses to model surface runoff and sediment washoff is not the true rainfall. In order to compensate for this problem, we examined TSS concentrations in stormwater runoff on a daily, not hourly basis.

Despite this, inaccurate hourly data will have an effect. Consider, for example, the precipitation data for a storm on September 26, 1993, when there was 1.56" of rain in the central UCRW (the middle section of the Upper Charles River Watershed). This was disaggregated by the precipitation disaggregation program to 1.55" of rain during one hour of the day, and 0.01" of rain at some other point during the day. During that one hour, the runoff and sediment washoff on both high density residential land

Average TSS Concentration in Stormwater By Land Use [mg/L]

		Year				
	Land Use	1992	1993	1994	1995	1996
1a	Open Space	174.68	152.06	195.98	240.90	513.95
	Wetlands	20.45	36.88	38.16	25.73	186.32
	Forest	32.94	38.39	52.32	44.98	226.23
	Low dens resid	180.65	111.92	134.46	177.58	334.21
	High dens resid	135.83	86.58	126.82	131.94	176.88
	Impervious	49.19	41.70	46.61	49.96	52.11
	Rain (inches)	47.96	45.99	50.33	41.09	58.76
1b	Open Space	304.50	49.40	122.69	70.38	381.44
	Wetlands	49.33	15.33	25.53	15.49	136.80
	Forest	48.32	18.42	93.92	13.36	109.78
	Low dens resid	165.71	46.72	117.37	58.42	240.15
	High dens resid	201.64	247.43	151.33	126.49	197.59
	Impervious	45.87	48.52	47.28	48.59	53.67
	Rain (inches)	47.21	45.11	49.92	39.19	57.23
1c	Open Space	44.24	109.77	363.82	178.96	823.91
	Wetlands	9.72	25.73	174.74	29.34	414.26
	Forest	5.59	26.03	192.42	28.56	473.86
	Low dens resid	60.69	87.38	189.53	148.28	490.36
	High dens resid	117.41	92.69	197.23	410.59	287.63
	Impervious	47.23	34.38	52.19	58.60	62.21
	Rain (inches)	46.05	43.13	51.71	36.61	57.30
2	Open Space	35.48	120.32	35.77	169.07	872.64
	Wetlands	6.20	24.65	7.08	23.00	416.72
	Forest	1.97	19.22	16.24	4.46	344.94
	Low dens resid	34.86	71.21	40.01	141.99	383.82
	High dens resid	129.20	64.45	249.72	179.78	214.35
	Impervious	43.65	31.43	46.48	43.24	53.95
	Rain (inches)	46.12	40.29	46.87	35.81	58.26
3	Open Space	412.04	267.29	281.79	216.78	1074.66
	Wetlands	123.05	55.92	53.17	61.33	324.73
	Forest	105.26	50.29	41.28	29.08	302.47
	Low dens resid	278.66	121.88	161.01	169.46	465.71
	High dens resid	268.66	129.20	196.59	201.10	249.12
	Impervious	61.99	46.87	62.19	52.06	55.73
	Rain (inches)	43.72	43.21	47.62	35.10	53.805

Table 4.15: HSPF simulated annual TSS concentration in stormwater by land use: 1992-1996
1a = Top of the Upper CRW; 1b = Middle of the Upper CRW; 1c = Bottom of the Upper CRW; 2 = Central CRW; 3 = Lower CRW.

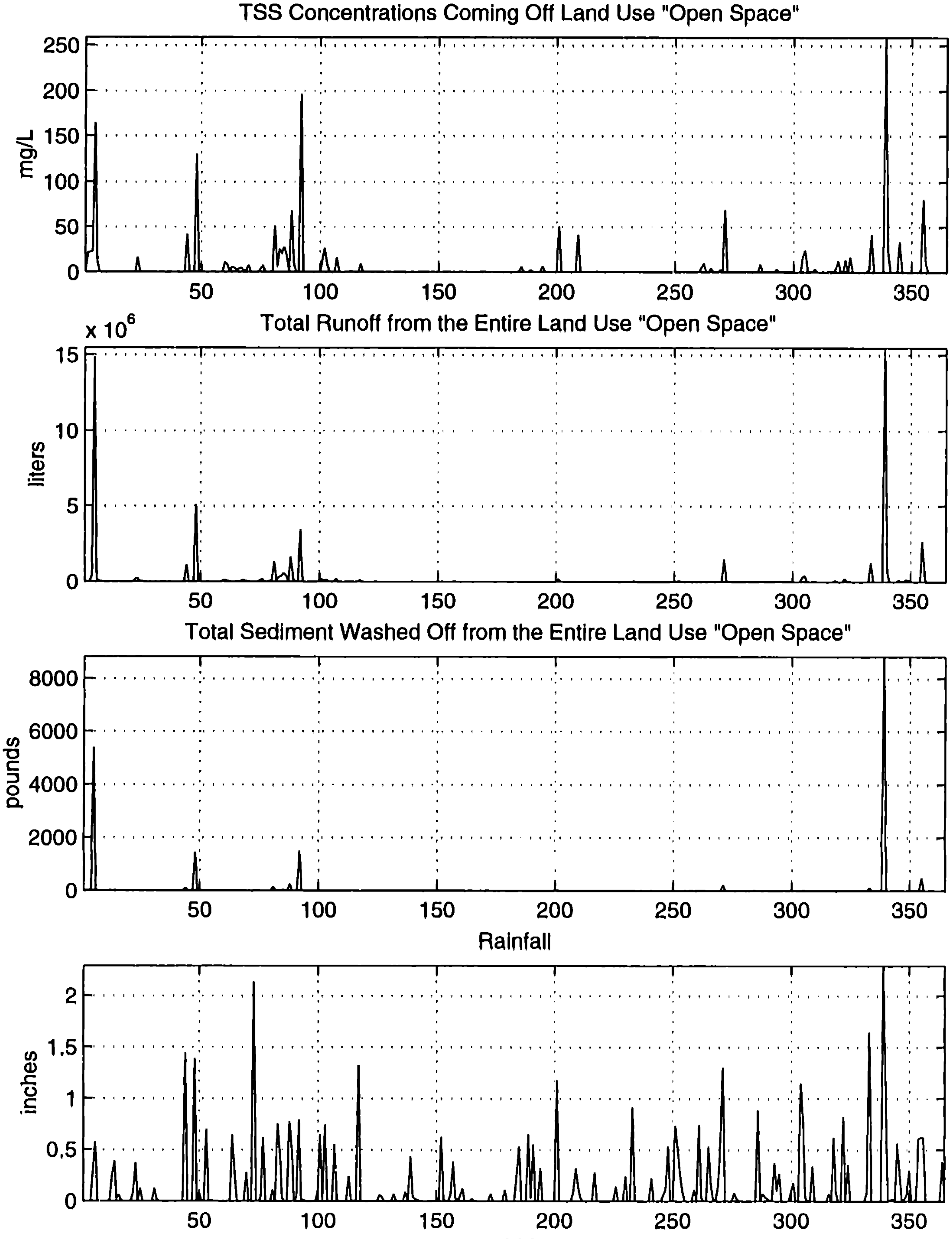
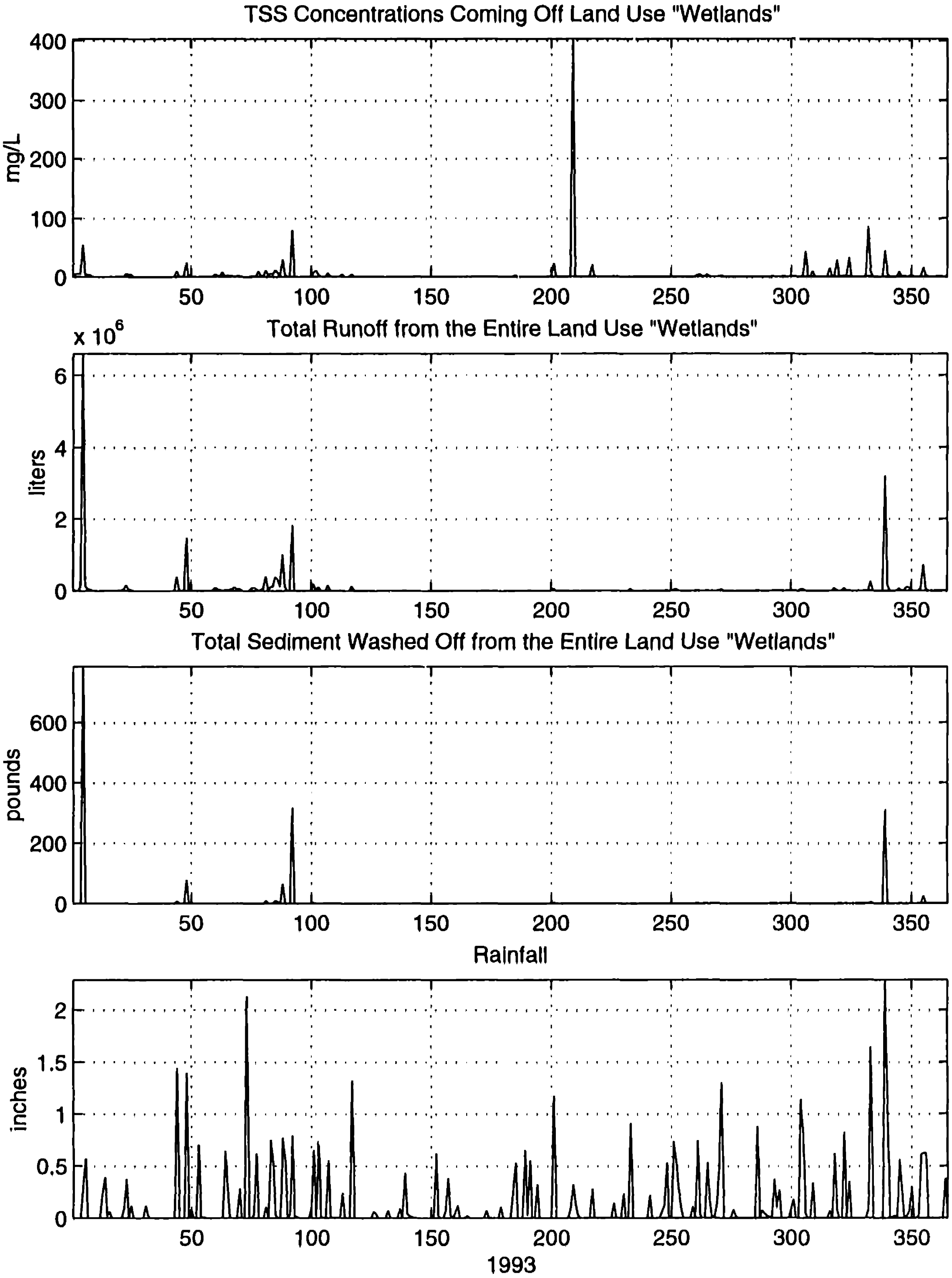


Figure 4-8: Open space: TSS concentration, runoff and sediment load over the year 1993. This is data from the upper part of the Upper Charles River watershed. The rainfall is the disaggregated precipitation for that portion of the watershed.


TSS Concentrations Coming Off Land Use "Wetlands"

Total Runoff from the Entire Land Use "Wetlands"

Total Sediment Washed Off from the Entire Land Use "Wetlands"

Rainfall

Figure 4-9: Wetlands: TSS concentration, runoff and sediment load over the year 1993. This is data from the upper part of the Upper Charles River watershed. The rainfall is the disaggregated precipitation for that portion of the watershed.

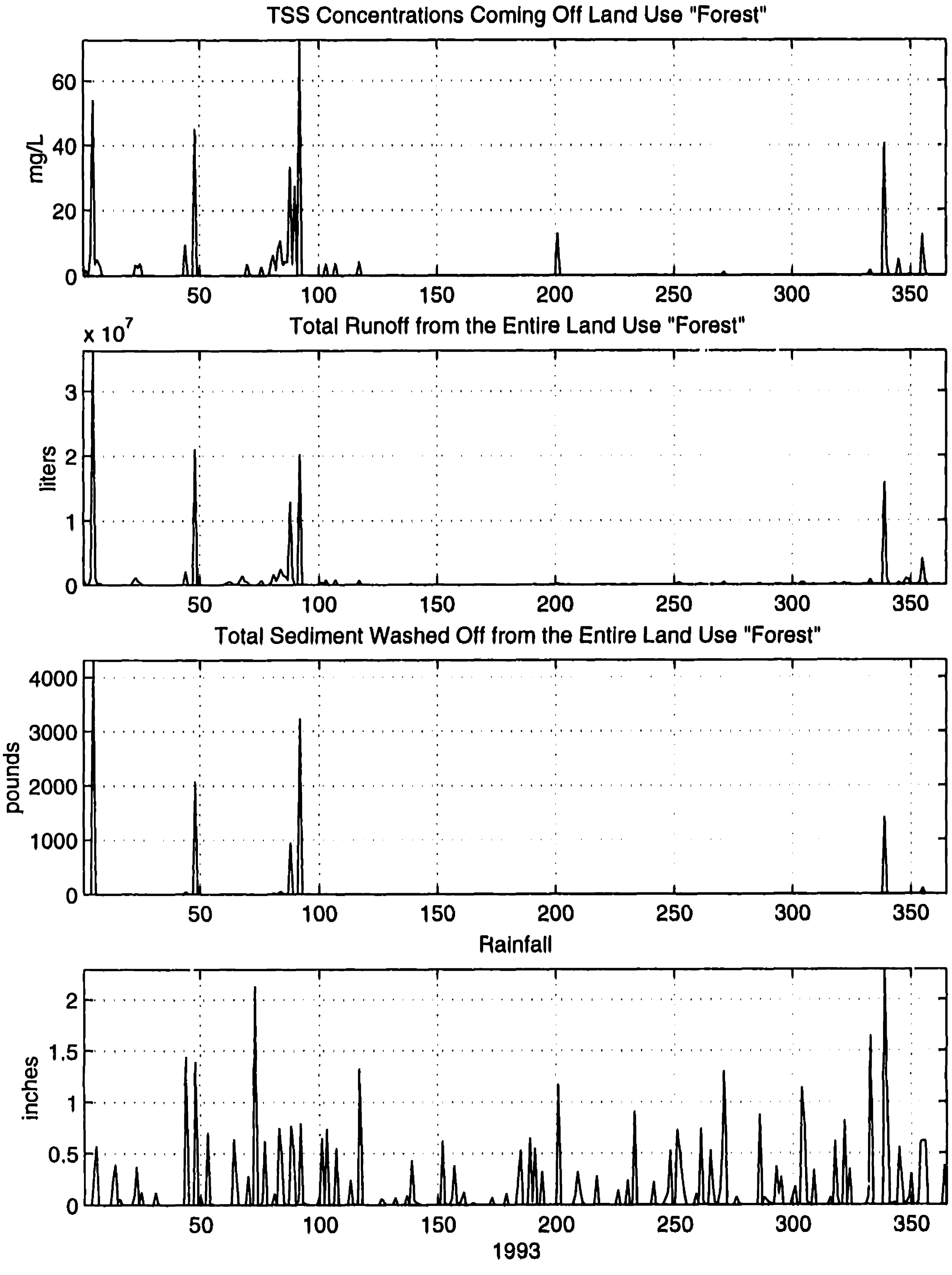


Figure 4-10: Forest: TSS concentration, runoff and sediment load over the year 1993. This is data from the upper part of the Upper Charles River watershed. The rainfall is the disaggregated precipitation for that portion of the watershed.

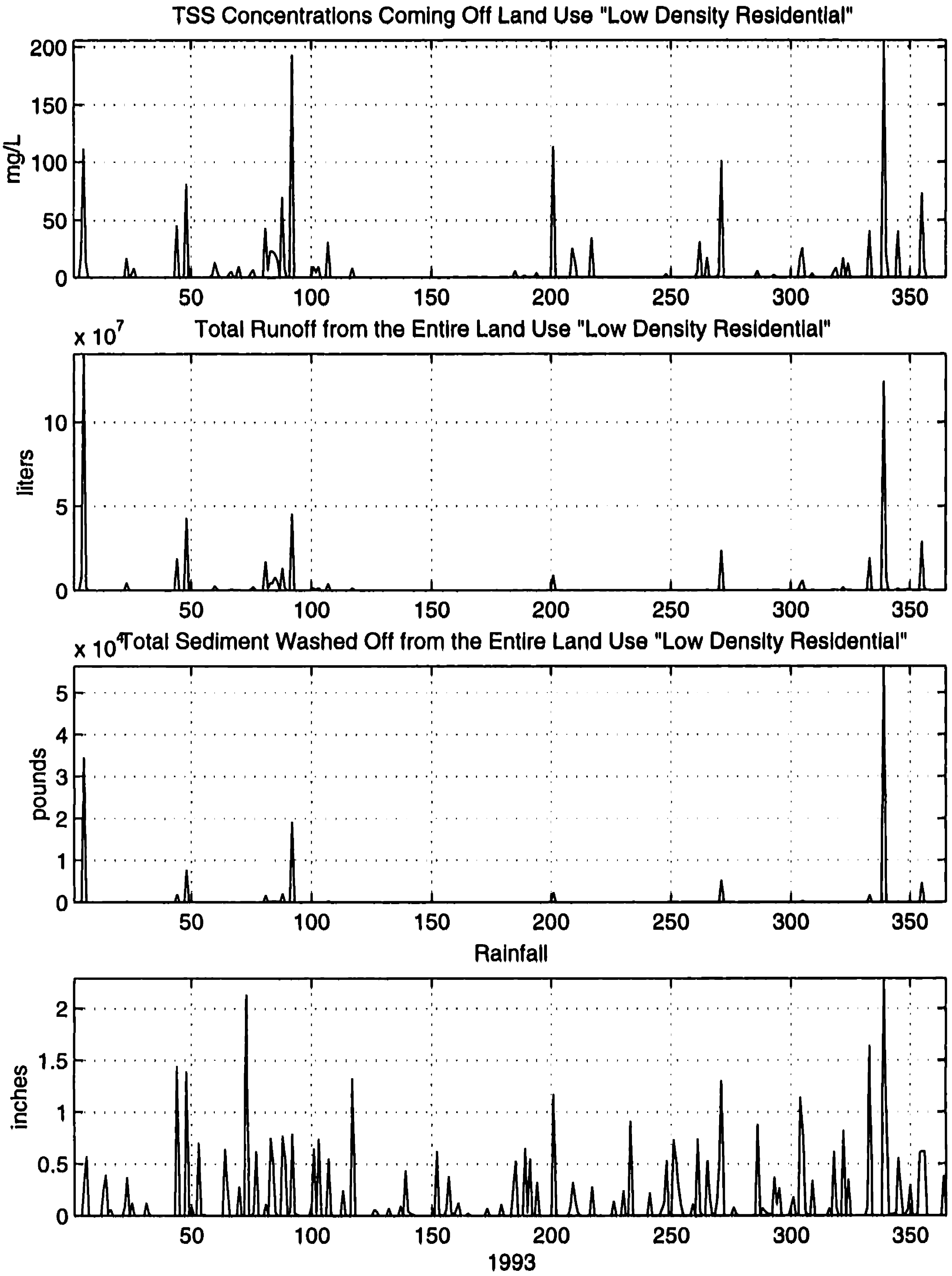
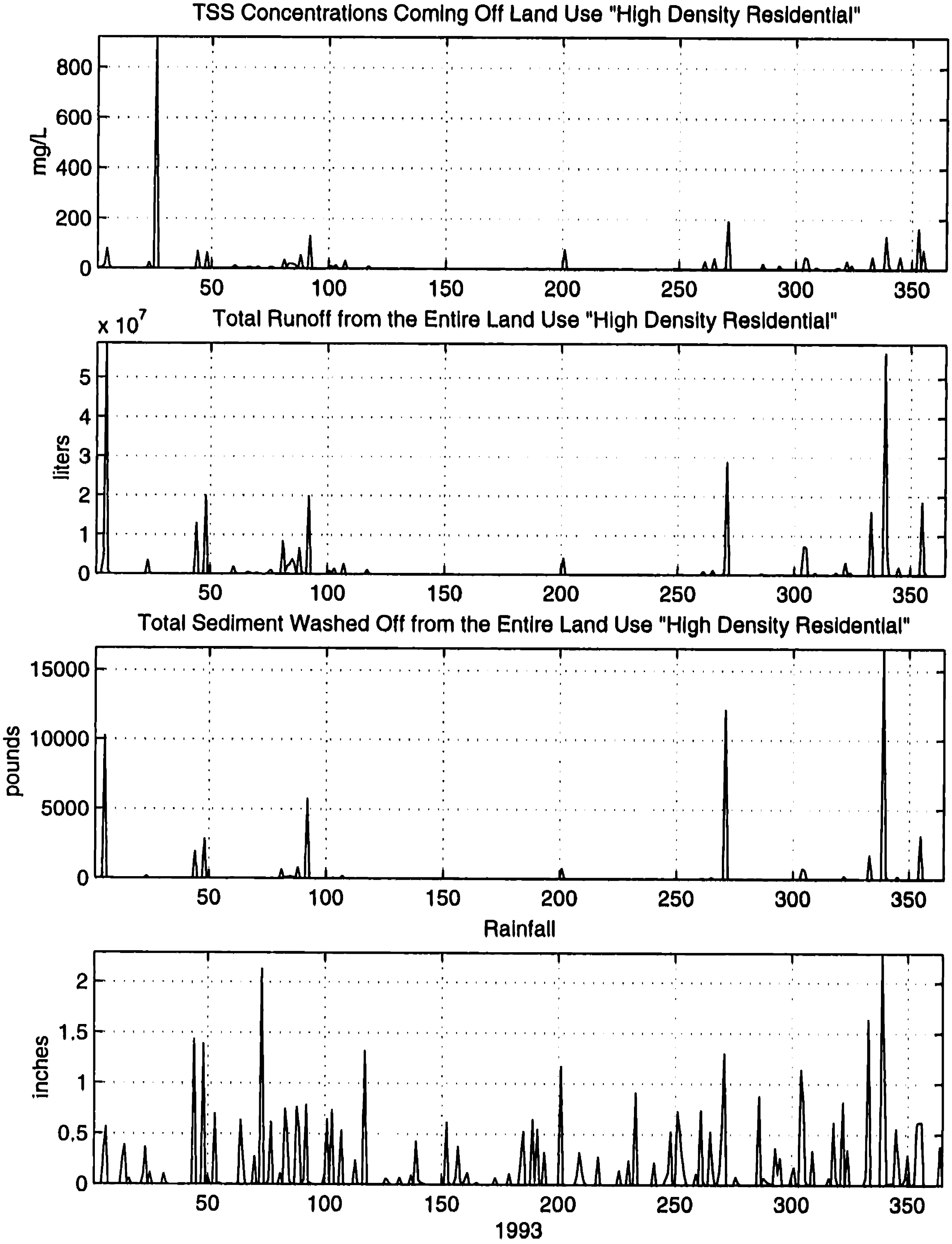


Figure 4-11: Low density residential: TSS concentration, runoff and sediment load over the year 1993. This is data from the upper part of the Upper Charles River watershed. The rainfall is the disaggregated precipitation for that portion of the watershed.


TSS Concentrations Coming Off Land Use "High Density Residential"

Total Runoff from the Entire Land Use "High Density Residential"

Total Sediment Washed Off from the Entire Land Use "High Density Residential"

Rainfall

Figure 4-12: High density residential: TSS concentration, runoff and sediment load over the year 1993. This is data from the upper part of the Upper Charles River watershed. The rainfall is the disaggregated precipitation for that portion of the watershed.

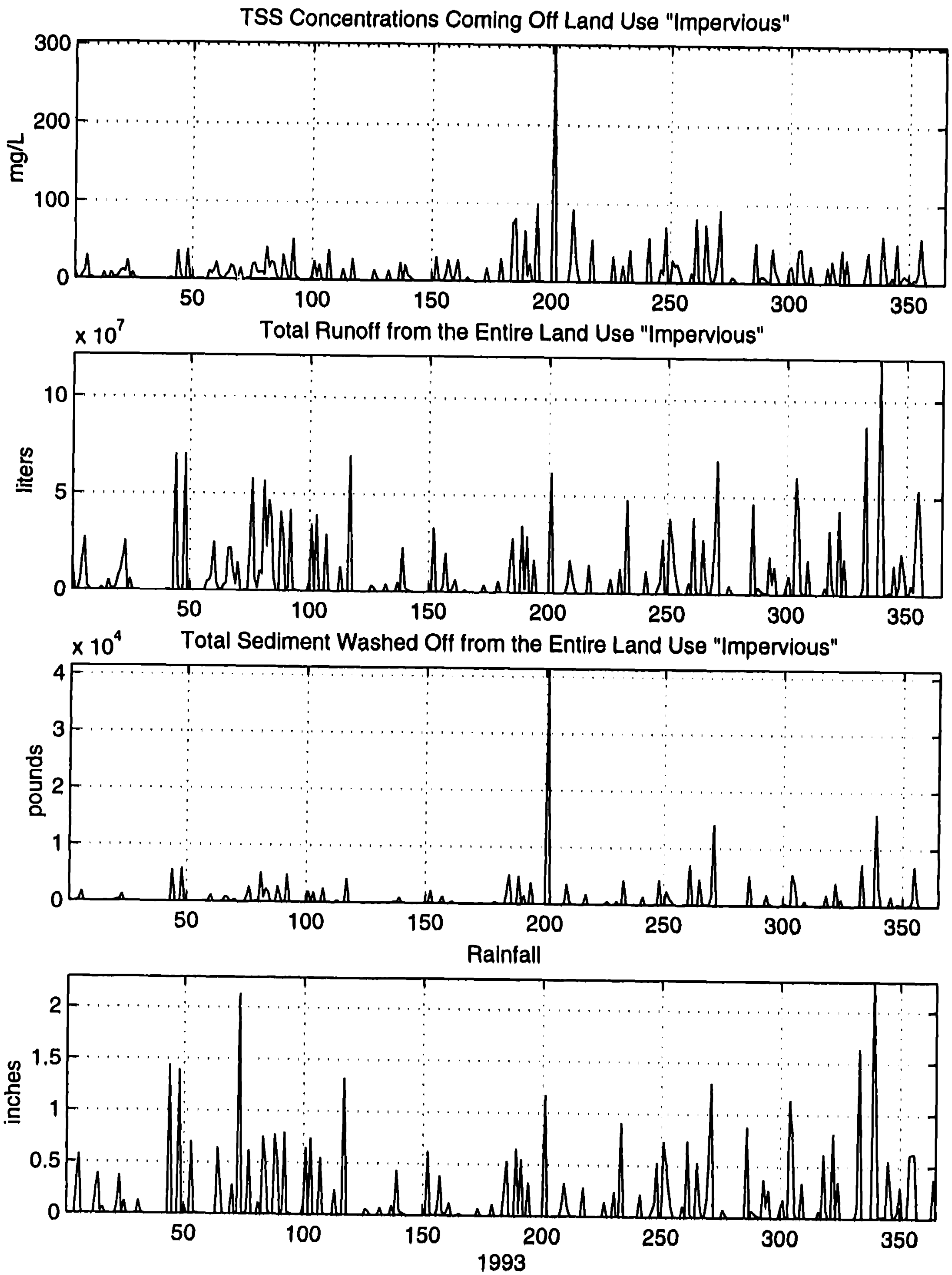


Figure 4-13: Impervious land: TSS concentration, runoff and sediment load over the year 1993. This is data from the upper part of the Upper Charles River watershed. The rainfall is the disaggregated precipitation for that portion of the watershed.

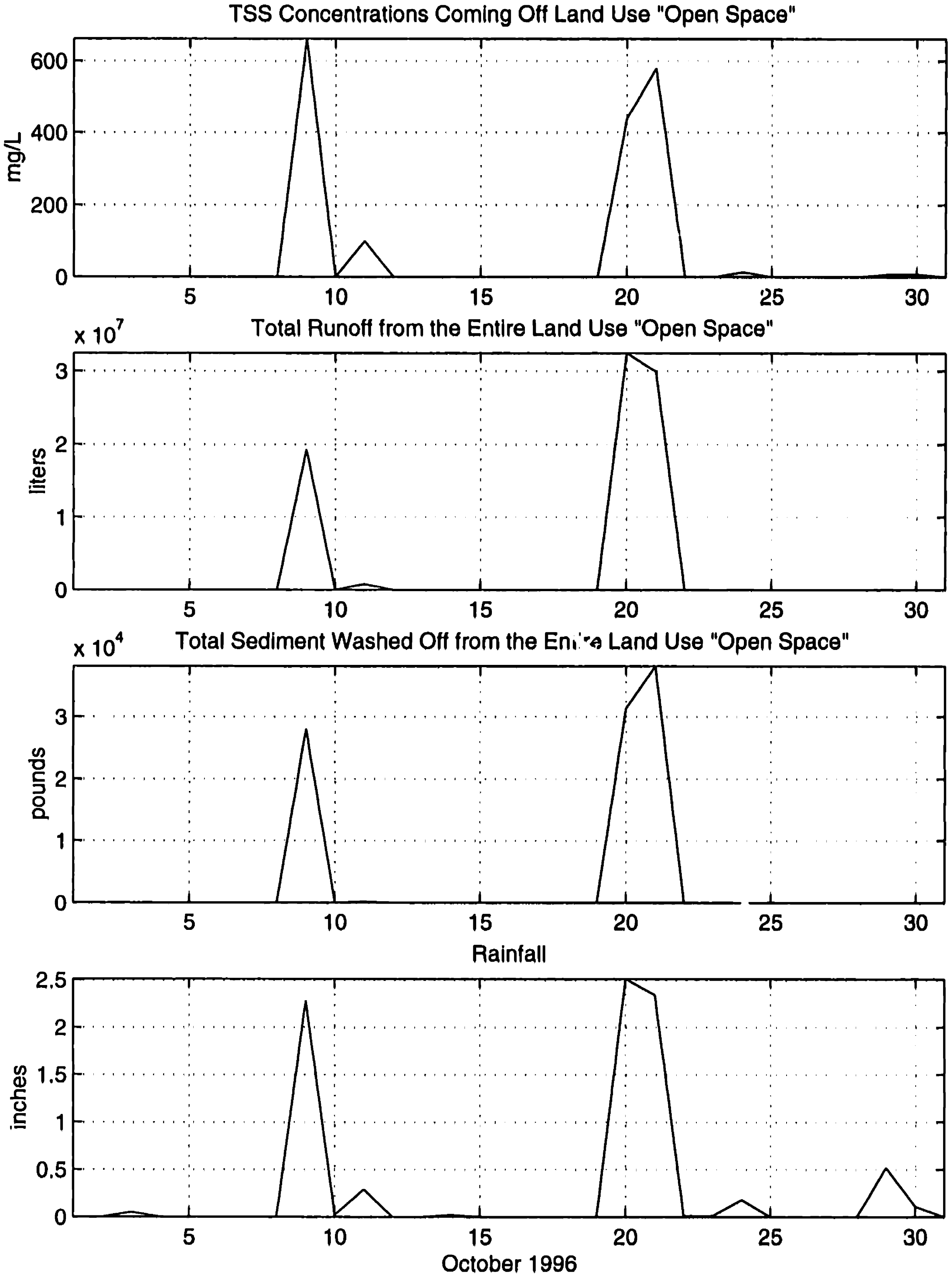
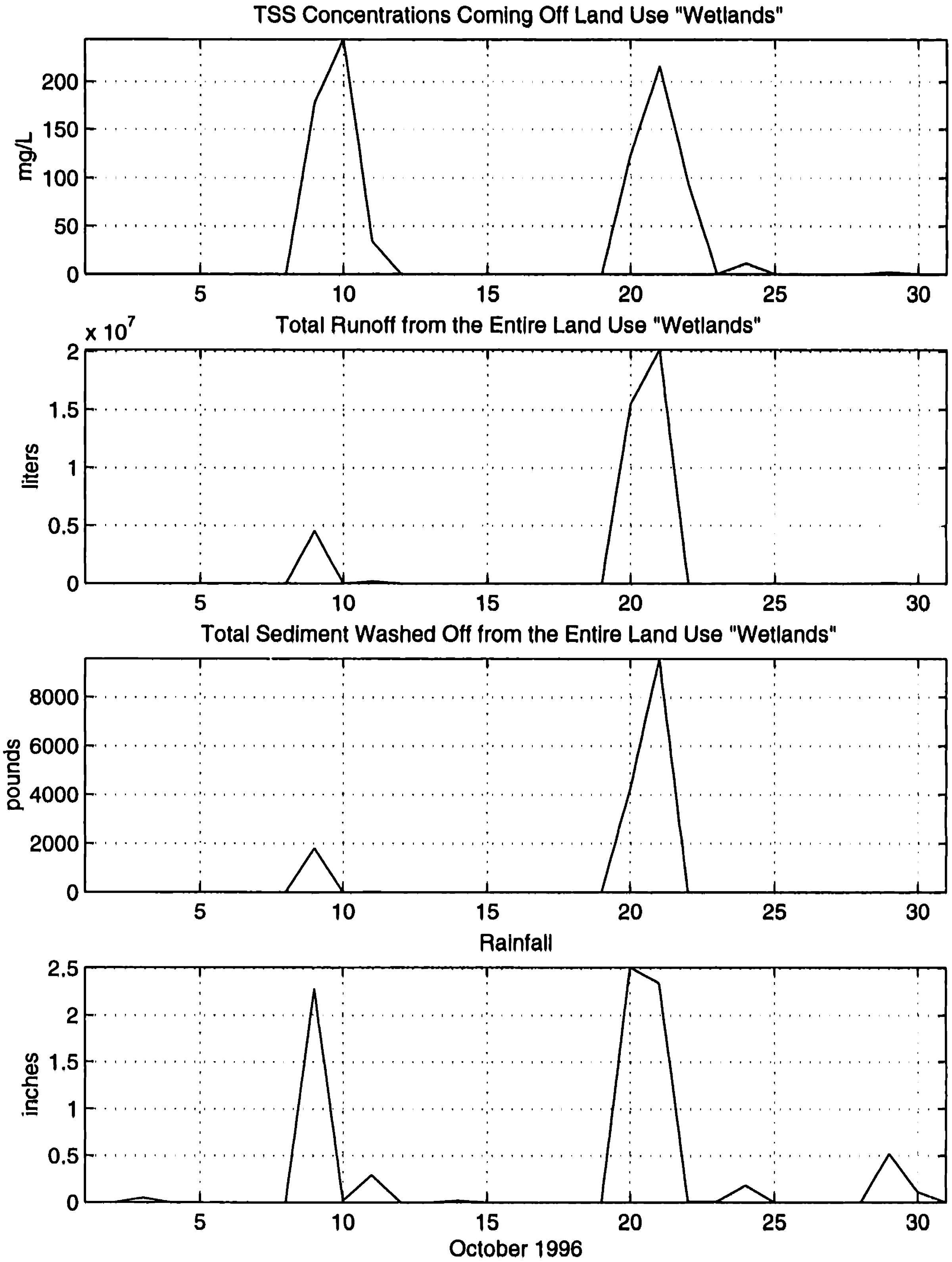


Figure 4-14: Open space: TSS concentration, runoff and sediment load in October 1996. This is data from the upper part of the Upper Charles River watershed. The rainfall is the disaggregated precipitation for that portion of the watershed.


TSS Concentrations Coming Off Land Use "Wetlands"

Total Runoff from the Entire Land Use "Wetlands"

Total Sediment Washed Off from the Entire Land Use "Wetlands"

Rainfall

Figure 4-15: Wetlands: TSS concentration, runoff and sediment load in October 1996. This is data from the upper part of the Upper Charles River watershed. The rainfall is the disaggregated precipitation for that portion of the watershed.

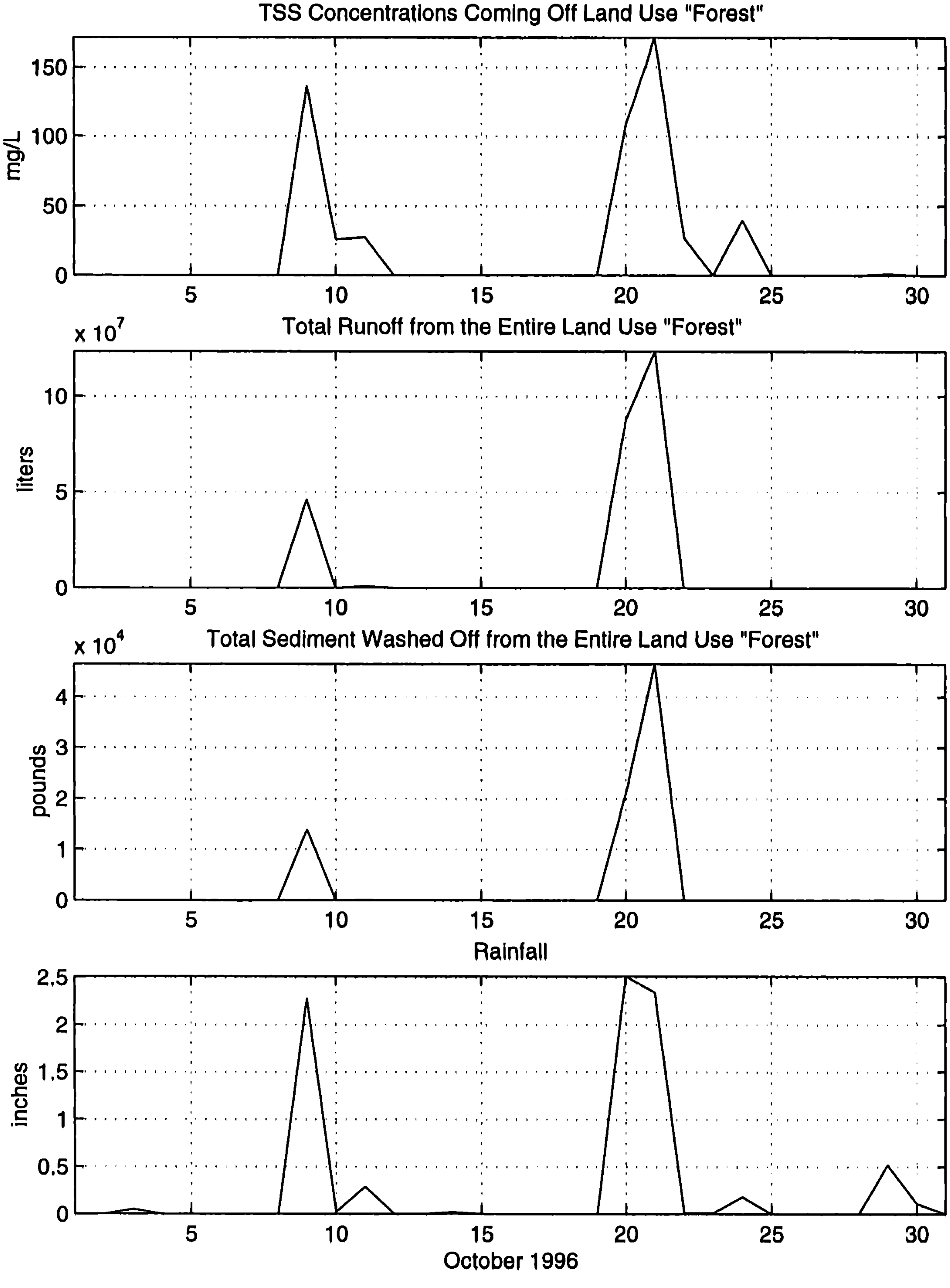


Figure 4-16: Forest: TSS concentration, runoff and sediment load in October 1996. This is data from the upper part of the Upper Charles River watershed. The rainfall is the disaggregated precipitation for that portion of the watershed.

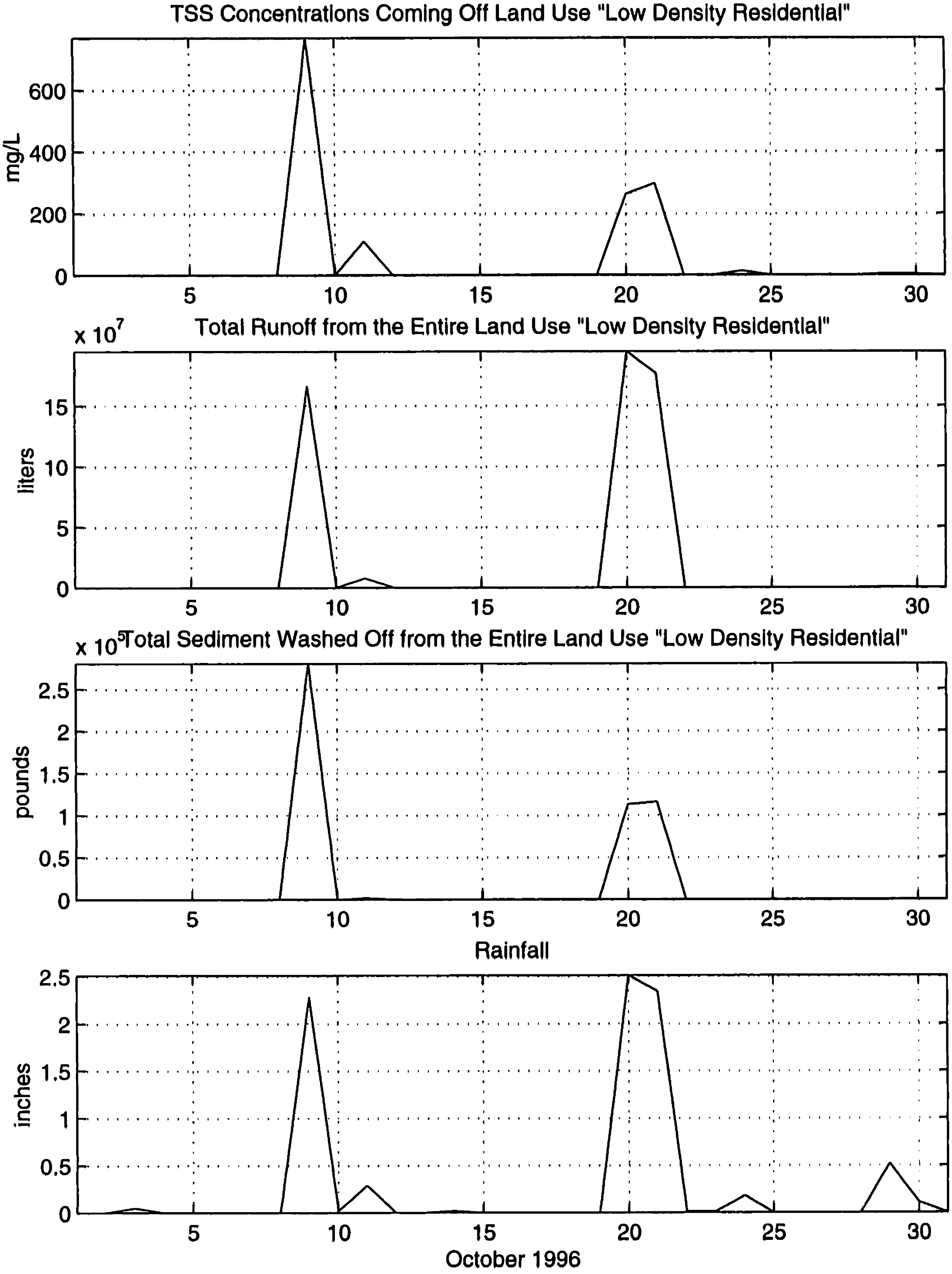


Figure 4-17: Low density residential: TSS concentration, runoff and sediment load in October 1996. This is data from the upper part of the Upper Charles River watershed. The rainfall is the disaggregated precipitation for that portion of the watershed.

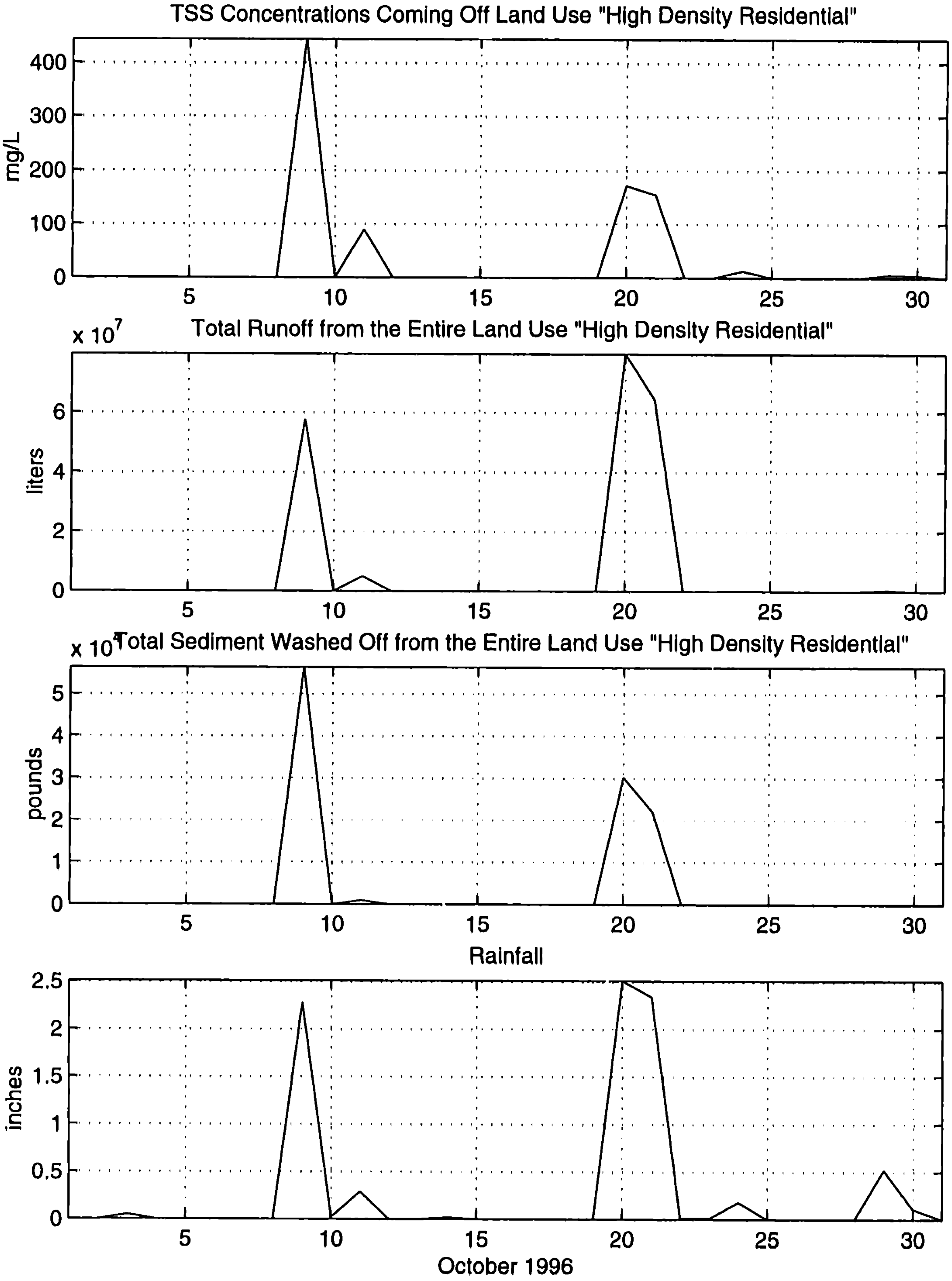


Figure 4-18: High density residential: TSS concentration, runoff and sediment load in October 1996. This is data from the upper part of the Upper Charles River watershed. The rainfall is the disaggregated precipitation for that portion of the watershed.

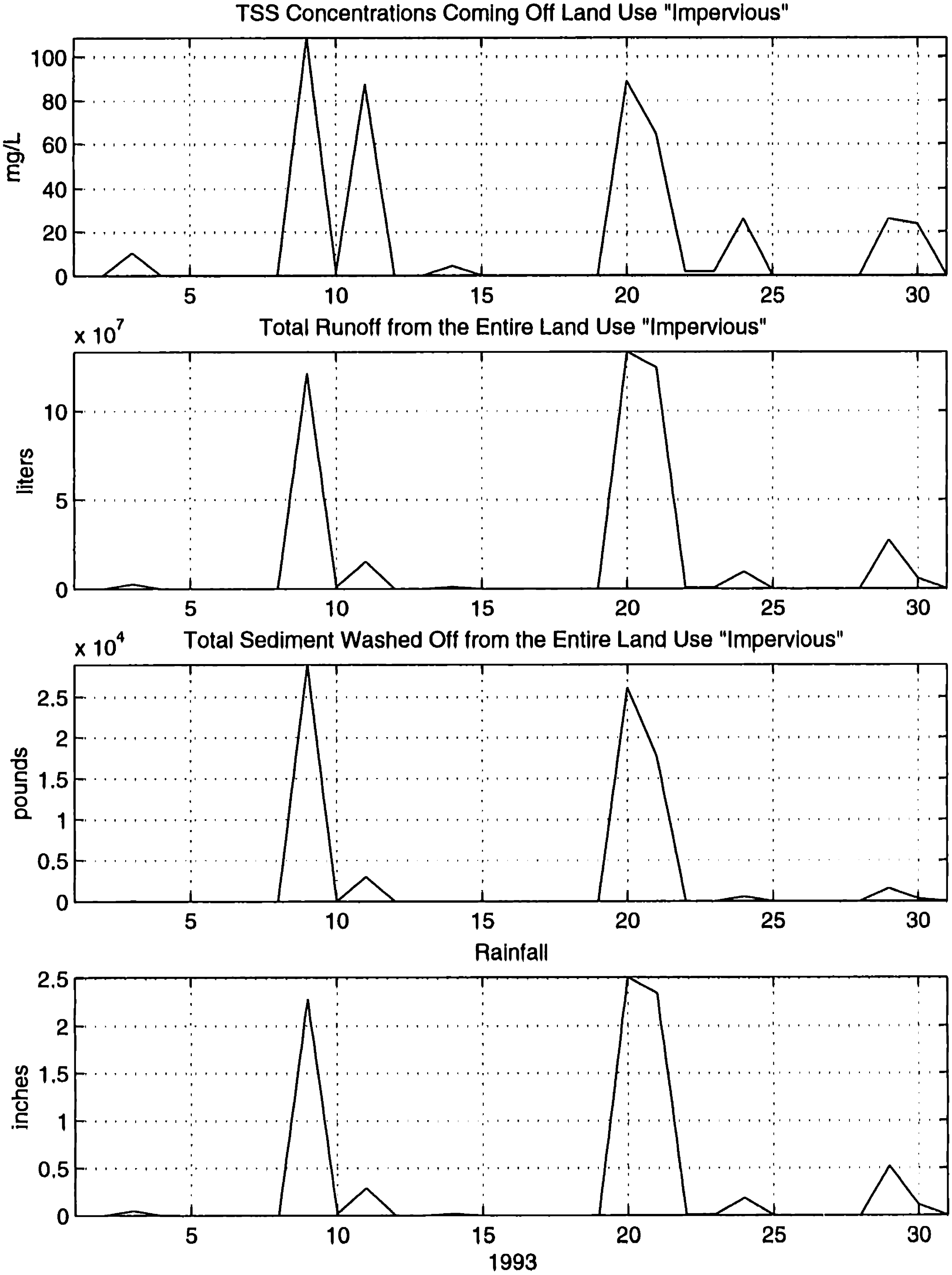


Figure 4-19: Impervious land: TSS concentration, runoff and sediment load in October 1996. This is data from the upper part of the Upper Charles River watershed. The rainfall is the disaggregated precipitation for that portion of the watershed.

Average TSS Concentration of Stormwater [mg/L] 1992-1996	
Land Use	Average TSS Concentration
Open space	177
Wetlands	33
Forest	35
Low dens resid	100
High dens resid	138
Impervious	48

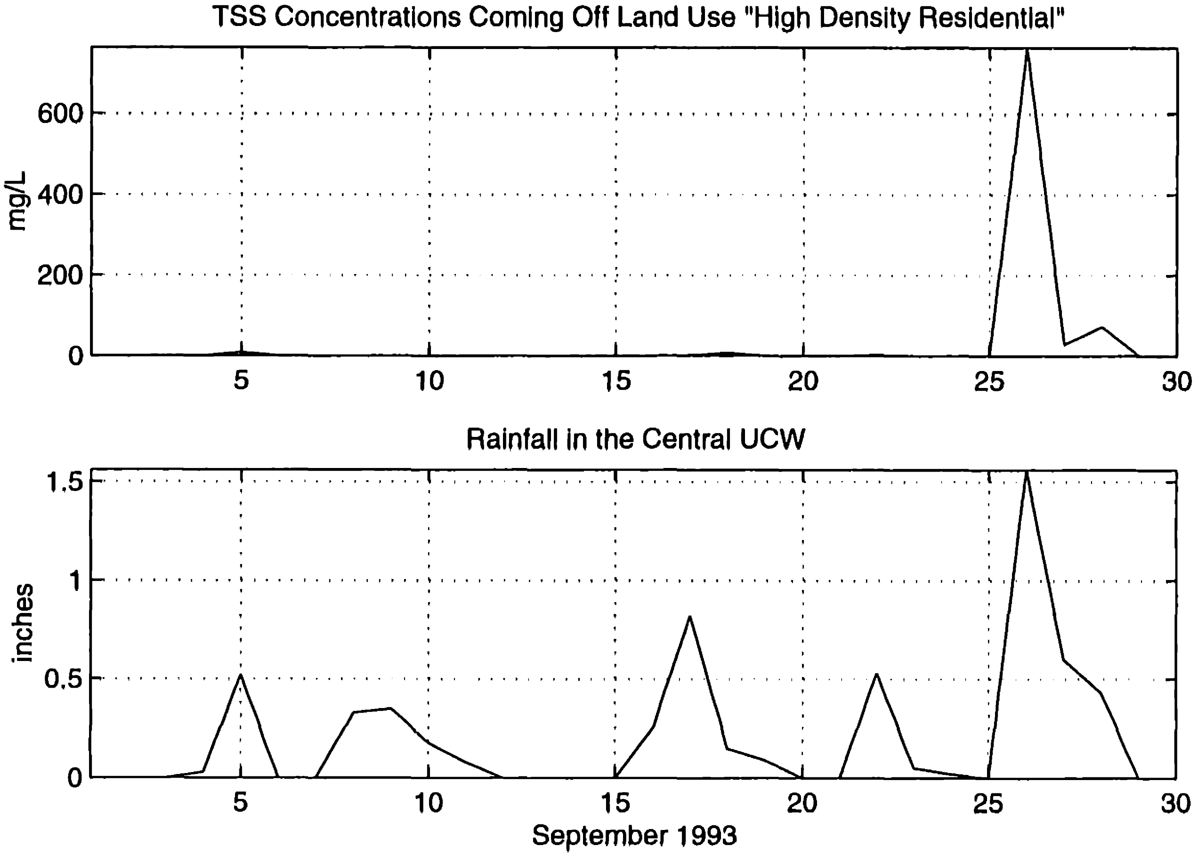
Table 4.16: Average TSS concentration of stormwater by land use (Summary of Table 4.15)

and impervious land respond dramatically to this surge of rain, while the other land uses do not. (The increase in modeled washoff on impervious land does not have an effect, since the central UCRW is not modeled with any impervious land.)

Date	Hour	Low dens resid		High dens resid		Rainfall
		Sediment (tons/ac)	Stormwater (inches)	Sediment (tons/ac)	Stormwater (inches)	(inches)
1993 Sep 26	11:00	0.00009	0.00929	0.07466	0.86408	1.55

Table 4.17: Effects of one hour of intense rain

As a result of this "blip" the TSS concentration in stormwater runoff for high density residential land increases to over 600 mg/L on September 26, 1993, in the central Charles River Watershed, as shown in Figure 4-20.



TSS Concentrations Coming Off Land Use "High Density Residential"

Rainfall in the Central UCW

Figure 4-20: Blip in stormwater TSS concentration on September 26, 1993, in the central Upper Charles River Watershed.

4.6 Calibration of Sediment Transport: TSS in the River

4.6.1 Total Suspended Solids: HSPF Results vs. CRWA Data

The Charles River Watershed Association (CRWA) has a sampling program whereby once a month, on a given day (e.g. in 1996, the samples were taken on the first Tuesday of each month) and at approximately the same time (6 a.m.), volunteers along the length of the river take water quality samples.

Total suspended solids (TSS) is among the water quality constituents that are monitored. In order to calibrate the HSPF sediment model, we used these CRWA values. Each of the CRWA sampling stations along the river corresponds with an HSPF reach; when calibrating the model we compared the TSS concentration reported by CRWA on a given day for a given reach with HSPF predictions.

Figures 4-21 through 4-25 show how HSPF predictions of TSS concentration in the river compare with CRWA measurements. The CRWA data is included in Appendix C. It is important to note that the detection limit is either 4 mg/L or 2 mg/L, depending on whether the CRWA lab or the MWRA lab was doing the analysis. On the plots shown here, half the detection limit is plotted.

4.6.2 Total Suspended Solids: HSPF Results vs. CDM Data

The environmental consulting firm Camp Dresser & McKee (CDM) prepared a report that analyzed whether "increased flow to the Charles River Pollution Control District (CRPCD) Wastewater Treatment Plant (WWTP) could be discharged to the Charles River without adversely affecting the water quality of the river [5, p. ES-1]." The analysis, entitled the *Upper Charles Wasteload Allocation Study*, included water quality data that were used to help calibrate the HSPF Charles River Watershed model.

The study area of CDM's report coincided with the HSPF Central Charles River

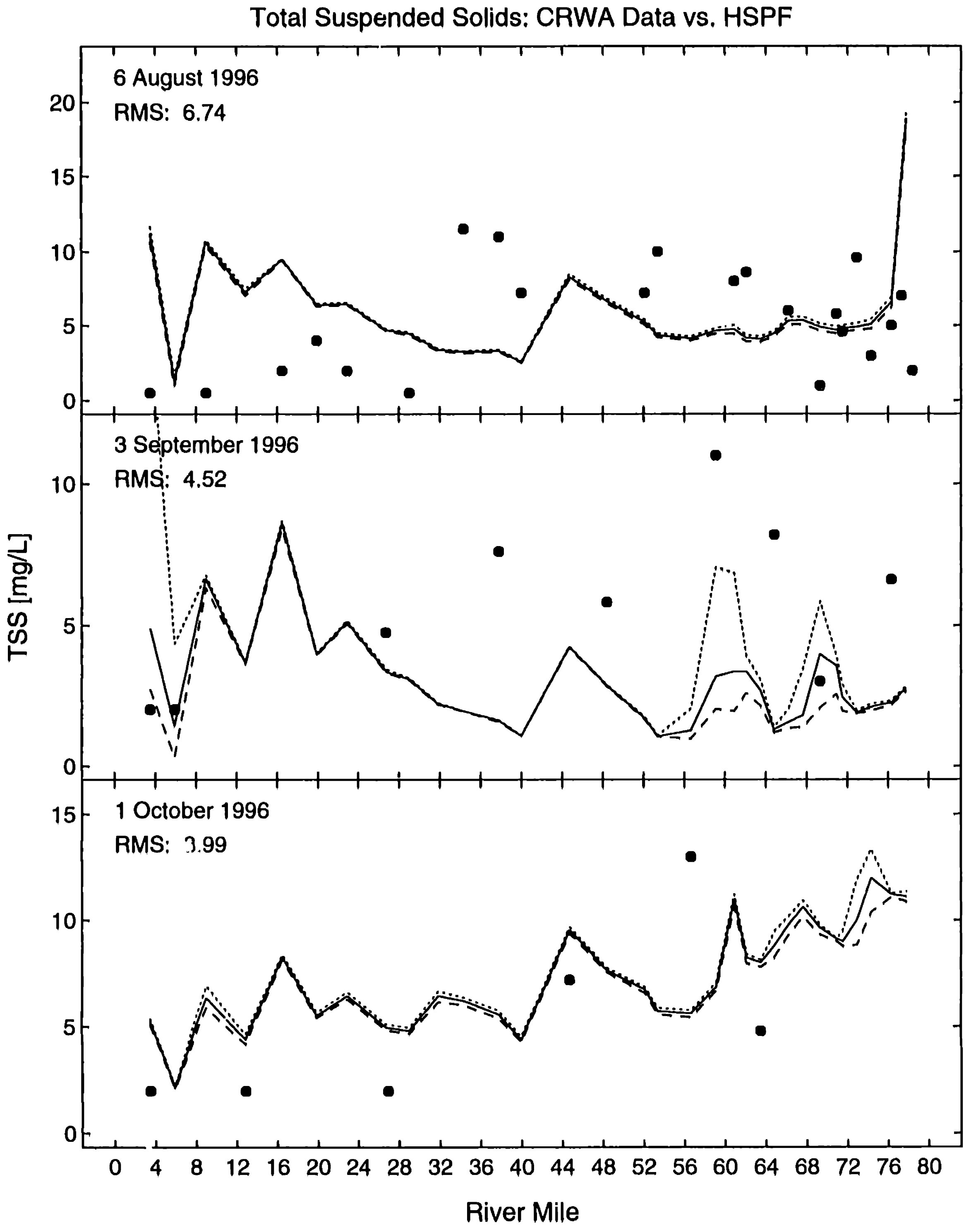


Figure 4-21: Comparison of CRWA data and model results I: 8/6/96, 9/3/96, 10/1/96

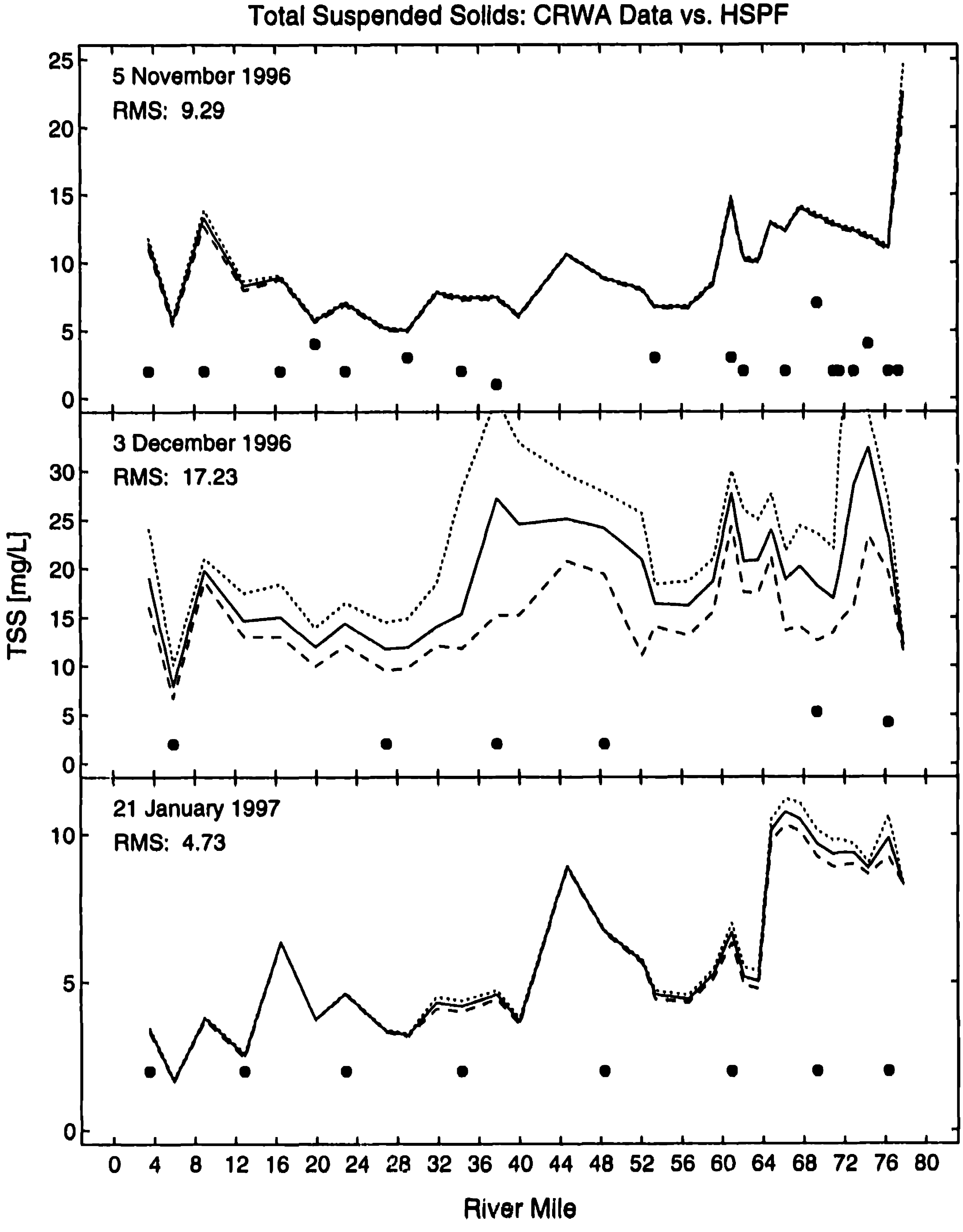


Figure 4-22: Comparison of CRWA data and model results II: 11/5/96, 12/3/96, 1/21/97

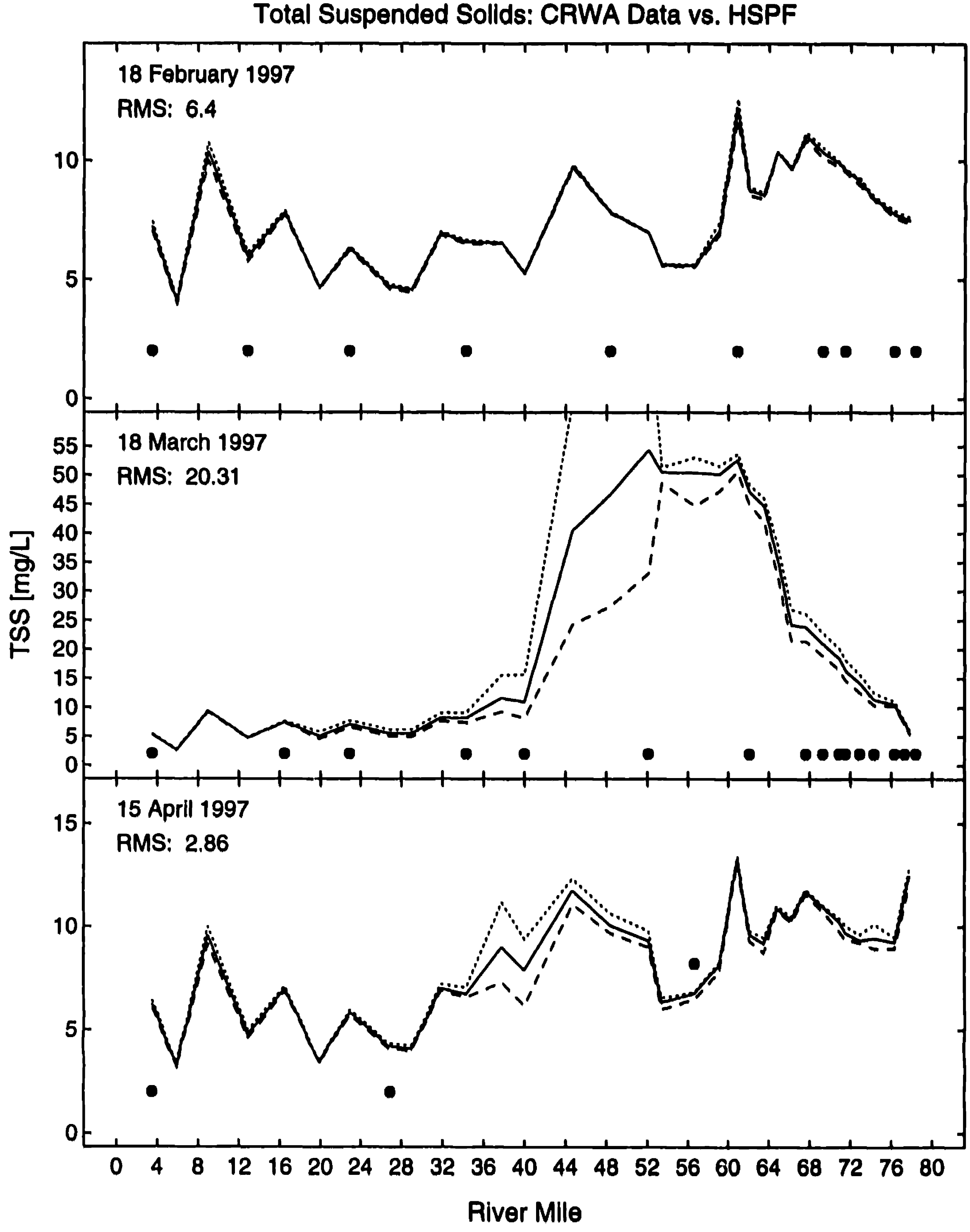


Figure 4-23: Comparison of CRWA data and model results III: 2/18/97, 3/18/97, 4/15/97

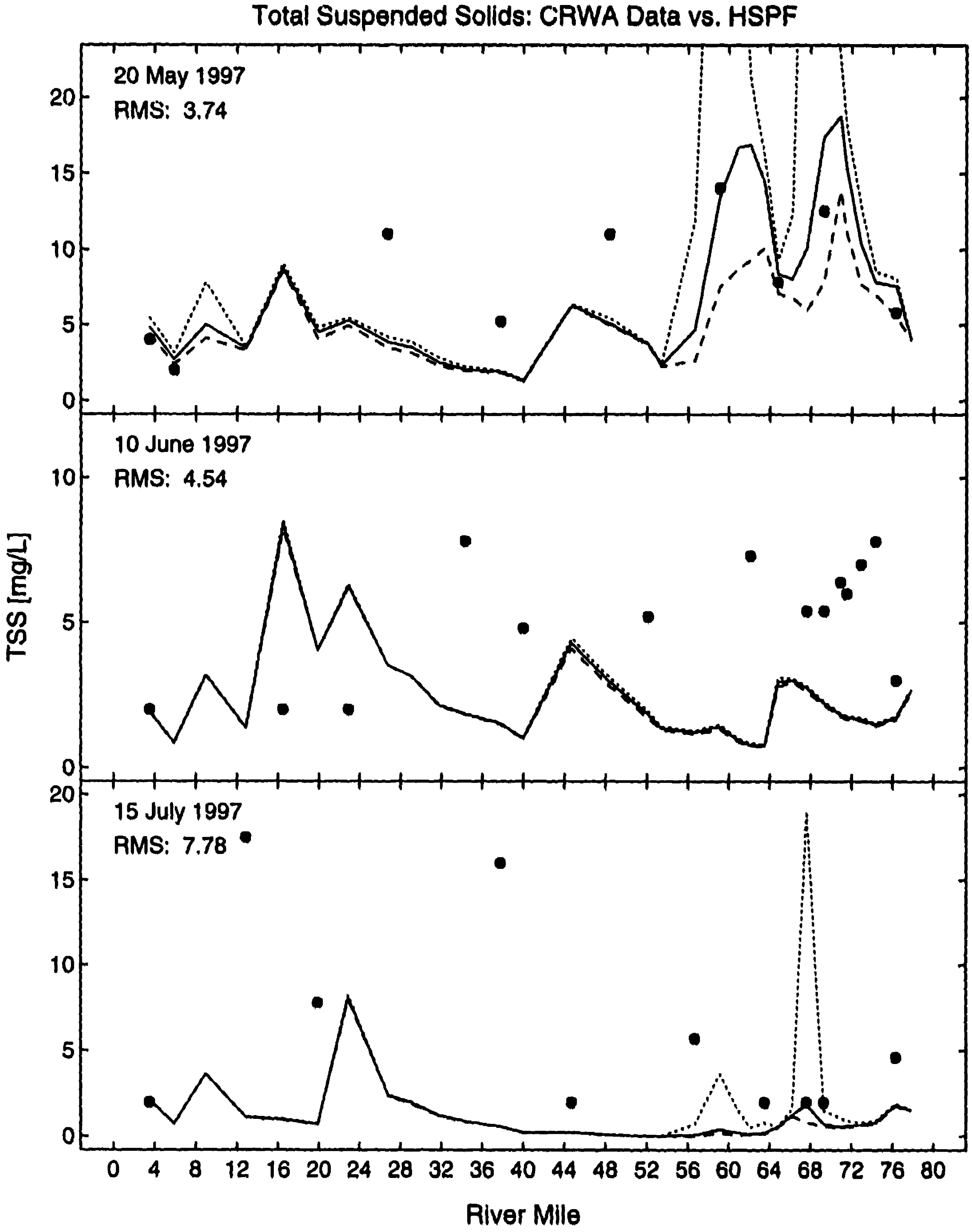


Figure 4-24: Comparison of CRWA data and model results IV: 5/20/97, 6/10/97, 7/15/97

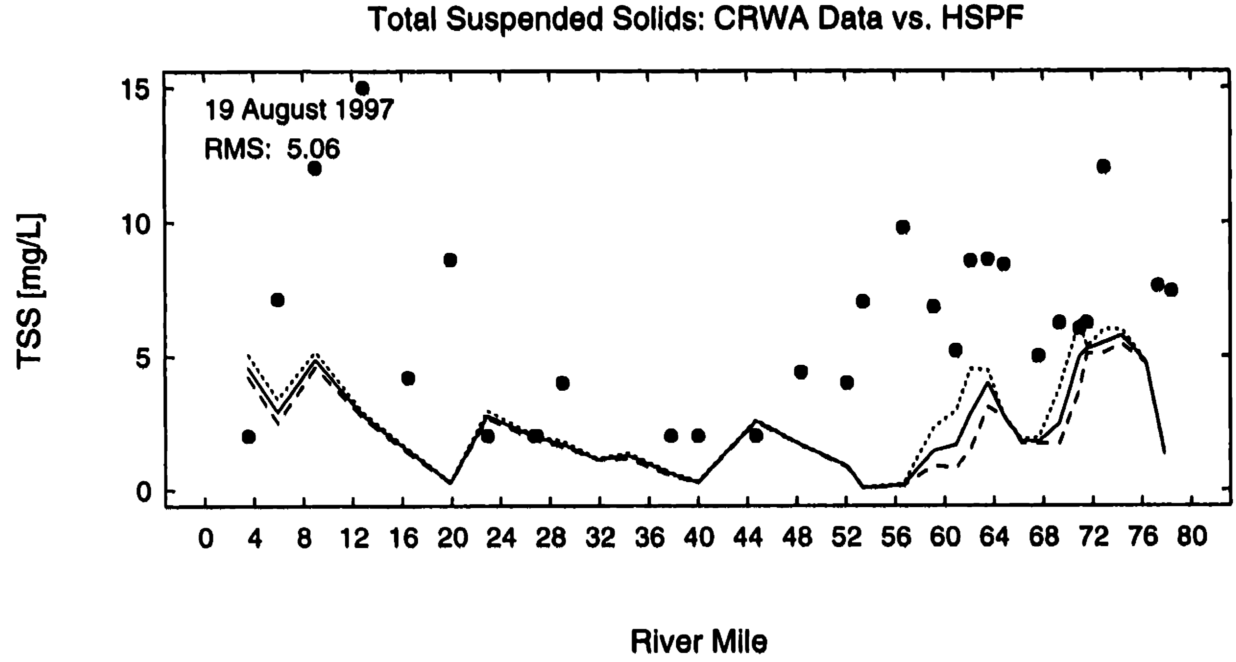


Figure 4-25: Comparison of CRWA data and model results V: 8/19/97

Watershed, including the last few reaches of the Upper CRW. CDM's study area begins from Populatic Pond (which corresponds to Reach 5, near the bottom of the Upper CRW) and ends at the Cochrane Dam (which corresponds to Reach 107, near the bottom of the Central CRW.) The CRPCD WWTP is just downstream of Populatic Pond in Medway.

As part of the report, CDM initiated a monitoring program, which collected water quality data on dry summer days. Three samples per day (morning, noon and evening) were collected at each of the sampling stations, which included nine stations on the Charles River and four locations at tributaries to the river.

The data collected for total suspended solids concentration is included in Appendix D. Figure 4-26 shows how the HSPF models predictions match with CDM's sampling data. For the first two days of sampling, 8/20/96 and 9/5/96, the TSS detection limit was 7 mg/L and all non-detectable points were graphed at half the detection limit, or 3.5 mg/L. On the final day, 10/8/96, the detection limit was 1 mg/L, and the data listed as non-detectable was graphed at 0.5 mg/L.

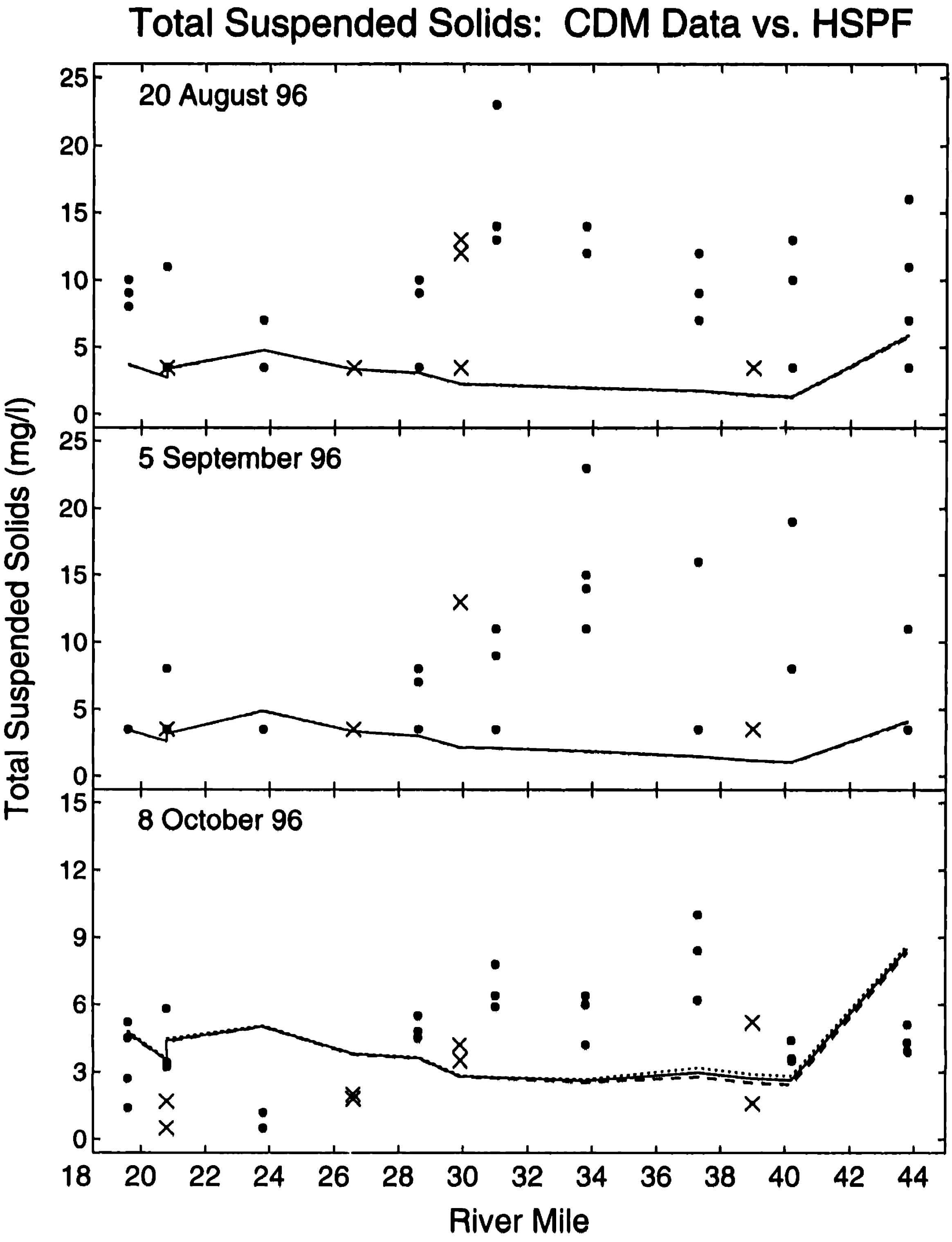


Figure 4-26: Comparison of CDM data and model results: 8/20/96, 9/5/96, 10/8/96

4.6.3 Calibration Issues

Of course, there is a tremendous amount of room for error. First of all, the sediment model depends heavily on the hydrology model. Over all, the calibration of the hydrology was extremely successful (comparison between modeled and measured daily streamflow at four Charles River streamflow gages yielded r-squared statistics that ranged from 0.596 to 0.789) [35, p. 116]. However, on certain days, the model simulation of the hydrology in the watershed does not accurately match the actual conditions. When the TSS was being calibrated for a day with an imperfect hydrology calibration then the TSS predictions will be skewed.

For example, one of the CRWA sampling days was 3 December 1996. As Figure 4-22 shows, there is very poor correlation between the HSPF predictions and the CRWA data; HSPF results are extremely high.

This can be seen even more clearly on 2 December, when the recorded flow at the Dover gage was 578 cfs. The HSPF simulation is hourly, and at the start of the day, the flow at Dover was simulated to be 223 cfs; by the end of the day the simulated flow was 1089 cfs. This variation has a great effect on the simulated suspended solids in the river on 2 December. Figure 4-27 shows the minimum, maximum and average TSS values along the river on 2 December 1996.

Table 4.18 lists the differences between the recorded and HSPF simulated flows at three different gages along the watershed for the dates of the CRWA sampling dates. Included in the table are the two previous days, since even if the hydrology on a sampling day is accurate, if it was inaccurate on a previous day then predictions of TSS concentrations will be inaccurate.

Second, the timing and intensity (on an hourly timescale) of the storms in the upper and middle Charles River subwatersheds are not perfectly accurate, since the precipitation gages available in or near those subwatersheds record only daily precipitation. As mentioned earlier in Section 4.5.5, a precipitation scheme was developed to create reasonable hourly data. However, in reality, the storm might have occurred at a different time during the day than the disaggregation formula indicates. Since

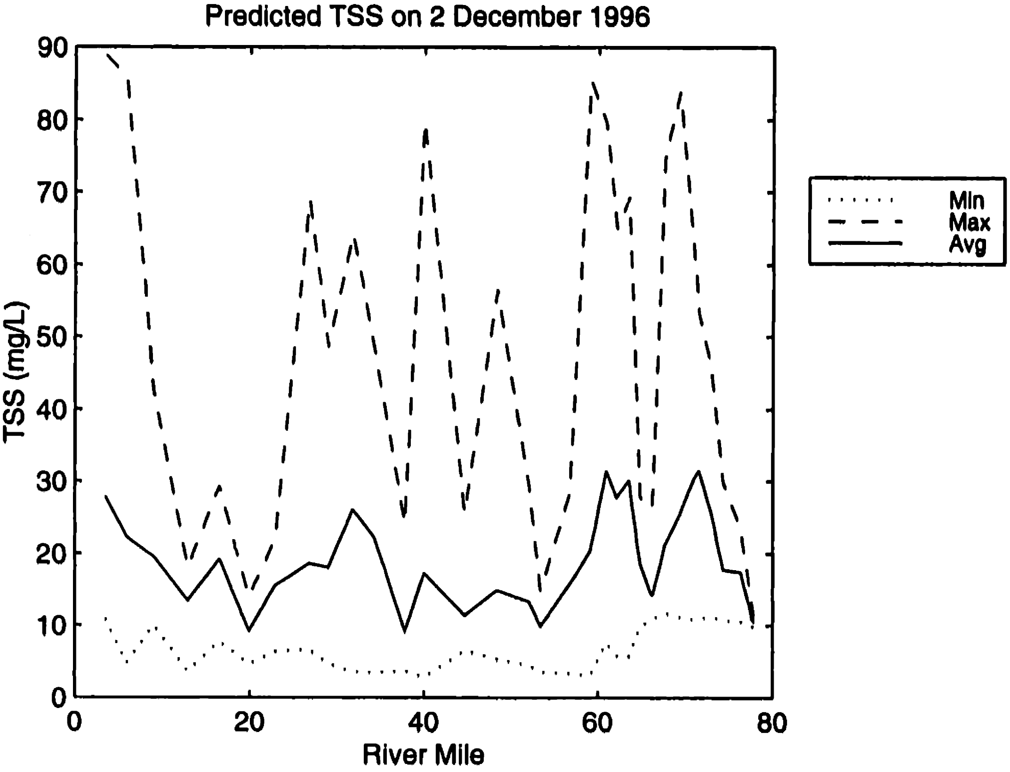


Figure 4-27: HSPF predictions of TSS along the river on 2 December 1996

the CRWA collects samples at 6 AM, the sampled TSS values might be lower than HSPF values if the HSPF modeled storm occurred before six in the morning but in reality occurred later in the day. In order to compensate for this, we looked at the minimum and maximum HSPF predictions, in addition to the average values. We assumed that the calibration was acceptable as long as the CRWA values fell into this envelope of predicted values. However, although this will compensate for the timing of a storm, it will not compensate for the storm's intensity. For example, the precipitation disaggregation might create a short intense storm when in reality the storm was less intense and had a longer duration. This would result in a discrepancy between the real and simulated sediment runoff into the river and in the sediment resuspension in the river.

Although over all the model produced reasonable results for TSS concentrations in the river, there were some results which seem rather unrealistic. Consider Table 4.19 as an example. TSS in reach 100 jumps from 0.48 to 120.17 in one hour. Spurts like this are especially likely to happen in a reach with a significant amount of impervious area draining to it. (Reach 100 and 83, however, are examples of reaches without any impervious land contributing runoff.)

In addition, it would have been helpful to have had more data about the characteristics of the soil being washed off the land and of the sediment in the river. For example, the sediment that is washed off the land is not separated into sand, silt and clay categories until it enters the river. The model then requires values for the fractions of sand, silt and clay in the sediment being washed into the river. Our model separates the sediment into 5% sand, 69% silt and 26% clay (or, 95% cohesive sediments) being washed off permeable land and 10% sand, 46% silt, and 44% clay (90% cohesive) from impermeable land. Since the sand that enters the river is more likely to deposit than the cohesive sediments, if we were to change these fractions so that more sand was entering the river, then in all likelihood, the TSS in the river would be reduced.

Scour has a very important effect on the TSS in the river. There are two ways for the HSPF modeler to calibrate the scour in the river. Either the critical shear stress for scour (which determines the point at which sediment will begin scouring from the bed) and the erodibility coefficient (which determines the rate at which sediment will scour) can be used to increase or decrease total suspended solids in the river. In effect, since each reach may have a different value for critical shear stress and erodibility coefficient, the calibration can potentially be a very unwieldy process. For the sake of simplicity (and, given our lack of data, simplicity was required), we attempted to reduce the number of different variables. Rather, as we described above, we used one critical shear stress and one erodibility coefficient for most of the reaches in the river.

Date	Flow [cfs]: Recorded (daily) vs. simulated (avg. of 24 hours)					
	Dover		Wellesley		Waltham	
	Recorded	Simulated	Recorded	Simulated	Recorded	Simulated
1996 Aug 4	104.00	159.39	102.00	170.45	145.00	178.28
1996 Aug 5	96.00	144.53	80.00	155.69	135.00	163.91
1996 Aug 6	87.00	131.70	75.00	140.25	116.00	148.45
1996 Sep 1	60.00	67.96	52.00	77.00	100.00	82.40
1996 Sep 2	60.00	64.93	49.00	101.79	103.00	120.20
1996 Sep 3	58.00	68.45	43.00	87.49	103.00	131.47
1996 Sep 29	199.00	276.98	244.00	345.79	340.00	419.22
1996 Sep 30	189.00	308.82	195.00	329.86	292.00	347.37
1996 Oct 1	179.00	299.27	185.00	336.92	251.00	362.97
1996 Nov 3	506.00	558.63	534.00	565.19	673.00	670.02
1996 Nov 4	459.00	511.46	498.00	528.22	629.00	625.44
1996 Nov 5	419.00	468.89	453.00	496.25	581.00	587.50
1996 Dec 1	510.00	219.48	543.00	237.54	626.00	300.72
1996 Dec 2	578.00	570.46	645.00	435.97	782.00	578.34
1996 Dec 3	584.00	1053.10	658.00	969.98	803.00	925.51
1997 Jan 19	402.00	287.99	318.00	263.87	349.00	327.20
1997 Jan 20	364.00	266.75	345.00	237.83	383.00	291.54
1997 Jan 21	327.00	249.37	325.00	225.46	371.00	276.23
1997 Feb 16	395.00	428.45	395.00	366.95	449.00	410.10
1997 Feb 17	393.00	446.87	387.00	420.87	437.00	465.60
1997 Feb 18	393.00	410.26	387.00	403.30	434.00	463.92
1997 Mar 16	424.00	846.38	248.00	754.00	343.00	699.92
1997 Mar 17	455.00	575.56	266.00	444.32	345.00	546.54
1997 Mar 18	473.00	522.06	274.00	341.66	351.00	408.19
1997 Apr 13	962.00	606.52	735.00	353.75	906.00	476.89
1997 Apr 14	902.00	688.76	683.00	374.07	836.00	413.20
1997 Apr 15	853.00	645.76	642.00	414.78	771.00	478.22
1997 May 18	279.00	131.87	265.00	83.95	303.00	102.76
1997 May 19	291.00	124.61	291.00	115.47	342.00	168.37
1997 May 20	376.00	131.53	384.00	96.65	458.00	191.42
1997 Jun 8	130.00	67.95	132.00	58.04	163.00	62.96
1997 Jun 9	124.00	62.76	104.00	55.11	150.00	60.10
1997 Jun 10	116.00	57.99	99.00	47.95	127.00	54.06
1997 Jul 13	26.00	18.72	34.00	16.64	39.00	15.39
1997 Jul 14	24.00	16.81	23.00	16.32	39.00	15.65
1997 Jul 15	22.00	15.33	21.00	17.53	36.00	16.79
1997 Aug 17	26.00	75.79	34.00	73.11	31.00	65.00
1997 Aug 18	36.00	64.18	28.00	107.83	35.00	149.68
1997 Aug 19	31.00	61.32	27.00	72.47	35.00	82.95

Table 4.18: Recorded vs. simulated flow, CRWA sampling date and previous two days

Date	Hour	Rainfall (in)	TSS (mg/L)	
			Reach 100	Reach 83
1995 Sep 17	01:00	0.00	0.01	0.97
1995 Sep 17	02:00	0.00	0.01	0.96
1995 Sep 17	03:00	0.00	0.01	0.95
1995 Sep 17	04:00	0.00	0.01	0.94
1995 Sep 17	05:00	0.00	0.01	0.94
1995 Sep 17	06:00	0.00	0.01	0.93
1995 Sep 17	07:00	0.02	0.01	0.79
1995 Sep 17	08:00	0.04	0.01	1.09
1995 Sep 17	09:00	0.12	0.02	2.64
1995 Sep 17	10:00	0.04	0.02	5.24
1995 Sep 17	11:00	0.03	0.02	3.35
1995 Sep 17	12:00	0.12	0.02	3.71
1995 Sep 17	13:00	0.20	0.02	6.80
1995 Sep 17	14:00	0.38	0.03	11.42
1995 Sep 17	15:00	0.41	0.48	31.09
1995 Sep 17	16:00	0.66	120.17	31.14
1995 Sep 17	17:00	0.58	220.07	138.00
1995 Sep 17	18:00	0.16	289.25	267.76
1995 Sep 17	19:00	0.01	160.41	46.53
1995 Sep 17	20:00	0.00	122.24	66.22
1995 Sep 17	21:00	0.00	96.80	57.86
1995 Sep 17	22:00	0.00	78.38	53.07
1995 Sep 17	23:00	0.00	63.58	50.22
1995 Sep 17	24:00	0.00	50.68	51.27
1995 Sep 18	01:00	0.00	40.06	51.37
1995 Sep 18	02:00	0.00	31.39	50.97
1995 Sep 18	03:00	0.00	24.46	50.26
1995 Sep 18	04:00	0.00	18.84	49.60
1995 Sep 18	05:00	0.00	14.37	48.49
1995 Sep 18	06:00	0.00	10.87	47.87
1995 Sep 18	07:00	0.00	8.17	47.22
1995 Sep 18	08:00	0.00	6.09	46.66
1995 Sep 18	09:00	0.00	4.50	46.43
1995 Sep 18	10:00	0.00	3.30	45.90
1995 Sep 18	11:00	0.00	2.39	45.44
1995 Sep 18	12:00	0.00	1.72	44.97
1995 Sep 18	13:00	0.00	1.22	44.56

Table 4.19: TSS concentration in two reaches during a storm

Chapter 5

Applying BMPs to the HSPF Model of the Charles River

Massachusetts DEP's Stormwater Management Standards require a reduction of 80% of the post-development average annual TSS loads. The HSPF hydrologic model of the Charles River Watershed can help us understand how the suspended solids concentration in the river will be affected due to a reduction in suspended solids in the washoff entering the river.

This evaluation is done in a two step process. First, we simulate "development" in the watershed by changing the land use data in certain areas. These changes should result in an increased TSS concentration in the river since they reduce open space and forest land and increase impervious and high density residential land. After we document these new TSS values, we then reduce by 80% the solids that enter the river from the newly developed land.

A few points must be noted at the outset. First, although certain towns in the watershed may choose to apply DEP's recommendations (which eventually will become regulations) to all development within the town, for most towns the stormwater standards apply only within the jurisdiction of the Conservation Commission, i.e., within the resource areas. As described in Section 2.2.4, a buffer zone of 100 feet is intended to protect the state's wetlands. In addition, the "riverfront area" extends for 200 feet on either side of a river or stream, and in certain places it only extends for 25 feet. Moreover, according to the Rivers Protection Act regulations, only 10% of the riverfront area may be developed at all, although no such restriction exists for the buffer zones of the other resource areas. Although we can guess, based on land use maps, what percentage of the riverfront area will potentially be developed, the guess might over- or underestimate reality. In our first case study, we simulate the development of all land under the jurisdiction of the Conservation Commission that may legally be developed (that is, 10% of the riverfront area and the entire buffer zone.) This is very likely an overestimate.

Another problem with HSPF's prediction derives from HSPF's lack of information about land use location. Each HSPF "subwatershed" (drainage area into one particular reach) is separated into six land uses. However, the model does not know where in the subwatershed each of these land uses is located. The Stormwater Management Standards require that post-development TSS loads must be reduced by 80%; yet, this requirement only applies in the riverfront area or buffer zones. In our test scenarios, we change land use from "open space" and "forest" to "high density residential" or "impervious land". However, the model does not know that the land use changes are to be made in the part of the subwatershed that is closest to the river. Therefore, the results will not accurately reflect the true land use changes.

5.1 Scour Versus Washoff of Sediment

Total suspended solids in the river can be affected either either by resuspension of sediment within the river, or by the solids concentration in runoff that washes into the river. HSPF models both washoff and resuspension. Before we begin to address any "what-if" scenarios, we need to ascertain how much of the modeled TSS in the river is due to each of these processes. If resuspension is responsible for a major amount of the TSS concentration, then reducing solids in stormwater entering the river would not have as great an effect as one might have hoped.

To answer this question, we tested the model by running it under two different conditions. The first run was the base run, and included all of the normal river

Fraction of TSS Due to Washoff But Not Scour			
[CRW1]		**[CRW3]**	
Reach 37	0.98	Reach 100	0.96
Reach 33	0.98	Reach 94	0.95
Reach 27	0.96	Reach 91	0.93
Reach 19	0.95	Reach 86	0.95
Reach 12	0.97	Reach 83	0.98
Reach 5	0.93	Reach 78	0.97
[CRW2]		Reach 75	0.96
		Reach 73	0.96
Reach 149	0.94	Reach 72	0.96
Reach 140	0.94	Reach 69	0.96
Reach 137	0.94	Reach 67	0.97
Reach 132	0.94	Reach 63	0.97
Reach 126	0.94	Reach 61	0.97
Reach 117	0.96	Reach 59	0.97
Reach 112	0.95	Reach 57	0.97
Reach 107	0.93	Reach 55	0.97
		Reach 53	0.97
		Reach 51	0.97

Table 5.1: Fraction of TSS due to washoff. TSS values are daily averages and the fraction for each reach has been averaged over the time period 6/1/96 to 8/31/97. Reaches are shown in an upstream to downstream order.

processes, i.e. washoff into the river, and deposition and scour within the river. The second run removed the simulation of scour in the river. To accomplish this, the critical shear stress for deposition was left at the same value as in the first run, but the critical shear stress for scour was increased to the maximum value allowed ($TAUCS = 10^{10}$). In other words, since the bed stress in the river never reached $TAUCS$, scour in the river was never turned on.

We then examined the suspended solids in the water column with and without the effect of scour. The results show that scour is responsible for about 5% of the TSS in the river. Table 5.1 shows the fraction of TSS due to the washoff component. The fraction was determined by dividing the TSS concentration for a no-scour scenario with that of a scour scenario.

5.2 Change in Land Use Due to Development

How do we use the HSPF model to determine the effect of the Stormwater Management Standards on TSS concentration in the Charles River? A number of scenarios can be run with the model. First, we can examine land use changes in a particular town in the Charles River Watershed. Alternatively, we can choose a more extreme scenario in which all of the towns in the watershed have land use changes that fall under the jurisdiction of the Stormwater Management Standards.

There are many ways to change the land use in the model in order to simulate development. We can change the open space and forest land to high density residential land, or to impervious land. (In reality, the development may be some combination of the two.) There is a big distinction between high density residential land and impervious land in the model, especially since HSPF models impervious land without any infiltration or evaporation. Unlike all of the pervious land categories, including high density residential land, there is no lag time between rainfall on impervious land and the runoff leaving the impervious land surface. As a result, we sometimes find "spikes" of TSS in the river due to this quick runoff.

When the land use changes from forest or open space to high density residential land or impervious land, there will be more sediment and solids buildup and washoff, but there will also be increased runoff. Additionally, the buildup and washoff of solids is dependent on the antecedent and storm conditions. Therefore, since TSS concentration is the ratio of the solids loading to the runoff volume, the increase (or decrease) in TSS due to changes in land use will be a non-linear function of the land use changes.

Ultimately we looked at two case studies, each with two scenarios. In each case study we examined land use changes in a single town. In Case Study 1 we simulated development only within the jurisdiction of the Conservation Commission. In Case Study 2 we simulated development throughout the town. For each case, we examined two types of land use changes, to impervious land and to high density residential land. The case studies are described in more detail later in this chapter.

5.2.1 Procedure

Before we begin with any model runs, we need to determine how much area lies in the riverfront area or the buffer zones and will therefore be affected by the Stormwater Management Standards. It is important to note that the regulations for the Rivers Act state that the riverfront area should include a "100 foot wide area of undisturbed vegetation"[1]. Thus, the potentially developable land that will be affected by the Stormwater Management Standards will not be directly alongside the river. In addition, the regulations further restrict development in the riverfront area to 10% of the area.

The HSPF model of the Charles River Watershed separates the watershed into "subwatersheds", each of which drains into one reach of the Charles River, or drains into a tributary to the Charles River. A town or city in the Charles River Watershed will lie within a number of subwatersheds, although it will certainly not coincide with 100% of the area of these subwatersheds. In many instances, the Charles River is the boundary between two towns. Since the subwatersheds ignore political boundaries, one town might lie on the northern side of the river, and another town might lie on the southern side, although both sides are part of the same subwatershed. Moreover, in some cases, a town lies alongside a reach of the Charles River, yet the subwatershed draining into that particular reach is almost entirely outside the town boundaries. In cases like these, the entire riverfront area (or at least one side of it) lies within the town boundaries but no other part of the subwatershed does. This might be irrelevant to the Conservation Commissions who have jurisdiction only within the riverfront area, but it is interesting for us, since we examine the effects of stormwater management within the riverfront area of a town as compared to stormwater management throughout the town In order to determine which subwatersheds relate to which towns, we used a map of the watershed which delineates both the towns and the subwatersheds.

We were unsure whether development would best be modeled with what HSPF considers impervious land or what it considers high density residential land. (Note

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[1] 310 CMR 10.58(4)(d)(1)(a)

that the latter category includes some commercial, industrial and transportation land, as does the impervious land use category). Therefore, we approached the problem using two methods. In Method I, the land in the riverfront area was converted to impervious land. In Method II, the area was converted to high density residential land. Although Method I is a "worse" scenario than Method II, both methods assume that all of the land in the riverfront area will be developed, and in reality this would never be the case. On the other hand, both of these methods underestimate development that takes place outside of the riverfront area but that will still "alter" the area and therefore be regulated. For example, if development is done outside the area, and a new storm drain that is associated with this development is placed inside the riverfront area, then this stormwater pipe must comply with the Stormwater Management Standards. Neither Method I nor Method II addresses these types of cases.

Determining the Change in Area

The procedure to determine the area of land per subwatershed under the jurisdiction of the Stormwater Management Standards and the Conservation Commission is as follows:

Riverfront area

(1) Determine the length of the Charles River * 200 ft per side. (If we are analyzing only one town, then chances are it will lie on only one side of the river.)

(2) Determine the length of any other perennial streams in the watershed * 200 ft per side.

(3) The sum of the areas of (1) and (2) is the total riverfront area. Since only 10% of the riverfront area may be developed, we must multiply this number by 0.1 to get the maximum area that might be developed.

(4) What is the land use in the riverfront area? What percentage of the land can be classified as open space, and what percentage is forest? These are the two land use types that will be changed. Use a land use map to determine these percentages. To determine the area of open space that will be converted into other land uses, multiply

the area from (3) by the percentage of riverfront area that is open space; do the same for the forest land.

Buffer zone

(5) Determine the perimeter of any ponds, lakes or reservoirs in the watershed.

(6) Multiply this perimeter by 100 ft to get the area of the buffer zone.

(7) What is the land use in the buffer zone? To determine the open space that will be converted, multiply the area of the buffer zone from (6) by the percentage of the buffer zone that is open space; do the same for the forest land.

Total Area Under the Jurisdiction of the Stormwater Management Standards

(8) To determine the total open space and forest land that may be converted to other land uses, add the results from (4) and (7). Reduce the amount of open space and forest land by these results.

(9) Method I: Increase the high density residential land in the watershed by adding the total land area change from (8) to the area of high density residential land

-or-

(10) Method II: Increase the impervious land in the watershed by adding the total land area change from (8) to the area of impervious land

Case Study: Franklin

A 1988 report by the Massachusetts Department of Environmental Management (DEM) projected that of all the Charles River Watershed communities, the town of Franklin (in the Upper Charles River Watershed) would have the largest percent change in population between the years 1985 and 2020, with a 44% increase in population [24, p.32]. Thus, we chose to use Franklin in our analysis of development in the watershed.

Interestingly, in March, 1998, the town of Franklin adopted the stormwater management guidelines as part of its town code. Therefore, even development that is not under the jurisdiction of Franklin's Conservation Commission will still be obligated to follow DEP's Stormwater Management Standards [2]. Indeed, those who were involved in the development of the Standards hope that all Massachusetts towns

Subwatershed Draining to Reach #	Percent of Subwatershed in Franklin
2	45%
5	10%
6	90%
7	30%
8	50%
9	50%
10	95%
11	50%
12	2%
13	95%
14	20%
15	5%
16	25%
45	20%
46	100%

Table 5.2: Reaches and subwatersheds corresponding to the town of Franklin. The higher numbered reaches are upstream of the the lower numbered reaches, except for reaches 45 and 46, which are tributaries to reaches 13 and 2, respectively.

would choose to apply the standards to areas outside the jurisdiction of the Wetlands Protection Act.

5.2.2 Development in Franklin

A detailed map of the Charles River Watershed that includes the HSPF reaches and subwatersheds show that the town of Franklin lies primarily within twelve subwatersheds (this count includes only those subwatersheds in which Franklin accounts for more than 10% of the basin area.) Table 5.2 lists the subwatersheds that coincide with the town of Franklin. Note that the higher numbered reaches are more upstream of the lower numbered reaches (and reaches 45 and 46 are tributaries to the river.) Detailed information about land use in the Franklin subwatersheds can be found in a later part of this section, in Tables 5.8, 5.9, and 5.10.

Case Study 1: New Development in the Buffer Zone and 10% of the Riverfront Area

Since the Stormwater Management Standards are intended to fall under the jurisdiction of the Wetlands Protection Act, we were first concerned with determining Franklin's riverfront area, and any other resources areas. Table 5.3 lists Franklin's riverfront area, on a subwatershed basis. The riverfront area is calculated by multiplying the length of the Charles River that is within Franklin borders by 200 ft (since Franklin lies on only one side of the Charles) and by multiplying the length of all perennial streams within Franklin by 400 ft, since both sides of the stream must be taken into account. Since development is only permitted on 10% of the riverfront area, Table 5.3 also shows 10% of the riverfront area.

Table 5.4 shows resource areas in Franklin other than the riverfront area. A resource area is defined as a bank, etc. bordering on any pond or lake, etc. (See Section 2.2.4 for more details.) Therefore, the ponds, lakes and reservoirs in Franklin are noted in Table 5.4. The buffer zone is defined as a 100 foot area that will protect the resource area.

For our first case study, we assume that all of the buffer zones and 10% of the Franklin riverfront area will be developed. In other words, all of the open space and forest in those resource areas will be converted either to impervious land or to high density residential land.

Table 5.5 lists the land use changes for this case study. The numbers in the table were determined using the information in Tables 5.3 and 5.4, following the procedure outlined above in Section 5.2.1. The land use changes reflect the percentages of open space and forest in the resource area. For example, if the riverfront area in a certain subwatershed contains no open space, then the open space will remain unchanged in this experiment.

When we examined TSS in Reaches 16 through 1, including tributaries Reach 46 (which flows into Reach 13) and Reach 43 (which flows into Reach 2) over a period of about a year and a half, we found that for most reaches, the TSS in the river

Reach #	Length of River	Other "Rivers"?	Length of Other Streams	Riverfront Area (RFA)		10% of RFA	Land Use Along RFA
	[mi]		[mi]	[ft^2]	[ac]	[ac]	
2	0	Miller Brook	1.2	2,534,400	58.18	5.82	forest 90% open 10%
5	0	-	-	-	-	-	-
6	0.62	-	-	654,720	15.03	1.5	forest
7	0	-	-	-	-	-	-
8	0.1	-	-	105,600	2.42	0.24	forest
9	0.44	-	-	464,640	10.67	1.07	forest
10	0.49	Shepards Brook	3.0	6,853,440	157.33	15.73	forest 40% open 40% ld res 20%
11	0.42	-	-	443,520	10.18	1.02	forest
12	0.77	-	-	813,120	18.67	1.87	forest 50% open 50%
13	0.23	Mine Brook	5.6	12,070,080	277.09	27.71	forest 60% open 10%
14	0.39	-	-	411,840	9.45	0.95	ld res
15	0.57	-	-	601,920	13.82	1.38	forest
16	0.42	-	-	443,520	10.18	1.02	forest
45	0	part of Uncas Brook	2	4,224,000	96.97	9.70	forest
46	0	part of Mine Brook (splits into two)	7.6	16,051,200	368.48	36.85	forest 60% open 10%

Table 5.3: Riverfront area for the town of Franklin.
"Reach #" refers to the subwatershed draining to the reach # indicated
"Length of River" column refers to the length of the Charles River that is within Franklin's borders.
"Other Rivers" refer to any other rivers, brooks, or streams that lie within Franklin; these too will have riverfront areas.
The "Riverfront Area" (RFA) is calculated by multiplying the length of the Charles river [mi] by 200 [ft] and by multiplying the length of the perennial stream [mi] by 400 [ft] (since both sides of the stream are located within Franklin); the units are then converted into ft^2 or acres. Since only 10% of the riverfront area may be developed, the riverfront area is then multiplied by 10%.
"Land Use Along RFA" is the land use (not including high density residential or impervious land) in the Franklin riverfront area. The land use information is based on a land use map provided by MassGIS.

Reach #	Other Resource Areas	Perimeter in Franklin	Buffer Zone		Land Use In Buffer Zone
		[mi]	[ft^2]	[ac]	
2	Franklin Reservoir	1.8	950,400	21.82	forest
5	Populatic Pond	0.6	316,800	7.27	forest
45	Uncas Pond	1.2	633,600	14.55	forest 80% open 10%
46	Beaver Pond	0.9	950,400	21.82	forest 50% open 45%
	Spring Pond	0.9			

Table 5.4: Resource areas and buffer zones for the town of Franklin. The buffer zone is defined to be within 100 feet of a resource area

Reach #	Open Space		Forest		Method I Impervious		Method II High Dens Resid	
	Before	After	Before	After	Before	After	Before	After
2	356.74	356.16	2870.79	2843.74	0	27.64	262.64	290.28
5	1.90	1.90	61.37	54.10	0	7.27	0	7.27
6	5.69	5.69	184.12	182.62	0	1.5	0	1.5
8	21.05	21.05	48.09	47.85	0	0.24	6.26	6.50
9	4.03	4.03	43.16	42.09	0	1.07	9.30	10.37
10	289.13	282.84	1509.64	1503.35	0	12.59	44.84	57.43
11	3.45	3.45	34.70	33.68	0	1.02	0	1.02
12	872.11	871.18	2469.28	2468.35	0	1.87	200.85	202.72
13	621.21	618.44	1724.84	1708.21	0	19.40	550.43	569.83
14[1]	4.80	4.80	11.80	11.80	0	0	0	0
15	352.28	352.28	1837.65	1836.27	0	1.38	95.42	96.80
16	13.85	13.85	19.39	18.37	0	1.02	2.97	3.99
45	463.38	461.93	2249.82	2228.49	0	22.79	249.70	272.49
46	641.39	627.89	2977.15	2944.13	0	46.52	494.48	541.00

Table 5.5: Case study 1: Land use changes in Franklin's resource areas

[1] The riverfront area in Reach 14's subwatershed consists of low density residential land, so there will be no land use changes

after Case Study 1 was implemented was not significantly different than before. We compared the post-development TSS in a given reach (averaged over a year and a half period) with the pre-development average TSS in that reach.[2] Tables 5.6 and 5.7 summarize the results. The model shows more change in TSS when the open space and forest in the resource areas are changed to impervious land than when they are changed to high density residential land. Our model of the watershed might not be intricate enough to sense how a small change in land use will affect suspended solids in the river. Had the subwatersheds been subdivided into much smaller sections, we might have seen more of a response in the river.

When development in the watershed is simulated using impervious land, the post-development average TSS is 3% higher than the pre-development TSS in Reach 2 (the most downstream river reach that abuts the town of Franklin.) When high density residential land is used instead, TSS in Reach 2 is only 0.3% higher after development.

Case Study 2: New Development Throughout Franklin

In our second case study, we assume that *all* of the open space and forest land in Franklin are converted to either impervious or high density residential land. (This is obviously a "worst case scenario" for Franklin.) This land use change allows for a more obvious increase in TSS in the river than Case Study 1.

Tables 5.8 5.9 and 5.10 show how the town of Franklin is divided into land uses. For this case study, all of the open space and all of the forest land in Franklin is converted. To determine the acreage to be converted, we multiply the acreage in each subwatershed by the percentage of the subwatershed that coincides with Franklin.

Tables 5.11 and 5.12 show the results of Case Study 2 for Method I (convert open space and forest land to impervious land) and Method II (convert open space and forest land to high density residential land), respectively. The results show that in Reach 2, TSS doubles if impervious land is used to simulate development, and TSS

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[2] Another way to do the comparison would be to compare on a daily basis the TSS in each reach to get a daily ratio, and then to average these ratios. This method of averaging would produce different results than the method used in the thesis. The method used in the thesis is more likely to smooth out extreme results on particular days.

Case Study 1, Method I Land Use Changes in Franklin's Resource Areas From Open Space and Forest to Impervious Land			
Reach	TSS_{after}/TSS_{before}	Reach	TSS_{after}/TSS_{before}
16	1.0010	8	1.0181
15	1.0011	7	1.0145
14	1.0010	6	1.0175
46 (flows into 13)	1.1828	5	1.0207
		4	1.0173
13	1.0150	3	1.0151
12	1.0125	45 (flows into 2)	1.0953
11	1.0131		
10	1.0181	2	1.0326
9	1.0201	1	1.0300

Table 5.6: Case Study 1: Comparison of TSS before and after land use changes in Franklin's resource areas, Method I (conversion of open space and forest to impervious land). Fractions represent new average TSS divided by original average TSS. The results are the average of a year and a half of projected data, from 1/1/96 until 8/31/97.

Case Study 1, Method II Land Use Changes in Franklin's Resource Areas From Open Space and Forest to High Density Residential Land			
Reach	TSS_{after}/TSS_{before}	Reach	TSS_{after}/TSS_{before}
16	1.0000	8	1.0016
15	1.0000	7	1.0004
14	1.0000	6	1.0012
46 (flows into 13)	1.0346	5	1.0026
		4	1.0023
13	1.0016	3	1.0021
12	1.0015	45 (flows into 2)	1.0043
11	1.0016		
10	1.0017	2	1.0032
9	1.0020	1	1.0034

Table 5.7: Case Study 1: Comparison of TSS before and after land use changes in Franklin's resource areas, Method II (conversion of open space and forest to high density residential land). Fractions represent new average TSS divided by original average TSS. The results are the average of a year and a half of projected data, from 1/1/96 until 8/31/97.

Reach #	Percent of Subwatershed in Franklin	Land Uses	Area Per Land Use [acres]	Case Study 2 New Land Area [acres]
2	45%	open space	356.74	196.21
		wetlands	381.73	same
		forest	2870.79	1578.93
		ld resid	1642.97	same
		hd resid	262.64	1715.03 (Method II)
		impervious	0	1452.39 (Method I)
5	10%	open space	1.90	1.71
		wetlands	26.32	same
		forest	61.37	55.23
		ld resid	14.16	same
		hd resid	0	6.33 (Method II)
		impervious	0	6.33 (Method I)
6	90%	open space	5.69	0.57
		wetlands	78.95	same
		forest	184.12	18.41
		ld resid	42.47	same
		hd resid	0	170.83 (Method II)
		impervious	0	170.83 (Method I)
7	30%	open space	37.70	26.39
		wetlands	37.18	same
		forest	231.26	161.88
		ld resid	171.50	same
		hd resid	0.46	81.15 (Method II)
		impervious	0	80.69 (Method I)
8	50%	open space	21.05	10.53
		wetlands	11.36	same
		forest	48.09	24.05
		ld resid	75.29	same
		hd resid	6.26	40.83 (Method II)
		impervious	0	34.57 (Method I)

Table 5.8: Subwatersheds and land uses corresponding to the town of Franklin

Reach #	Percent of Subwatershed in Franklin	Land Uses	Area Per Land Use [acres]	Case Study 2 New Land Area [acres]
9	50%	open space	4.03	2.02
		wetlands	11.47	same
		forest	43.16	21.58
		ld resid	26.59	same
		hd resid	9.30	32.90 (Method II)
		impervious	0	23.60 (Method I)
10	95%	open space	289.13	14.46
		wetlands	105.05	same
		forest	1509.64	75.48
		ld resid	1018.57	same
		hd resid	44.84	1753.67 (Method II)
		impervious	0	1708.83 (Method I)
11	50%	open space	3.45	1.73
		wetlands	3.44	same
		forest	34.70	17.35
		ld resid	8.11	same
		hd resid	0	19.08 (Method II)
		impervious	0	19.08 (Method I)
12	2%	open space	872.11	854.67
		wetlands	147.97	same
		forest	2469.28	2419.89
		ld resid	1349.53	same
		hd resid	200.85	267.68 (Method II)
		impervious	0	66.83 (Method I)
13	95%	open space	621.21	31.06
		wetlands	366.92	same
		forest	1724.84	86.24
		ld resid	1198.59	same
		hd resid	550.43	2779.18 (Method II)
		impervious	0	2228.75 (Method I)

Table 5.9: Subwatersheds and land uses corresponding to the town of Franklin (continued)

Reach #	Percent of Subwatershed in Franklin	Land Uses	Area Per Land Use [acres]	Case Study 2 New Land Area [acres]
14	20%	open space	4.80	3.84
		wetlands	8.64	same
		forest	11.80	9.44
		ld resid	113.06	same
		hd resid	0	3.32 (Method II)
		impervious	0	3.32 (Method I)
15	5%	open space	352.28	334.67
		wetlands	68.33	same
		forest	1837.65	1745.77
		ld resid	731.86	same
		hd resid	95.42	204.92 (Method II)
		impervious	0	109.50 (Method I)
16	25%	open space	13.85	10.39
		wetlands	5.84	same
		forest	19.39	14.54
		ld resid	9.75	same
		hd resid	2.97	11.28 (Method II)
		impervious	0	8.31 (Method I)
45	20%	open space	463.38	370.70
		wetlands	550.98	same
		forest	2249.82	1799.86
		ld resid	1039.73	same
		hd resid	249.70	792.34 (Method II)
		impervious	0	542.64 (Method I)
46	100%	open space	641.39	0
		wetlands	227.18	same
		forest	2977.15	0
		ld resid	1135.24	same
		hd resid	494.48	4113.02
		impervious	0	3618.54 (Method I)

Table 5.10: Subwatersheds and land uses corresponding to the town of Franklin (continued)

Case Study 2, Method I Land Use Changes in Town of Franklin From Open Space and Forest to Impervious Land			
Reach	$\mathrm{TSS}_{after}/\mathrm{TSS}_{before}$	Reach	$\mathrm{TSS}_{after}/\mathrm{TSS}_{before}$
16	1.0077	8	1.7188
15	1.0267	7	1.6375
14	1.0415	6	1.7463
46 (flows into 13)	7.3695	5	2.1941
		4	2.0200
13	1.6527	3	1.9036
12	1.5617	45 (flows into 2)	1.5635
11	1.5911		
10	2.3729	2	2.0568
9	1.9075	1	1.8204

Table 5.11: Case Study 2: Comparison of TSS concentrations before and after land use changes in Franklin, Method I (conversion of open space and forest to impervious land). Fractions represent new average TSS divided by original average TSS. The results are the average of a year and a half of projected data, from 1/1/96 until 8/31/97.

increases by 13% if high density residential land is used.

5.2.3 Effects of Development on Sediment Load

When changes in land use increase the amount of impermeable or high density residential land, there will be increased sediment load to the river. Yet, at the same time, there will also be an increased volume of stormwater washing off the watershed, since less water will evaporate and infiltrate, and the water will run off more rapidly.

We have shown in the previous section that TSS in the Charles River near Franklin, in the most downstream reach, will increase somewhat due to development. It would be of interest to determine how the sediment load changes as a result of land use changes. Using the parameters input by the modeler in sections SEDMNT and SOLIDS, the HSPF model predicts the sediment and solids load to the river, in units of tons/acre, for each time interval. (In our case, a time step is one hour.) In Table 4.9, we reported the annual sediment loads off of the Charles River Watershed

Case Study 2, Method II Land Use Changes in Town of Franklin From Open Space and Forest to High Density Land			
Reach	$\mathrm{TSS}_{after}/\mathrm{TSS}_{before}$	Reach	$\mathrm{TSS}_{after}/\mathrm{TSS}_{before}$
16	0.9998	8	1.1114
15	1.0013	7	1.0769
14	1.0013	6	2.0129
46 (flows into 13)	2.0591	5	1.1505
		4	1.1406
13	1.0741	3	1.1312
12	1.0776	45 (flows into 2)	1.0883
11	1.0861		
10	1.0976	2	1.1348
9	1.1087	1	1.1375

Table 5.12: Case Study 2: Comparison of TSS concentrations before and after land use changes in Franklin, Method II (conversion of open space and forest to high density residential land). Fractions represent new average TSS divided by original average TSS. The results are the average of a year and a half of projected data, from 1/1/96 until 8/31/97.

by land use, as simulated by HSPF.

Table 5.13 shows how much sediment, in tons per acre, is washed off the land during the time period 1/1/96 – 8/31/97, which is the time period that was used for Case Studies 1 and 2.

Using the values in Table 5.13 we can determine the sediment load before and after development. In Case Study 1, a small percentage of the open space and forest land was converted to either impervious land or high density residential land. In Case Study 2, all of the open space and forest land in Franklin is converted. In each case, there will be increased sediment load due to the change in land use, as shown in Tables 5.14 and 5.15. These tables report the sediment loads for Subwatershed 2 (which is the area that drains into Franklin's most downstream reach). We can see from these results that the change in TSS in the river due to development is not linearly proportional to the change in sediment load, due to flow changes.

Sediment Load [tons/acre] 1/1/96 - 8/31/97	
open space	0.1802
wetlands	0.0530
forest	0.0473
low dens resid	0.1964
high dens resid	0.2821
impervious	0.5971

Table 5.13: Sediment load off the watershed near Franklin, in tons/acre, by land use

Case Study 1: Development in Resource Area Only			
Subwatershed 2: 1/1/96 - 8/31/97			
Pre-Development Conditions			
	Area [acres]	Washoff [tons/acre]	Sediment Load [tons]
open space	356.74	0.1802	64.28
wetlands	381.73	0.0530	20.23
forest	2870.79	0.0473	135.79
low dens resid	1642.97	0.1964	322.68
high dens resid	262.64	0.2821	74.09
impervious	0	0.5971	0
TOTAL			617.07
Post-Development Conditions			
	Area [acres]	Washoff [tons/acre]	Sediment Load [tons]
open space	356.16	0.1802	64.18
wetlands	381.73	0.0530	20.23
forest	2843.74	0.0473	134.51
low dens resid	1642.97	0.1964	322.68
Method I			
high dens resid	262.64	0.2821	74.09
impervious	27.64	0.5971	16.50
TOTAL METHOD I			632.19
Ratio of loads after and before dev (Method I):			1.0245
Method II			
high dens resid	290.28	0.2821	81.89
impervious	0	0.5971	0
TOTAL METHOD II			623.49
Ratio of loads after and before dev (Method II):			1.0104

Table 5.14: Case Study 1: Comparison of sediment loads before and after development

Case Study 2: Development Throughout Franklin			
Subwatershed 2: 1/1/96 - 8/31/97			
Pre-Development Conditions			
	Area [acres]	Washoff [tons/acre]	Sediment Load [tons]
open space	356.74	0.1802	64.28
wetlands	381.73	0.0530	20.23
forest	2870.79	0.0473	135.79
low dens resid	1642.97	0.1964	322.68
high dens resid	262.64	0.2821	74.09
impervious	0	0.5971	0
TOTAL			617.07
Post-Development Conditions			
	Area [acres]	Washoff [tons/acre]	Sediment Load [tons]
open space	196.21	0.1802	35.36
wetlands	381.73	0.0530	20.23
forest	1578.93	0.0473	74.68
low dens resid	1642.97	0.1964	322.68
Method I			
high dens resid	262.64	0.2821	74.09
impervious	1452.39	0.5971	867.22
TOTAL METHOD I			1394.26
Ratio of loads after and before dev (Method I):			2.2595
Method II			
high dens resid	1715.03	0.2821	483.81
impervious	0	0.5971	0
TOTAL METHOD II			936.76
Ratio of loads after and before dev (Method II):			1.5181

Table 5.15: Case Study 2: Comparison of sediment loads before and after development

5.2.4 Reduction of TSS Entering the River by 80%

The final step for each case study is to suppress 80% of the solids that leave the land surface from the newly developed land and enter the river. This is intended to simulate BMP implementation, as required by the Stormwater Management Standards.

The HSPF uci file contains a section of code called MASS-LINK which "contains the specific time series to be transferred from one operation to another [3, p. 654]." In order to transfer solids and sediment from the land surface (the PERLND and IMPLND modules) to the river (the RCHRES module), the sediment that leaves PERLND and the solids that leave IMPLND are divided into sand, silt, and clay categories and are then routed into RCHRES. In our uci file, 5% of the sediment from PERLND was routed to the sand inflow into RCHRES, 69% of the sediment was routed to the silt inflow, and 26% was routed to the clay inflow. For IMPLND, the percentages for sand, silt and clay were, respectively, 10%, 46% and 44%.

The original set-up of the MASS-LINK code allows for 100% of the sediment and solids to enter the river as sand, silt and clay. When we implemented BMPs in the model, we restricted the transfer of sediment and solids to only 20% of what was produced on the land by creating new MASS-LINK blocks. The newly developed areas (subsections of Franklin's subwatersheds) were associated with these new MASS-LINK blocks, and all other areas remained as before. For example, in Case Study 1, Method I, some (depending on the size of the resource area) of the open space and forest land in a given watershed were converted to impervious land. That newly created impervious land - and only that land - was associated with the new "80%-reduced" MASS-LINK.

Case Study 1: Development in Franklin's Resource Areas

When the 80% reduction rule was applied to the newly developed land in the resource areas of Franklin, there was not much improvement in the river. The results are shown in Tables 5.16 and 5.17. If impervious land has been used to simulate development, then Reach 2 shows a 3% improvement (i.e. decrease in TSS post- development) when

<table>
<tr><th colspan="4">Post Development</th></tr>
<tr><th colspan="4">Case Study 1, Method I (Change to Impervious Land)
Followed by 80% TSS Reduction</th></tr>
<tr><th>Reach</th><th>$TSS_{with.BMPs}/TSS_{without}$</th><th>Reach</th><th>$TSS_{with.BMPs}/TSS_{without}$</th></tr>
<tr><td>16</td><td>0.9991</td><td>8</td><td>0.9831</td></tr>
<tr><td>15</td><td>0.9990</td><td>7</td><td>0.9840</td></tr>
<tr><td>14</td><td>0.9991</td><td>6</td><td>0.9828</td></tr>
<tr><td rowspan="2">46
(flows into 13)</td><td rowspan="2">0.8621</td><td>5</td><td>0.9810</td></tr>
<tr><td>4</td><td>0.9844</td></tr>
<tr><td>13</td><td>0.9855</td><td>3</td><td>0.9866</td></tr>
<tr><td>12</td><td>0.9884</td><td rowspan="2">45
(flows into 2)</td><td rowspan="2">0.9298</td></tr>
<tr><td>11</td><td>0.9881</td></tr>
<tr><td>10</td><td>0.9837</td><td>2</td><td>0.9716</td></tr>
<tr><td>9</td><td>0.9818</td><td>1</td><td>0.9743</td></tr>
</table>

Table 5.16: Case Study 1: Post development, comparison of TSS before and after 80% reduction, Method I (the development was simulated with the conversion of open space and forest to impervious land) Fractions represent the TSS in the river after the implementation of BMPs (80% reduction) divided by the TSS before the BMPs were implemented. The results are the average of a year and a half of projected data, from 1/1/96 until 8/31/97.

BMPs are implemented. If high density residential land is used, then TSS in Reach 2 is reduced by only 0.4%. Table 5.18 shows how the loads from the subwatershed that drains into Reach 2 (Franklin's most downstream reach) are reduced with the use of BMPs. For Method I, the loads are reduced by 98% when the BMPs are applied, and for Method II, the loads are reduced by 99%. These results shown that when BMPs are required only for development in the riverfront area and other resource areas, the change in loading and in TSS in the river may not be significant.

However, as we mentioned above, it is important to remember that although the HSPF model is applying the land use changes, it it not aware that the land use changes are very close to the river. This might be one reason for the small TSS improvement in the river. On the other hand, Case Study 1's assumption that all of the land in 10% of the riverfront area and in the buffer zones would be developed may be an over-estimation.

<table>
<tr><th colspan="4">Post Development</th></tr>
<tr><th colspan="4">Case Study 1, Method II (Change to High Density Residential Land)
Followed by 80% TSS Reduction</th></tr>
<tr><th>Reach</th><th>$\mathrm{TSS}_{with.BMPs}/\mathrm{TSS}_{without}$</th><th>Reach</th><th>$\mathrm{TSS}_{with.BMPs}/\mathrm{TSS}_{without}$</th></tr>
<tr><td>16</td><td>0.9999</td><td>8</td><td>0.9979</td></tr>
<tr><td>15</td><td>0.9999</td><td>7</td><td>0.9976</td></tr>
<tr><td>14</td><td>1.0000</td><td>6</td><td>0.9978</td></tr>
<tr><td rowspan="2">46
(flows into 13)</td><td rowspan="2">0.9688</td><td>5</td><td>0.9969</td></tr>
<tr><td>4</td><td>0.9974</td></tr>
<tr><td>13</td><td>0.9979</td><td>3</td><td>0.9978</td></tr>
<tr><td>12</td><td>0.9983</td><td rowspan="2">45
(flows into 2)</td><td rowspan="2">0.9964</td></tr>
<tr><td>11</td><td>0.9983</td></tr>
<tr><td>10</td><td>0.9981</td><td>2</td><td>0.9964</td></tr>
<tr><td>9</td><td>0.9978</td><td>1</td><td>0.9968</td></tr>
</table>

Table 5.17: Case Study 1: Post development, comparison of TSS before and after 80% reduction, Method II (the development was simulated with the conversion of open space and forest to high density residential land) Fractions represent the TSS in the river after the implementation of BMPs (80% reduction) divided by the TSS before the BMPs were implemented. The results are the average of a year and a half of projected data, from 1/1/96 until 8/31/97.

Case Study 1: Development in Resource Area Only							
Post-dev land use	open space	wetlands	forest	low dens resid	high dens resid	imperv	
Tons washoff per acre 1/1/96-8/31/97	0.1802	0.0530	0.0473	0.1964	0.2821	0.5971	
Method I: Development = Impervious Land							
Acreage in developed Subwatershed 2	356.16	381.73	2843.74	1642.97	262.64	27.64	
Newly developed acreage	0	0	0	0	0	27.64	
Tons of solids leaving land use	64.2	20.2	134.5	322.7	74.1	16.5	632.2
Tons leaving land after 80% reduction on the newly dev. land	64.2	20.2	134.5	322.7	74.1	3.3	619.0
						ratio:	0.98
Method II: Development = High Density Residential Land							
Acreage in developed Subwatershed 2	356.16	381.73	2843.74	1642.97	290.28	0	
Newly developed acreage	0	0	0	0	27.64	0	
Tons of solids solids leaving land use	64.2	20.2	134.5	322.7	74.1 + 7.8 (new) = 81.9	0	623.5
Tons leaving land after 80% reduction on the newly dev. land	64.2	20.0	134.5	322.7	74.1 + 0.2(7.8) = 75.7	0	617.3
						ratio:	0.99

Table 5.18: Case Study 1: Comparison of solids loading before and after 80% reduction, for Method I (the development was simulated with the conversion of open space and forest to impervious land) and Method II (development was simulated with conversion to high density residential land.)

Case Study 2: Development throughout Franklin

When the 80% reduction rule was applied to all newly developed land throughout Franklin, much more improvement in the river could be seen than in Case Study 1. More improvement is seen when impervious land is used to simulate development (Method I) than when high density residential land is used (Method II). However, even with Method II (high density residential land), BMP application does significantly reduce TSS levels in the river. In Reach 2, the most downstream reach in Franklin, TSS is 62% lower when Method I is implemented, and 86% lower when Method II is implemented. The results are shown in Tables 5.19 and 5.20. Table 5.21 shows how the loads from the subwatershed that drains into Reach 2 are reduced with the BMPs. For Method I, the loads are reduced by 50% when the BMPs are applied, and for Method II, the loads are reduced by 65%. Compared with Case 1, these are significant changes. Of course, different subwatersheds will show different results. (Only 45% of subwatershed 2 is in Franklin.)

It must be pointed out that Case Study 2 will never be a realistic scenario, since it assumes that all open space and forest land will be converted. This case was intended to show the extreme condition, and was never intended to be simulate reality.

Comparison With Pre-Development Conditions

As mentioned above, the use of BMPs in Case Study 1 does not result in significantly improved water quality in the river. In Reach 2, TSS decreases by about 3% (Method I). However, earlier in the chapter we reported that when we compare pre- and post-development for Case Study 1, Method I, the TSS in Reach 2 *increases* by about 3%. (See Table 5.6.) Therefore, in effect, the post-development use of BMPs will actually *maintain* the pre-development water quality (using TSS as an indicator.) Similar conclusions can be drawn when comparing TSS in Reach 2 for Case Study 1, Method II and for Case Study 2.

Post Development			
Case Study 2, Method I (Change to Impervious Land) Followed by 80% TSS Reduction			
Reach	$\text{TSS}_{with.BMPs}/\text{TSS}_{without}$	Reach	$\text{TSS}_{with.BMPs}/\text{TSS}_{without}$
16	0.9930	8	0.6597
15	0.9743	7	0.6479
14	0.9633	6	0.6529
46 (flows into 13)	0.3630	5	0.5362
		4	0.5775
13	0.6712	3	0.6101
12	0.7047	45 (flows into 2)	0.7920
11	0.6989		
10	0.5825	2	0.5810
9	0.6410	1	0.6203

Table 5.19: Case Study 2: Post development, comparison of TSS before and after 80% reduction, Method I (the development was simulated with the conversion of open space and forest to impervious land) Fractions represent the TSS in the river after the implementation of BMPs (80% reduction) divided by the TSS before the BMPs were implemented. The results are the average of a year and a half of projected data, from 1/1/96 until 8/31/97.

Post Development			
Case Study 2, Method II (Change to High Density Residential Land) Followed by 80% TSS Reduction			
Reach	$TSS_{with.BMPs}/TSS_{without}$	Reach	$TSS_{with.BMPs}/TSS_{without}$
16	0.9996	8	0.8850
15	0.9976	7	0.8796
14	0.9977	6	0.8920
46 (flows into 13)	0.4172	5	0.8261
		4	0.8481
13	0.8917	3	0.8668
12	0.9098	45 (flows into 2)	0.9528
11	0.9056		
10	0.8980	2	0.8574
9	0.8863	1	0.8633

Table 5.20: Case Study 2: Post development, comparison of TSS before and after 80% reduction, Method II (the development was simulated with the conversion of open space and forest to high density residential land) Fractions represent the TSS in the river after the implementation of BMPs (80% reduction) divided by the TSS before the BMPs were implemented. The results are the average of a year and a half of projected data, from 1/1/96 until 8/31/97.

Case Study 2: Development Throughout Franklin							
Post-dev land use	open space	wetlands	forest	low dens resid	high dens resid	imperv	
Tons washoff per acre 1/1/96 - 8/31/97	0.1802	0.0530	0.0473	0.1964	0.2821	0.5971	
Method I: Development = Impervious Land							
Acreage in dev Sub-watershed 2	196.21	381.73	1578.93	1642.97	262.64	1452.39	
Newly dev acreage	0	0	0	0	0	1452.39	
Tons of solids leaving land use	35.4	20.2	74.7	322.7	74.1	867.2	1394.3
Tons leaving land after 80% reduct on the newly dev land	35.4	20.2	74.7	322.7	74.1	173.4	700.5
						ratio:	0.50
Method II: Development = High Density Residential Land							
Acreage in dev Sub-watershed 2	196.21	381.73	1578.93	1642.97	1715.03	0	
Newly dev acreage	0	0	0	0	1452.39	0	
Tons of solids leaving land use	35.4	20.2	74.7	322.7	74.1 + 409.7 (new) = 483.8	0	936.8
Tons leaving land after 80% reduct. on the newly dev land	35.4	20.2	74.7	322.7	74.1+ 0.2(409.7) = 156.0	0	609.0
						ratio:	0.65

Table 5.21: Case Study 2: Comparison of solids loading before and after 80% reduction, for Method I (the development was simulated with the conversion of open space and forest to impervious land) and Method II (development was simulated with conversion to high density residential land.)

Chapter 6

Summary and Conclusions

6.1 HSPF Results

Once the HSPF model was calibrated for hydrology and subsequently for sediment transport, it was used to test certain scenarios involving changes in land use. It was used to test the effectiveness of DEP's recently issued Stormwater Management Standards. Specifically, the model was used to test whether the use of BMPs that remove 80% of the solids from stormwater will result in a decrease in TSS levels in the river. To accomplish this, development was simulated in the town of Franklin (in the lower part of the Upper Charles River Watershed) by changing the land use data. Open space and forest land were changed to either impervious land (Method I) or high density residential land (Method II). In Case Study 1', only the resource areas and 10% of the riverfront area in Franklin were developed. This area is only a fraction of the total area of the town. This development scenario was selected because the Stormwater Management Standards only apply to this small area. In Case Study 2, all of the open space and forest land were converted to either impervious or high density residential land. This represents a "worst case" scenario.

The model runs showed that if development takes place only in the riverfront area and resource areas of a town, river TSS is not significantly affected. Similarly, when BMPs are applied only in the newly developed parts of resource areas, water quality does not change noticeably. On the other hand, the river does show much decreased

TSS levels when all of the open space and forest land in the town are developed. However, we must point out that is is not a realistic scenario and is only intended to show the upper limits of the water quality improvement in the river.

One interesting result from the scenario runs shows that when the BMPs are applied to post-development conditions, the water quality in the river, as measured by TSS, is comparable to the *pre*-development, base case scenario.

6.2 Use of the HSPF Model to Evaluate Stormwater Management Practices

In order to evaluate the Stormwater Management Standards, the HSPF model of the Charles River Watershed was calibrated for sediment transport. However, there is a lot of uncertainty in the sediment calibration. The main issue is the lack of data necessary to calibrate the model. Although the model should ideally be calibrated with measured sediment load data, this type of data was not available for the calibration. There is also no data about sediment sizes in the stormwater washoff and in the river. One additional problem is the lack of hourly precipitation data in the Upper and Middle Charles River Watersheds. When the hydrology of the watershed was calibrated, Socolofsky noted that the lack of hourly precipitation data would have an effect on the ability of the model to predict water quality parameters [43].

Given this uncertainty, the HSPF model can nevertheless be used as a tool to evaluate stormwater management practices, since the model is run with various scenarios that can compare to the base case. Even if the base case is not perfectly accurate, the comparison can still be useful.

However, there are other issues that can affect the capability of the model to predict the effects of development and the use of best management practices. Development is simulated in the model with land use changes. However, as mentioned in Chapter 5, HSPF does not know where the land use changes are. To answer questions about the effectiveness of stormwater BMPs, a smaller model would have been more useful. The subwatersheds that drain into the Charles River have large areas. The riverfront area is only a small fraction of that area, and therefore changes to the land use in that small fraction of land do not show up in the river.

In view of all of the uncertainties, there is basis to conclude that the HSPF model is not the best model to use to answer our questions about the efficiency of stormwater BMPs. It is too complex a tool for our purposes, and requires a lot of data before it can be used to make accurate predictions.

6.3 Massachusetts DEP Stormwater Management Standards

DEP's Stormwater Management Standards are very extensive and detailed, and are the result of a lot of gathering of information and consensus building. However, despite their detail, the Standards apply only in very specific circumstances. They do not apply to all new and re-development in the Commonwealth, but only within the jurisdiction of the state's Conservation Commissions, as defined in the Wetlands Protection Act. According to the HSPF model run results reported in Chapter 5, if development were limited only to the riverfront area and resource areas of a town, river water quality (using TSS as an indicator) would not be greatly affected. Similarly, when BMPs are applied only in the newly developed parts of resource areas (such that only 20% of post-development solids are allowed to enter the river), water quality does not show much improvement. The river will show a reaction only when the development extends beyond the riverfront area. Yet, because the jurisdiction for the Stormwater Management Standards comes from the Wetlands Protection Act and the Rivers Act, the Standards do not apply to areas beyond the resource areas. Since DEP can't create jurisdiction that is outside the law, the Standards can't extend outside the resource area. Unless the Massachusetts legislature were to create a new law that addresses stormwater management throughout the state, it will be difficult for the Department of Environmental Protection to regulate stormwater. The cities and towns themselves will need to be proactive and create stormwater management programs and institute bylaws. The legislation is more far-reaching in some other states. For example, Maryland's Stormwater Management Act of 1982 legislates that all municipalities within the state must require the use of BMPs for all new development [20].

Aside from the issue discussed above, DEP's Stormwater Management Standards are further restricted to larger-scale development. They do not apply to single family homes or in fact to any residential subdivision of four or fewer lots. For subdivisions of nine or fewer lots, where a critical area is not affected, the standards apply "to the extent practicable." As a result, in some towns, the Standards will never be utilized. For example, in the town of Dover, most of the development involves single family homes, and as a result the Conservation Commission in Dover has no experience with the Stormwater Management Standards [4]. The town of Sherborn is similar; according to Sherborn's Conservation Agent, only single family homes have been built since the early 1990's, when a small subdivision was built [16].

However, when the towns apply the Stormwater Management Standards to development outside the jurisdiction of the Conservation Commissions, they can potentially be very useful. The Standards, therefore, can be looked upon as guidelines for the towns. If the towns make stormwater management a priority, then they would do well to incorporate the Standards into their bylaws. The town of Franklin applies the Standards to development outside the jurisdiction of the Wetlands Protection Act. The town of Natick applies the policy to single family homes, through its Aquifer Protection District Bylaw [56].

Indeed, one of the respondents to the BMP survey issued by the Charles River Watershed Association commented that there should be an effort to help incorporate the stormwater management policy into plans that are not under the jurisdiction of the Conservation Commissions [56]. Perhaps the respondent is suggesting that towns may need some assistance to incorporate the DEP's policy into their own bylaws.

The education of the public about stormwater management and its importance is the responsibility of the state, and the individual towns and cities, rather than the

Conservation Commissions. The DEP has provided education for the Conservation Commissioners and the other town officials who will be administering the stormwater management standards. However, it is also very important to educate the public, so that businesses and individuals are aware of the repercussions of their actions.

This kind of publicity can take many forms. For example, in metropolitan Boston one can find painted notices on the pavement at the curb beside storm drains. These notices warn people not to dump anything into the drain, because it drains into the Charles (or Muddy) River. This simple notice alerts people to the consequences of their actions.

A very important method of stormwater management involves source control. Source control practices prevent pollutants from entering the stormwater and thus prevent the necessity for expensive structural controls. Source control is implemented by people and businesses all over the watershed, not simply in the resource areas.

There are other issues that the Stormwater Management Standards do not address. First, the Standards allow that the 80% solids reduction be reached by lining up BMPs in series. However, although the mathematics may add up to 80% reduction on paper, it is very likely that the real BMPs may not perform that way. For example, as mentioned in Section 3.3, detention BMPs are much better at removing larger particles than smaller particles. It is possible that the very small particles will never be removed, no matter how many BMPs are lined up in series.

Another issue raised by the literature is that not all sites will exhibit a first flush effect. The Stormwater Management Standards do not address this concern, and require that only the first flush (either 1 inch or 0.5 inch of runoff times the total post-development impervious area) must be treated.

Another question, which requires far more research that is beyond the scope of this thesis, asks whether TSS is a good indicator pollutant. As mentioned in Section 3.3, the removal of TSS might not remove certain pollutants, such as dissolved metals, that are more toxic to a particular water body. Also, fine particles are less likely to be removed, yet they contain a higher share of sorbed contaminants due to their greater surface area. It has been suggested each site needs to be assessed individually;

otherwise BMPs will be built that do not address the problem and time and money will be wasted.

There is also a concern that maintenance might be neglected, and as a result, BMPs will fail. Standard #9 requires that there must be an operation and maintenance plan in place. This is an essential requirement. However, the question remains whether the Conservation Commissions will enforce this requirement after the project has been completed. Will the site be checked a year after the development is completed? What about five years?

Studies have found a high incidence of failure among common BMPs. In many cases, the BMPs were not operating correctly. For example, a 1992 study by Lindsey, et. al., studied 258 BMPs in Maryland and found that some kind of "maintenance action" was needed in 69% of the BMPs [20]. Of the 116 detention basins studied, about 82% required some kind of maintenance. The BMP problems listed by the authors include the following: inappropriate ponding of water, slow infiltration, incorrect flow patterns, clogging of the facility, excessive treatment of debris, water bypassing the facility, design shortcomings, structural failures, and erosion at intake or outfall.

Each type of BMP will require a different type of maintenance. The frequency of the maintenance will depend on the type and amount of pollutants that the BMP treats. Care must be taken that sediment does not build up too much, and that outlets do not become clogged with debris. In dry BMPs, vegetative growth musc be monitored and removed or mowed when necessary.

Since the maintenance and operation of BMPs is a long-term commitment, the authorities need to ensure that there is a party of a fund that is responsible for the cost of maintaining the BMP.

Another comment that was mentioned in one the returned BMP surveys, completed by a Conservation Commission Member from Somerville, was that the Standards need to provide more detailed strategies for redevelopment projects [10]. Somerville's projects are usually redevelopment projects, rather than new development.

Despite its shortcomings, however, the Stormwater Management Policy is a very valuable tool, especially if towns use it as a guideline for local action.

Appendix A

Definitions

A.1 Soils: Sand, Silt and Clay

Soils are generally classified into sand, silt and clay, and the HSPF model separates the sediment and solids that wash off from the land into the river into these three basic categories. Similarly, the sediment that is transported and stored in the river is also categorized in this way.

The Natural Resources Conservation Service (NRCS) of the United States Department of Agriculture (USDA) classify soil into three basic categories depending on particle size. USDA's broad scheme is given in Table A.1.

There are other soil classification systems which vary slightly from the USDA classification. Another classification system, taken from the American Society of Civil

USDA	
Classification	Size (mm)
Gravel	> 2.0
Sand	0.05 – 2.0
Silt	0.002 – 0.05
Clay	< 0.002

Table A.1: USDA sediment grade scale. (Source: [Appendix C][49]). The sand category is subdivided into "very coarse", "coarse", "medium", "fine", and "very fine". The clay category is subdivided into "coarse" and "fine"

ASCE	
Classification	Size (mm)
Gravel	>2
Very coarse sand	2 - 1
Coarse sand	1 - 0.5
Medium sand	0.5 - 0.25
Fine sand	0.25 - 0.125
Very fine sand	0.125 - 0.062
Coarse silt	0.062 - 0.031
Medium silt	0.031 - 0.016
Fine silt	0.016 - 0.008
Very fine silt	0.008 - 0.004
Coarse clay	0.004 - 0.002
Medium clay	0.002 - 0.001
Fine clay	0.001 - 0.0005
Very fine clay	0.0005 - 0.00024

Table A.2: ASCE sediment grade scale. (Source: [54, p.20])

Engineers' 1975 text, *Sedimentation Engineering* [54, p.20] is given in Table A.2. Yet another scheme, the MIT classification, is given in Table A.3

A.2 Hydrologic Groups

Soils are categorized into one of four hydrologic groups:

Group A: High infiltration rate when wet, low runoff potential. (Sands)

Group B: Moderate infiltration rate when wet.

Group C: Slow infiltration rate when wet.

Group D: Very slow infiltration rate when wet, high runoff potential.

A.3 Universal Soil Loss Equation

The Universal Soil Loss Equation (developed by Wischmeier and Smith [54], [36]) is given in Equation A.1:

MIT	
Classification	Size (mm)
Coarse sand	2 - 0.6
Medium sand	0.6 - 0.2
Fine sand	0.2 - 0.06
Coarse silt	0.06 - 0.02
Medium silt	0.02 - 0.006
Fine silt	0.006 - 0.002
Coarse clay	0.002 - 0.0006
Medium clay	0.0006 - 0.0002
Fine clay	< 0.0002

Table A.3: MIT classification of soil size. (Source: [22, p.B-8])

$$A = RKLSCP \tag{A.1}$$

where A = computed annual soil loss per acre (in tons/ac/yr or tonnes/ha/yr)

R = rainfall energy factor, also called the erosion index because it indicates the erosion potential of the rainfall. This value will range depending on the location of the rain. The units for R are "rainfall erosion index" units. In Massachusetts the rainfall erosion index is in the range of 125 to 155 units [21].

K = soil erodibility factor, indicates the erosion capability of the soil, in units of tons/acre per unit of R measured for a cultivated continuous fallow plot of slope 9% and length 72.6 feet. K can range from 0.02 to 0.70 tons/acre/unit R [54, p. 442] and depends on the properties of the soil.

L and S = factors that account for the slope length and slope gradient, respectively, of the plot of land.

C = cover and management factor, or cropping factor, is the ratio of the soil loss of the land to the soil loss from a tilled piece of land under the identical conditions.

P = support practice factor, or the erosion control practice factor, is the ratio of the soil loss when an erosion practice is in place to the soil loss from straight-row farming.

Appendix B

Nationwide Urban Runoff Program

The Environmental Protection Agency Published the results of the Nationwide Urban Runoff Program in 1982 and 1983 [51], [53] and [52]. Some of the information found in those reports is summarized here.

B.1 Background

As described briefly in Section 2.1.1, the U.S. EPA, in conjunction with the U.S. Geological Survey (USGS), organized the Nationwide Urban Runoff Program (NURP) in order to gather information about urban stormwater. The program consisted of 28 separate projects in different U.S. cities; NURP coordinated all of these individual projects into one program; it set standards and guidelines, provided guidance and support, and allowed for communication by setting up national meetings. Ultimately, all of the data collected by the various projects were stored in one database, and the data was analyzed.

Each of the projects that participated in NURP was seeking to solve a problem relating to urban stormwater pollution. The 28 NURP projects were selected so that the data collected would provide a "representative mix" of conditions, including the type of receiving water body, type of sewerage system in place, precipitation, and land use [51].

TSS	total suspended solids
BOD	biochemical oxygen demand
COD	chemical oxygen demand
TP	total phosphorus (as P)
SP	soluble phosphorus (as P)
TKN	total Kjeldahl nitrogen (as N)
NO_2-N + NO_3-N	nitrite and nitrate (as N)
Cu	total copper
Pb	total lead
Zn	total zinc

Table B.1: NURP standard pollutants

B.2 Event Mean Concentrations of Pollutants

The National Urban Runoff Program collected data on a number of standard pollutants, listed in Table B.1. The NURP report lists the "event mean concentration", or the EMC, of each pollutant at each collection site. The EMC is defined as the total constituent mass discharge divided by the total runoff volume. Stormwater samples were collected during rainfall events, defined by the NURP report as "separate precipitation events when there was an intervening time period of at least 6 hours without rain [51, p. 5-4]."

After statistically analyzing the data from all of the sites, NURP concluded that the EMC data for each pollutant at nearly every site has a lognormal probability distribution. Therefore, the final report lists site EMC data with the mean, median, and coefficient of variation. Note that loading data (mass per watershed area) is not reported, since this data is heavily affected by the magnitude of the storm.

NURP also found that the site median EMC from all test sites fits a log-normal probability distribution. Table B.2, taken from the NURP report, gives the median estimated mean concentrations for all of the sites in the study, by land use. (Note that there were different numbers of sites in each land use category.) Table B.3 shows the national median EMCs of urban pollutants. As the NURP report states, "having determined...that geographic location, land use category, or other factors

Pollutant	Residential		Mixed Uses		Commercial		Open/Non-urban	
	Median	CV	Median	CV	Median	CV	Median	CV
TSS (mg/L)	**101**	**0.96**	**67**	**1.14**	**69**	**0.85**	**70**	**2.92**
BOD (mg/L)	10.0	0.41	7.8	0.52	9.3	0.31	-	-
COD (mg/L)	73	0.55	65	0.58	57	0.39	40	0.78
Tot Pb (μg/L)	144	0.75	114	1.35	104	0.68	30	1.52
Tot Cu (μg/L)	33	0.99	27	1.32	29	0.81	-	-
Tot Zn (μg/L)	135	0.84	154	0.78	226	1.07	195	0.66
TKN (μg/L)	1900	0.73	1288	0.50	1179	0.42	965	1.00
NO_{2-3}-N (μg/L)	736	0.83	558	0.67	572	0.48	543	0.91
Tot P (μg/L)	383	0.69	263	0.75	201	0.67	121	1.66
Sol P (μg/L)	143	0.46	56	0.75	80	0.71	26	2.11

Table B.2: Median EMCs for all sites by land use category (Source: [51, p.6-31])

appear to be of little utility in explaining overall site-to-site variability...the best general characterization of urban runoff can be obtained by pooling the site data for all sites (other than the open/non-urban ones) [51, p. 6-43]." It is obvious from the data shown in Tables B.2 and tab:urban-site-med that there were wide ranges reported for EMC values.

Pollutant	Event to Event Variability in EMCs (Coeff. Var.)	Site Median EMC	
		For Median Urban Site	For 90th Percentile Urban Site
TSS (mg/L)	**1–2**	**100**	**300**
BOD (mg/L)	0.5–1.0	9	15
COD (mg/L)	0.5–1.0	65	140
Total Pb (μg/L)	0.5–1.0	144	350
Total Cu (μg/L)	0.5–1.0	34	93
Total Zn (μg/L)	0.5–1.0	160	500
TKN (mg/L)	0.5–1.0	1.50	3.30
NO_2–N + NO_3–N (mg/L)	0.5–1.0	0.68	1.75
Total P (mg/L)	0.5–1.0	0.33	0.70
Soluble P (μg/L)	0.5–1.0	0.12	0.21

Table B.3: Median EMCs for all urban sites (Source: [51, p.6-43])

Appendix C

CRWA TSS Sampling Data

The Charles River Watershed has recorded monthly TSS data along the length of the Charles River. Although we had access to data from 8/6/96 until 12/16/97, the HSPF model of the Charles River stopped at the end of August, 1997; therefore, we used the CRWA data up until 8/19/97.

Tables C.1 and C.2 give the TSS data from samples collected by the CRWA volunteers and analyzed in either the MWRA lab or the CRWA lab.

Site	Reach	River Mile	1996 Sampling Date				
			8/6	9/3	10/1	11/5	12/3
35CS	37	3.5	1.0[a]	4.0[b]	4.0[b]	2.0	NA
59CS	33	5.9	NA	4.0[b]	NA	NA	4.0[b]
90CS	27	9.0	1.0[a]	NA	NA	2.0	NA
13CS	19	12.9	NA	NA	4.0[b]	NA	NA
165S	12	16.5	4.0[b]	NA	NA	4.0[b]	NA
199S	5	19.9	4.0	NA	NA	4.0	NA
229S	149	22.9	4.0[b]	NA	NA	4.0[b]	NA
267S	140	26.7	NA	4.75	NA	NA	NA
269T	140	26.9	NA	NA	4.0[b]	NA	4.0[b]
290S	137	29.0	1.0[a]	NA	NA	3.0	NA
318S	132	31.8	NA	NA	NA	NA	NA
343S	126	34.3	11.5	NA	NA	4.0[b]	NA
378S	117	37.8	11.0	7.6	NA	1.0	4.0[b]
400S	112	40.0	7.2	NA	NA	NA	NA
447S	107	44.7	NA	NA	7.2	NA	NA
484S	100	48.4	NA	5.8	NA	NA	4.0[b]
521S	94	52.1	7.2	NA	NA	NA	NA
534S	91	53.4	10.0	NA	NA	3.0	NA
567S	86	56.7	NA	NA	13.0	NA	NA
591S	83	59.1	NA	11.0	NA	NA	NA
609S	78	60.9	8.0	NA	NA	3.0	NA
621S	75	62.1	8.6	NA	NA	4.0[b]	NA
635S	73	63.5	NA	NA	4.8	NA	NA
648S	72	64.8	NA	8.2	NA	NA	NA
662S	69	66.2	6.0	NA	NA	4.0[b]	NA
675S	67	67.6	NA	NA	NA	NA	NA
012S	63	69.3	1.0	3.0	NA	7.0	5.3
700S	61	70.9	5.8	NA	NA	4.0[b]	NA
715S	59	71.5	4.6	NA	NA	4.0[b]	NA
729S	57	72.9	9.6	NA	NA	4.0[b]	NA
743S	55	74.3	3.0	NA	NA	4.0	NA
763S	53	76.3	5.0	6.6	NA	2.0	4.2
773S	51	77.3	7.0	NA	NA	4.0[b]	NA
784S	51	78.4	2.0	NA	NA	NA	NA

Table C.1: 1996 CRWA Sampling Dates. Some samples were analyzed in the MWRA lab and others were analyzed in the CRWA lab. Where there were two values for a given sample, the average is reported.

[a] below MWRA's detection limit of 1 mg/L. For data analysis, the value 0.5 mg/L was used.

[b] below CRWA's detection limit of 4 mg/L. For data analysis, the value 2.0 mg/L was used.

Site	Reach	River Mile	1997 Sampling Date							
			1/21	2/18	3/18	4/15	5/20	6/10	7/15	8/19
35CS	37	3.5	4.0[b]	4.0[b]	4.0[b]	4.0[b]	4.0	4.0[b]	4.0[b]	4.0[b]
59CS	33	5.9	NA	NA	NA	NA	4.0[b]	NA	NA	7.1
90CS	27	9.0	NA	NA	NA	NA	NA	NA	NA	12.0
13CS	19	12.9	4.0[b]	4.0[b]	NA	NA	NA	NA	17.5	15.0
165S	12	16.5	NA	NA	4.0[b]	NA	NA	4.0[b]	NA	4.2
199S	5	19.9	NA	NA	NA	NA	NA	NA	7.8	8.6
229S	149	22.9	4.0[b]	4.0[b]	4.0[b]	NA	NA	4.0[b]	NA	4.0[b]
267S	140	26.7	NA	NA	NA	NA	11.0	NA	NA	4.0[b]
269T	140	26.9	NA	NA	NA	4.0[b]	NA	NA	NA	4.0[b]
290S	137	29.0	NA	NA	NA	NA	NA	NA	NA	4.0
318S	132	31.8	NA	NA	NA	NA	NA	NA	NA	NA
343S	126	34.3	4.0[b]	4.0[b]	4.0[b]	NA	NA	7.8	NA	NA
378S	117	37.8	NA	NA	NA	NA	5.2	NA	16.0	4.0[b]
400S	112	40.0	NA	NA	4.0[b]	NA	NA	4.8	NA	4.0[b]
447S	107	44.7	NA	NA	NA	NA	NA	NA	4.0[b]	4.0[b]
484S	100	48.4	4.0[b]	4.0[b]	NA	NA	11.0	NA	NA	4.4
521S	94	52.1	NA	NA	4.0[b]	NA	NA	5.2	NA	4.0
534S	91	53.4	NA	NA	NA	NA	NA	NA	NA	7.0
567S	86	56.7	NA	NA	NA	8.2	NA	NA	5.7	9.8
591S	83	59.1	NA	NA	NA	NA	14.0	NA	NA	6.8
609S	78	60.9	4.0[b]	4.0[b]	NA	NA	NA	NA	NA	5.2
621S	75	62.1	NA	NA	4.0[b]	NA	NA	7.3	NA	8.55
635S	73	63.5	NA	NA	NA	NA	NA	NA	4.0[b]	8.6
648S	72	64.8	NA	NA	NA	NA	7.8	NA	NA	8.4
662S	69	66.2	NA	NA	NA	NA	NA	NA	NA	27.0
675S	67	67.6	NA	NA	4.0[b]	NA	NA	5.4	4.0[b]	5.0
012S	63	69.3	4.0[b]	4.0[b]	4.0[b]	NA	12.5	5.4	4.0[b]	6.2
700S	61	70.9	NA	NA	4.0[b]	NA	NA	6.4	NA	6.0
715S	59	71.5	NA	4.0[b]	4.0[b]	NA	NA	6.0	NA	6.2
729S	57	72.9	NA	NA	4.0[b]	NA	NA	7.0	NA	12.0
743S	55	74.3	NA	NA	4.0[b]	NA	NA	7.8	NA	NA
763S	53	76.3	4.0[b]	4.0[b]	4.0[b]	NA	5.8	6.0	4.6	NA
773S	51	77.3	NA	NA	4.0[b]	NA	NA	NA	NA	7.6
784S	51	78.4	NA	4.0[b]	4.0[b]	NA	NA	NA	NA	7.4

Table C.2: 1997 CRWA Sampling Dates. Some samples were analyzed in the MWRA lab and others were analyzed in the CRWA lab. Where there were two values for a given sample, the average is reported.

[a] below MWRA's detection limit of 1 mg/L. For data analysis, the value 0.5 mg/L was used.

[b] below CRWA's detection limit of 4 mg/L. For data analysis, the value 2.0 mg/L was used.

Appendix D

CDM TSS Sampling Data

Tables D.2, D.3, and D.4 list the TSS concentration data collected by Camp Dresser & McKee for their 1997 report, *Upper Charles River Wasteload Allocation Study*. Table D.1 explains where each sampling location is situated, as paraphrased from the CDM report.

River Site	Reach	Mile from Mouth[1]	Description
CR1	4	58.8	downstream of outlet to Populatic Pond
CR2	3	57.6	just upstream of the mouth of the Mill River
CR3	145	54.6	along the Millis/Medfield border
CR4	137	49.8	further downstream on the Millis/Medfield border
CR5	132	47.4	southern Sherborn
CR6	126	44.6	Sherborn
CR7	119	41.1	upstream of the South Natick Dam
CR8	112	38.2	Needham/Dover border
CR9	107	34.6	upstream of the Cochrane Dam
tributaries			
MR1	2	57.6	Mill River
SR1	140	51.8	Stop River
BB1	133	48.5	Bogastow Brook
WB1	114	39.4	Waban Brook

Table D.1: CDM sampling locations and corresponding HSPF reaches

[1] The CDM river miles are measured from the mouth; the HSPF study has measured the miles from the head of the river. To convert: HSPF mile = 78.4 - CDM mile

20 August 1996			
TSS Detection limit = 7 mg/L			
Sample	AM	Midday	PM
CR1	9.00	10.00	8.00
CR2	11.00	-1	-1
CR2D	NA	-1	NA
CR3	7.00	-1	7.00
CR4	10.00	-1	9.00
CR4D	NA	-1	NA
CR5	23.00	14.00	13.00
CR6	14.00	14.00	12.00
CR7	7.00	9.00	12.00
CR8	10.00	13.00	-1
CR9	11.00	7.00	16.00
CR9D	NA	-1	NA
MR1	-1	-1	-1
SR1	-1	NA	NA
BB1	-1	13.00	12.00
WB1	-1	-1	-1

Table D.2: CDM TSS Data for 8/20/96.
A value of -1 indicates that TSS was "not detected"; for purposes of analysis, the TSS value was considered to be half the detection limit, or 3.5 mg/L.
A "D" in the sample number indicates a duplicate sample
An "F" indicates that the sample was filtered when standard procedure was to collect an unfiltered sample.
A "U" indicates that the sample was not filtered when standard procedures was to collected a filtered sample.

5 September 1996			
TSS Detection limit = 7 mg/L			
Sample	AM	Midday	PM
CR1	NA	-1	-1
CR1F	NA	NA	NA
CR2	-1	-1	8.00
CR2D	NA	-1	NA
CR3	-1	-1	-1
CR3U	NA	NA	NA
CR4	7.00	-1	8.00
CR5	9.00	11.00	-1
CR6	23.00	14.00	11.00
CR6D	NA	15.00	NA
CR7	-1	16.00	-1
CR8	8.00	8.00	19.00
CR9	NA	-1	11.00
CR9D	NA	-1	NA
CR9F	NA	NA	NA
MR1	NA	-1	NA
SR1	-1	-1	-1
BB1	NA	13.00	NA
WB1	NA	-1	NA

Table D.3: CDM TSS Data for 9/5/96.
A value of -1 indicates that TSS was "not detected"; for purposes of analysis, the TSS value was considered to be half the detection limit, or 3.5 mg/L.
A "D" in the sample number indicates a duplicate sample
An "F" indicates that the sample was filtered when standard procedure was to collect an unfiltered sample.
A "U" indicates that the sample was not filtered when standard procedures was to collect a filtered sample.

8 October 1996			
TSS Detection limit = 1 mg/L			
CR1	5.2	1.4	4.5
CR1D	NA	2.7	NA
CR1F	NA	NA	NA
CR2	3.2	3.4	5.8
CR3	1.2	1.2	-1
CR4	4.8	5.5	4.5
CR5	6.4	5.9	7.8
CR6	6.0	4.2	6.4
CR7	8.4	10.0	6.2
CR8	3.5	3.6	4.4
CR9	4.3	3.9	17.00
CR9D	NA	5.1	NA
CR9F	NA	NA	NA
BB1	4.2	3.5	NA
MR1	1.7	-1	NA
SR1	1.8	2.0	NA
WB1	5.2	1.6	NA

Table D.4: CDM TSS Data for 10/8/96.
A value of -1 indicates that TSS was "not detected"; for purposes of analysis, the TSS value was considered to be half the detection limit, or 0.5 mg/L.
A "D" in the sample number indicates a duplicate sample
An "F" indicates that the sample was filtered when standard procedure was to collect an unfiltered sample.

Appendix E

M&E/MWRA Report: Estimation of Stormwater Flows and Loads

As discussed in Section 4.5.2, the 1994 report by Metcalf & Eddy (M&E) for the Massachusetts Water Resources Association (MWRA), *Sub-Task 2.5.5: Final Technical Memorandum Estimation of Stormwater Flows and Loads*, proved useful for the calibration of sediment in the Charles River model.

E.1 Review of Previous Stormwater Studies: TSS Concentrations

Table E.1 summarizes the statistics for each of the five studies reviewed in the M&E report. The report ultimately used the first four of these studies to select a constant concentration for TSS and the other stormwater pollutants.

E.2 Overlap with the Charles River Watershed

As described in Section 4.5.2, the M&E report included two receiving water segments that coincided with parts of the Charles River Watershed. Tables E.2 and E.3 explain how these two receiving water segments coincided with HSPF reaches; the land use

TSS Concentration Statistics [mg/L]						
Study	Arithmetic Mean	Standard Deviation	Median	Minimum	Maximum	Sample Size
1	41.7	75.6	26.5	5	542	54
2	44.6	48.1	36.0	4	148	7
3	22.4	29.4	9.0	3	92	9
4	27.9	21.2	22.0	4	76	15
1-4 Overall	37.5	63.1	22.0	3	542	85
5	20.5	23.3	13.5	2.5	96	14
1-5 Overall	35.1	59.3	19.0	2.5	542	99

Table E.1: Summary of Previous Boston Stormwater Studies: TSS Concentration
1 = MWRA: Final Combined CSO Facilities Plan and Final Environmental Impact Report (1989)
2 = Boston Water and Sewer Commission Sewer Separation Study (1988 and 1990)
3 = MWRA's Toxic Reduction Program (1990)
4 = Boston Water and Sewer Commission: Part 2 of NPDES Permit Application (1993)
5 = MassPort at Logan Airport: NPDES Permit Application (1992)

<table>
<tr><th colspan="2">"Upper Charles"</th></tr>
<tr><td>Subwatershed relating to HSPF reach number</td><td>Percentage of subwatershed included in "Upper Charles"</td></tr>
<tr><td>155</td><td>28%</td></tr>
<tr><td>156</td><td>37%</td></tr>
<tr><td>157</td><td>79%</td></tr>
<tr><td>161</td><td>74%</td></tr>
<tr><td>164</td><td>28%</td></tr>
<tr><td>165</td><td>9%</td></tr>
<tr><td>158, 159, 160, 162, 163</td><td>100%</td></tr>
<tr><td colspan="2"><i>Plus, there is additional land in the "Upper Charles" receiving water segment that does not coincide with the Charles River Watershed. This land is roughly twice the size of the area of the land associated with reaches 160 and 162, combined.</i></td></tr>
<tr><td>160, 162</td><td>192%</td></tr>
</table>

Table E.2: How the M&E "Upper Charles" receiving water segment relates to reaches in the Charles River Watershed model

distribution in these reaches were used to determine the land uses for the "Upper Charles" and "Lower Charles" receiving water segments. Table E.4 shows the actual division of area by land use for each of the two receiving water segments.

The division of the "Upper Charles" and "Lower Charles" receiving water segments into HSPF reaches was done by examining the M&E map overlaid on top of the map of the Charles River Watershed with the reaches delineated. The author accepts that this method is not too precise; nevertheless, for our purposes, it is precise enough. The exercise was intended to roughly compare the HSPF and M&E results.

"Lower Charles"	
Subwatershed relating to HSPF reach number	Percentage of subwatershed included in "Lower Charles"
151	28%
152	19%
155	27%
156	9%
161	19%
251	9%
256	58%
153, 154	100%

Table E.3: How the M&E "Lower Charles" receiving water segment relates to reaches in the Charles River Watershed model

Land Use	**"Upper Charles"** [acres]	**"Lower Charles"** [acres]
Open Space	1134.29	1193.20
Wetlands	359.68	329.72
Forest	292.10	310.11
Low dens. residential	574.55	478.19
High dens. residential	3305.78	1805.28
Impervious	2443.44	1427.63
Total Area According to Our Calculations	8109.83	5544.14
Actual Area Reported by M&E	8107.93	5548.42

Table E.4: Attempt to distinguish land use in "Upper Charles" and "Lower Charles"

Appendix F

BMP Survey to Charles River Watershed Communities

The following survey was sent to 28 communities in the Charles River watershed. In most cases, the survey was sent to the Conservation Commission of the town. In other cases, the survey was sent to the Department of Public Works, the Town Planner, or the Town Engineer. The majority of the surveys were not been returned to CRWA by the time this thesis was published, and therefore the thesis does not include an analysis of the results.

I. Community Survey

1. Which of your town boards require the use of DEP's stormwater policy?

☐ Conservation Commission

☐ Planning Board

☐ Other (please list) ______________________________

☐ They are not being applied in our town (Please state why not) __________

2. Single-family homes are not covered by the stormwater policy. However, does your town routinely apply the policy to single family homes (for example, do you require infiltration of roof runoff?

☐ Yes

☐ No

3. Which BMPs have been used in your worn within the last 18 months? Check

all that apply.

☐ Extended Detention Pond
☐ Wet Pond
☐ Vegetated Water Quality Swale
☐ Infiltration Trench
☐ Infiltration Basin
☐ Dry Well
☐ Organic Filter
☐ Water Quality Inlet
☐ Sediment Trap
☐ Drainage Channel
☐ Deep Sump/Hooded Catch Basin
☐ Street Sweeping
☐ Other or Brand Name systems

name(s): ____

____

____

____

II. Project Survey

On the following five pages you will be asked the same questions about five projects that have been proposed in your town, one from each of the categories below:

- 2- to 4-lot subdivision
- 5- to 9-lot subdivision
- > 9-lot subdivision
- Redevelopment
- New commercial development

Please select one project in each category and respond to questions 4 through 11 for each project type indicated at the top of the page.

Project Type: [*One of the five categories listed above*]

4. Project name: ____________________

DEP No.: ____________________

Date Order of Conditions was issued: ____________________

5. Please attach the project stormwater management form for this project, if available. (This is a 2-page DEP form.)

6. Which BMPs were used in this project? Was the drainage area for each BMP indicated in the Notice? What are the operation and maintenance requirements? (Please fill out the chart on the reverse side.)

7. Was an operation and maintenance plan submitted for this project?

☐ Yes

☐ No

8. If so, does the Order of Conditions require the operations and maintenance plan to be in place in perpetuity?

☐ Yes

☐ No

9. Who is responsible for operation and maintenance?

Name: ____________________

Address: ____________________

____

Phone: ____________________

10. Does the Order of Conditions or operations and maintenance plan require testing of BMPs?

☐ Yes - How often? ____________________

☐ No

11. Please provide project engineer and owner contact information:

Engineer: ____________________	Owner: ____________________
Address: ____________________	Address: ____________________
____________________	____________________
Phone: ____________________	Phone: ____________________

6. Which BMPs were used in this project? Was the drainage area for each BMP indicated in the Notice? What are the operation and maintenance requirements? (Please fill out the table following the example).

BMP		Drainage Area	Activities and Frequency of Operation and Maintenance	
			Inspection	Cleaning
√	Extended Detention Pond	*approx. 2 acres*	*check inlet and outlet pipes quarterly, sediment build-up 2X per yr*	*clean pipes as needed, dredge at least every 2 yr*
	Extended Detention Pond			
	Wet Pond			
	Vegetated Water Quality Swale			
	Infiltration Trench			
	Infiltration Basin			
	Dry Well			
	Sand Filter			
	Organic Filter			
	Water Quality Inlet			
	Sediment Trap			
	Drainage Channel			
	Deep Sump/Hooded Catch Basin			
	Street Sweeping			
	Other or Brand-name Systems:			

III. Further Information, Comments and Suggestions:

12. Do you find the stormwater policy to be helpful in your review and permitting process?

☐ Yes

☐ No – Why not? ____

____

13. Have you attended a DEP stormwater training workshop?

☐ Yes

☐ No

14. What would make the stormwater policy more useful to you in terms of project review and permitting?

____

____

____

15. Any other comments?

____

____

____

____

Thank you for your time.

Appendix G

Map of the Charles River Watershed Communities

The Charles River Watershed, which includes about 310 square miles of drainage area, encompasses 35 cities and towns. The Charles River is just under 80 miles long, beginning in Hopkinton, just upstream of Echo Lake, and ending in Boston Harbor.

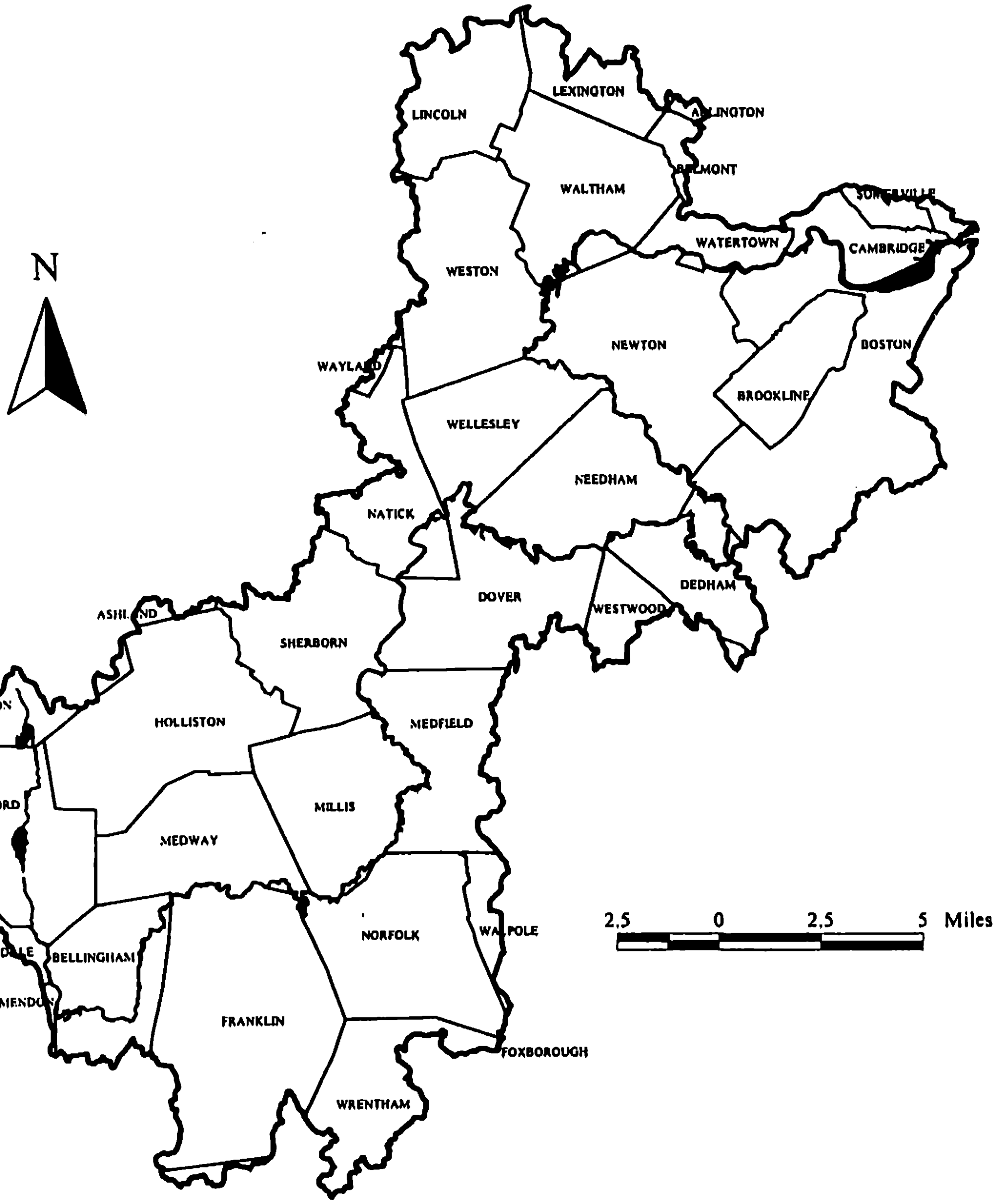

Figure G-1: The thirty-five communities which comprise the Charles River Watershed. [Source: MassGIS and CRWA]

Bibliography

[1] AQUA TERRA Consultants. Hspf training workshop (handouts and documentation), March 1998. Handouts and documentation from the HSPF Training Workshop held in Boston, MA on March 3-6, 1998.

[2] Bruce Babcock, Town Engineer, Franklin, Massachusetts, private communication.

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