Low-Impact Development in the Assabet River Watershed: Site Hydrologic Design and Watershed-Scale Implications

By

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SUBMITTED TO THE DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

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ABSTRACT

Low-Impact Development (LID) is a relatively new approach to stormwater management. It aims to mimic natural hydrology through increased recharge and decreased runoff. LID technologies focus on distributed treatment of stormwater, as opposed to traditional centralized management. The potential benefits include improved water quality in runoff, decreased flooding in rivers and streams, and increased baseflow critical to surface water quality. This thesis investigates two important aspects of any new stormwater management technology: the site level design and large-scale implications.

A case study for site-level design is performed in the town of Acton in central Massachusetts. An LID stormwater management design is completed on a three-acre site. The design implements LID technologies, such as rain garden storage areas, pervious pavement, and curb cuts. Pre-developed, existing, and LID-designed scenarios are analyzed. A computer program called the Site Low-Impact Development Design (SLIDD) Model is developed to account for the distributed nature and unique characteristics of the LID technologies. Analysis reveals that LID is capable of not only improving the existing site hydrology, but returning a developed site to natural hydrologic conditions. The design is able to control both peak runoff rates and runoff volume.

The watershed-scale implications of LID are of great importance, especially as implementation of such technologies increase. The potential benefits are analyzed using a water balance model of the Upper Nashoba Brook Watershed in Massachusetts. It is observed that LID implementation on a large scale can improve baseflow during critical summer low-flow months. It is also noted that LID can decrease flooding through the reduction of overland flow and interflow. The importance of using progressive stormwater management techniques like LID in the further development of the area is highlighted by an analysis of the decline of baseflow to zero during summer months with increased development. While the benefits strongly support LID, several concerns are noted. Both the decrease of ground water quality through increased recharge of contaminated stormwater and potential economic and logistic concerns of an increasing water table are potential liabilities of LID. The conditions under which LID could cause these problems are discussed, as well as potential solutions.

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1 Introduction

The environmental movement of the early 1970s changed how natural resources were managed in the United States. Environmental disasters, including the Chernobyl nuclear accident, the Cuyahoga River "burning on newscasts all over the world" (Graham 1999), and Rachel Carson's account of pesticide dangers all sparked fear in the American public (Graham 1999). At the same time, the baby boom and suburbanization drove the economy into a period of long-term growth (due to new infrastructure needs), and exposed the public to nature. As a result, a movement arose within the middle class fueled by an emerging appreciation for nature and the environment. The deficiencies of environmental management and regulation were attributed to natural resource agencies, largely formed during the Progressive Era. It was argued that "the administrative agencies tended to be captured by self-interested clients and congressional subcommittee members whose gains from their decisions were symbiotic to the agencies' needs for their political support" (Andrews 1999). Also, states were not trusted to handle environmental management and regulation, as they were believed to be "engaged in a race to the bottom to minimize environmental protection in order to attract business" (Graham 1999). The solution was a huge initiative, driven by public upheaval, to set national standards on the quality of natural resources.

The remedial environmental laws were defined by national standards that required quick action from the entities that were being regulated. These entities were almost entirely composed of large polluting companies and wastewater treatment plants. Laws required that technologies be implemented at the *end of the pipe* to minimize pollution. The hypothesis was that the introduction of pollution-removal technologies would transfer harmful substances to controllable forms and clean up the nation's natural resources. As decades passed, a large improvement was observed. Many waterways began to be fishable and swimmable. Still though, many ecosystems suffered from urban and agricultural pollution. Most large businesses and wastewater treatment plants had already been addressed, and the attention began to shift to other sources.

In 1998, President Clinton signed the Clean Water Action Plan, which emphasizes this new shift in management:

> We have made tremendous strides in cleaning up our rivers, lakes and coastal waters, largely by controlling pollution from factories and sewage plants. Yet 40 percent of our surveyed waterways are still too polluted for fishing and swimming. The largest remaining challenge is reducing "nonpoint" pollution: runoff from farms, city streets and other sources. (EPA 2004).

Population growth and urban sprawl in the United States have exposed many new ecosystems to urban pollution. In developing areas, rainwater carrying auto emissions and fertilizers is routed directly to nearby surface waters. The Clean Water Action Plan was intended to attract attention to this large and formerly ignored problem. Due to this increased attention on pollution loads from nonpoint sources, research and literature has grown in controlling and managing the problem. The following section summarizes the literature on nonpoint source pollution control.

2 Nonpoint Source Pollution Control

The management of nonpoint sources varies according to the land use. For example, the strategies for managing sources of pollution from an urban area differ from those of a forest or agricultural area. Because this paper focuses on controlling the impact of developing areas, I will concentrate on the management of nonpoint sources from urban areas. The following strategies were emphasized by Kwon et al. (2002):

- Land Use Planning
- Land Conservation
- Site Design
- Erosion and Sediment Control
- Stormwater Best Management Practices (BMPs)

2.1 *Land Use Planning*

Land use defines the type of surface cover, present chemicals, and population density. In considering these factors, a manager must be able to predict the effects and plan accordingly to future land use changes. The following list shows various land use management techniques (Kwon et al. 2002).

- Watershed-Based Zoning
- Overlay Zoning
- Floating Zones
- Incentive Zoning
- Performance Zoning
- Urban Growth Boundaries
- Large-Lot Zoning
- Infill Community Development
- Transfer of Development Rights

These types of zoning techniques are designed to minimize the amount of impervious surfaces and negative effects of nonpoint source pollution to local water bodies.

2.2 *Land Conservation*

Land conservation is closely related to land use planning, and deals with selecting areas that should be maintained in order to ensure the integrity of the surface water systems. Main areas that should be included are critical habitats, aquatic corridors, and undeveloped areas of hydrologic function (i.e. forests). Riparian buffers, the area where land meets water, are of particular importance. They function to regulate environmental conditions, remove sediment and nutrients from stormwater, and stabilize and protect the stream banks. While these areas are managed because of their benefits to the watershed, other areas should be managed because of their potential harm. Water pollution hazards (i.e. landfills, septic systems, and impervious areas), for example, should be located and set away from water bodies.

2.3 *Site Design*

As a community grows and develops, the way new sites are designed plays a critical role. Traditionally, suburban developments have been characterized by very wide streets and large amounts of impervious area. Recently, innovative ways of designing a site minimize impacts to the ecosystem. There are three categories of site design that can be altered to lessen nonpoint source pollution:

- Residential streets and parking lots – minimize unnecessary impervious surfaces
- Lot development – consolidate the developed portions of the property
- Conservation of natural areas – protect natural water bodies and vegetation by minimizing clearing

2.4 *Erosion and Sedimentation Control*

Erosion and sedimentation of soils during construction is detrimental to stormwater and surface water quality. There are many methods to control this problem, such as limiting clearing and grazing, stabilizing drainage ways, phasing construction, protecting steep cuts and slopes, and installing controls along the perimeter to filter sediments. These types of strategies should be included in a watershed management plan.

2.5 *Stormwater Best Management Practices (BMPs)*

Stormwater BMPs are designed to delay, store, capture, infiltrate, and treat rain water in an effort to lessen the impacts of urban development on water quality and quantity. Stormwater should be managed to meet the following goals (Kwon et al. 2002):

- Maintain groundwater quality and recharge.
- Reduce stormwater pollutant loads
- Protect stream channels
- Prevent increased overbank flooding
- Safely convey extreme floods

These goals have traditionally been met using structural designs, such as detention and infiltration basins. The results have often been inadequate, and have been observed to even exacerbate problems. Recently, a new stormwater management philosophy and set of technologies has formed called Low-Impact Development (LID). It is largely based on the themes of nonpoint source pollution control.

3 Low-Impact Development

Historically, stormwater management has focused on flood protection through the controlled release of water. The most commonly used technology for this concept is the detention basin. The strategy is to remove water from most of the site to on-site detention basins as quickly as possible and to then control the rate of release, instead of the volume. As development increased in urban areas, the detention basin became deficient at preventing flooding downstream. The volume of water produced from urban areas upstream overloaded the water systems. People began to see that lowering runoff volume could even further prevent flooding. Infiltration basins arose as a technology that could decrease the amount of runoff volume through infiltration and recharge of the groundwater aquifer. By the 1970's, infiltration basins were widespread in the U.S. (Potter 2003). Infiltration basins have many downfalls though. They are costly to maintain and need favorable soils and sufficient depth to groundwater (Potter 2003). Also, because they are large basins used at a centralized location, runoff is still taken off the site as quickly as possible. As a result, the natural hydrology of the area is not preserved. More recently, a technology called low-impact development arose that focuses not only on preserving the natural water balance, but on preserving the entire ecosystem. Low-impact development uses this same idea of increased recharge and evapotranspiration, but in a decentralized manner. The use of many small infiltration devices makes LID easier to site and allows for enhanced infiltration. In addition, the technologies can be altered for the storm water conditions. For example, bioretention cells can be used for more polluted water instead of pure infiltration areas. The hydrologic objective of LID is to mimic the undeveloped site conditions.

LID Technologies

LID technologies reduce runoff through infiltration and evapotranspiration at the site level. From a hydrologic standpoint, there are three major groups of LID technologies: trench, swale, and surface cover. This section will expand on the functions of each group.

- **Trench**

Trench infiltration is functionally the same as the large infiltration basins, but on a much smaller scale. Trenches recharge the aquifer through infiltration to subsurface soils. Soils in trench systems are usually replaced with higher conductivity soils, such as sand. A schematic of the trench system is shown in Figure 1 (Coffman 2004).

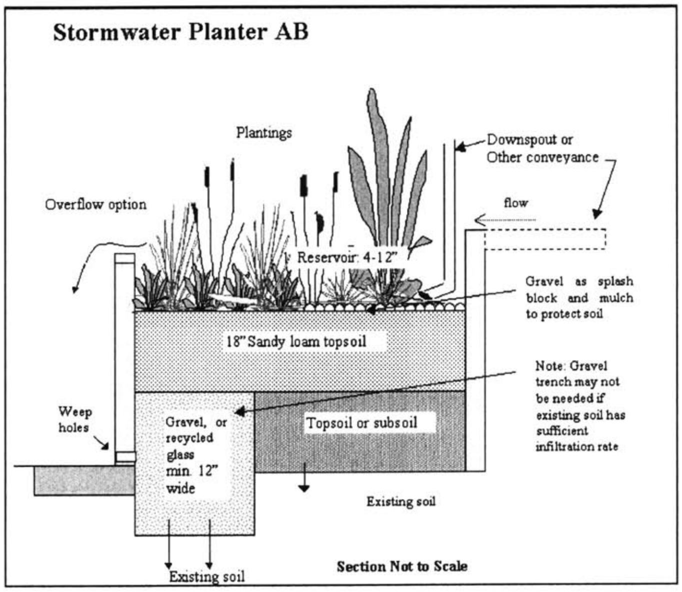


Figure 1: Trench infiltration system

Besides promoting infiltration, the trenches can serve additional functions. Rain gardens, a trench technology, also increase the amount of water transpired to the atmosphere by plants. Another form of trench technology, Bioretention cells, degrades contaminants in the water through natural processes, such as phytoremediation and bioremediation. As a result, they readily degrade organic contaminants. The design of rain gardens requires a known soil hydraulic conductivity. This parameter is necessary for predicting the outflow of the system. Optimally, the gardens should not have ponded water for more than four hours. An under-drain is often installed to ensure this property.

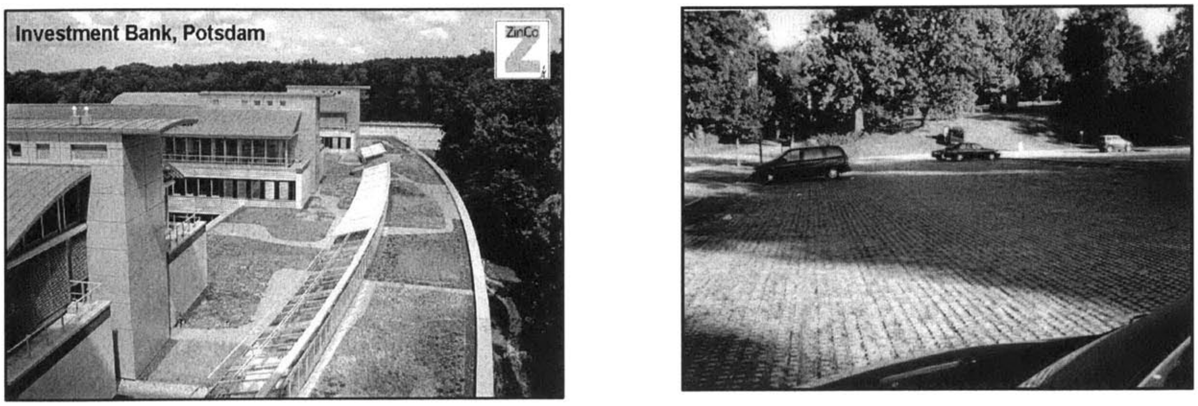
- **Swale**

Swales are depressions that capture and infiltrate water. During high rainfall events, swales can also transport water. Functionally, they replace the pipe in "pipe and pond" conventional situations. Biofiltration swales can be used to improve the quality of the storm water runoff. An application of a vegetative swale is illustrated in Figure 2. Through natural processes similar to those used in the bioretention cells (bioremediation/ phytoremediation), various contaminants can be degraded (Coffman 2004).

Figure 2: Swale technology

- **Surface Cover**

Changing the characteristics of the ground surface can improve on-site infiltration and evapotranspiration, and allow you to manage more storm water on-site. The three major examples of surface technologies are green roofs, pervious paving, and soil amendments. Buildings are one of the major impervious areas in suburban and urban settings. Green roofs allow building roof surfaces to store and evapotranspire water. Pavement is the other major type of impermeable surface in urban developments. Permeable pavements allow stormwater to infiltrate to the underlying soils and aquifer. Figure 3 demonstrates typical applications of green roof and porous paver systems. They can be made of varying materials, such as grass, stone, and gravel. Site construction causes soil compaction, which can greatly reduce the hydraulic conductivity of the soil. Amending and aerating the soil allows root structures to penetrate and improves the soil quality. This technique has been proven to lower runoff rates and volumes (Coffman 2004).



Green Roof

Pervious Pavement

Figure 3: Surface cover systems

4 Assabet River Watershed

The Assabet Watershed encompasses all or part of 20 different communities. The watershed is shown in Figure 4.

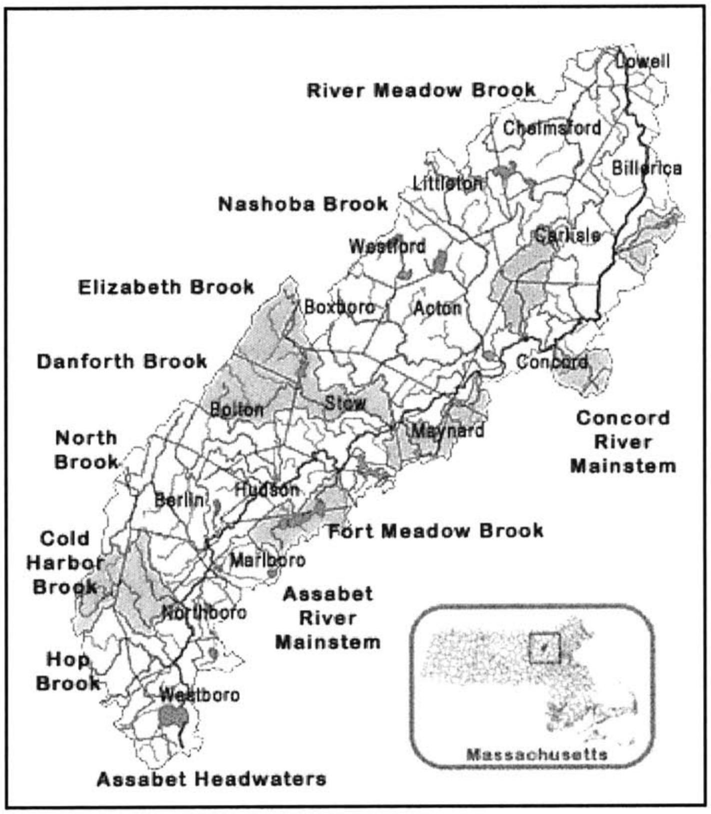


Figure 4: Assabet Watershed

Seven of these 20 communities derive public drinking water from the Assabet aquifer and/or surface water sources in the watershed. These seven communities include Acton, Concord, Hudson, Marlborough, Maynard, Northborough, and Westborough. As of late 2002, Acton and Maynard were the only two towns that had public water supplies derived solely from Assabet watershed groundwater supplies (MDEP 2002).

In 1986, a group of concerned citizens who recognized developmental impacts on the Assabet watershed established the Organization for the Assabet River (OAR). OAR is a 501(c)(3) nonprofit group whose mission is to preserve, protect, and enhance the Assabet River, its tributaries, and watershed. In January 2002 a two-year joint project between OAR and the Assabet Consortium began in an effort to study specific Assabet River impacts on water quality. The project was funded through a $350,000 EPA EMPACT Metro grant. According to the

Assabet River Stream Watch Organization's preliminary findings "the Assabet has already lost much of its baseflow because of existing groundwater withdrawals, sewering, and extensive paved and otherwise impervious surfaces where water can't infiltrate back into the aquifers" (Stream Watch).

The loss of groundwater infiltration, which directly results in base flow reduction into the Assabet River, is especially pronounced in summer months. In fact, in the summer of 1995 the United States Geological Survey recorded Assabet River flows that were less than the sum of the wastewater effluent being discharged into it (Roy 1998). During the peak summer months, there is increased groundwater demand from residents to irrigate lawns and wash cars. Acton alone experiences a 30% average increase in water demand during summer months (2002 water use data). In addition to the increased human demand, there is seasonal increase in evapotranspiration due to flora bloom.

Compounding the increased groundwater demand, there is an increase in surface-water loss due to elevated air temperatures and a loss of supply from upriver snow melts. Hard-pipe sewering of impervious surface runoff has a year-round impact on groundwater recharge, but the traditionally high nutrient loaded summer runoff is a particularly large contributor to the Assabet water quality problems.

For these reasons it is vital for all Assabet water consumers, especially those like Acton and Maynard who have high groundwater demand, to look for ways to budget their demands and explore methods to maximize opportunities for groundwater recharge. Acton currently holds a Massachusetts Water Management Act (WMA) registration and withdrawal permit for up to 1.9 million gallons per day (MGD) or 700.9 million gallons per year (MGY). Town water-use data for 2002 indicates a total of 680 MG consumed that year. With demand nearly maximized, the only plausible method of increasing baseflow and permitted withdrawal allowance is to enhance recharge to the groundwater aquifer.

Further, the only way to have a significant impact on the quantity of aquifer recharge is to 1) increase precipitation, or 2) better manage precipitation runoff to optimize infiltration. Since changing weather cycles is neither possible nor desired, the only real option is to maximize stormwater infiltration and aquifer recharge. Unfortunately, current thinking and conventional stormwater management have not centered on the idea of maximizing infiltration. Instead, conventional stormwater management has been to carry runoff (e.g. via gutters, curbs, etc.) to a collection area (e.g. sewer intake, detention area, etc.) and convey it via hard-pipe infrastructure to the river. This method succeeds in abating localized flooding, but fails tremendously in many other respects. By collecting the runoff in hard, impervious devices, the speed of the runoff is increased, which leads to increased sediment loading. Additionally, total pollutant loading is concentrated and directed downstream and released as a point discharge. This hard-piped, accelerated collection and conveyance method prevents any possibility of infiltrative recharge or natural water quality improvement.

5 Motivation

Use of Low-Impact Development has grown in the United States. LID technologies have been implemented across the country, including in Maryland, Illinois, Minnesota, Oregon, and Washington. Pilot studies have indicated that LID is able to reduce runoff volume from sites, and therefore reduce anthropogenic impacts on an ecosystem. Consequently, more municipalities are beginning to accept LID as a more appropriate way to manage stormwater.

The rise in popularity has warranted a deeper understanding of the technologies. The following two sections will examine the design of LID technologies at the site scale and the effects of implementing LID as a management practice at the watershed scale. In the first section, I will develop a systematic approach to hydrologic site design, based on the NRCS method. In the second section, I will evaluate potential benefits and liabilities of LID.

The Assabet River Watershed was chosen as the study area. As discussed earlier, the watershed has suffered from water quality problems, many of which are attributed to low summer baseflow. LID implementation is a feasible solution in this scenario. The design section of this report looks at a small site in the Assabet River Watershed containing the Discover Museums of Acton, Massachusetts. The watershed-scale implications are analyzed using a water balance of the Upper Nashoba Brook Watershed, a sub-basin of the Assabet River Watershed.

6 Site Conceptual Design

6.1 *Case Study Overview – Acton Discovery Museums*

The Discovery Museums, located in Acton, Massachusetts, was used as a case study for the design of LID technologies. The site is located in the Assabet River Watershed. An aerial photograph is shown in Figure 5. The Discovery Museums site was chosen because some LID technologies (pervious pavement, rain garden) had already been implemented under an Intel grant. Jim Brown, Najwa Obeid, and I developed an LID design for the entire Discovery Museums site as part of a project for the Masters of Engineering program at the Massachusetts Institute of Technology. The project team evaluated expanding the northeast parking lot so that the southwest parking lot could be converted into a green space. Runoff from the parking lots was designed to be managed in LID facilities. This chapter introduces the Discovery Museums site, describes our design process, and details the conceptual LID design. Chapter 7 then describes how I sized and analyzed the LID features from a hydrologic standpoint.

6.2 *Existing Conditions*

The Discovery Museums are located on a three-acre (135,000 sf) L-shaped lot in a primarily residential area of Acton, Massachusetts. The site has a fairly steep slope from south to north with a small ridge separating the site into two distinct sub-basins as illustrated in Figure 5. Runoff from sub-basin #1 drains to the conservation area to the north. Sub-basin #1 runoff is primarily caused by overland sheet and concentrated flow. There are no stormwater catchments or piped discharges on this side of the site.

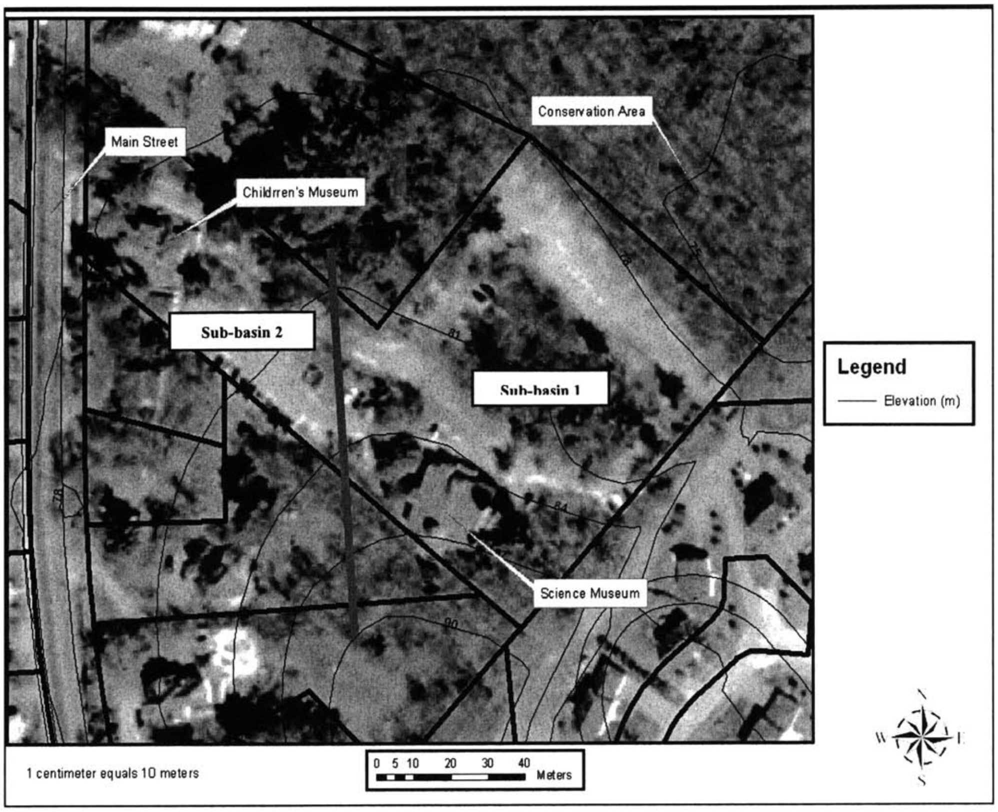


Figure 5: Discovery Museums existing site layout

Runoff from sub-basin #2 drains towards Main Street. Catch basins located in the west parking lot and at the bottom of the museum entrance driveway collect runoff from Sub-basin #2. The catch basins are piped to a public storm-sewer in the street at the base of the entrance driveway.

The total paved and unpaved areas of the site are illustrated in Figure 6. There are currently 1.19 acres (51,900 sf) of paved surface, which represents approximately 40% of the total site area. There are three main museum structures and two maintenance tool sheds. The impervious area created by these structures totals 0.15 acres (6700 sf). The site is comprised of a Soil Conservation Service (SCS) Hydrologic Group C soil. This soil type coupled with the wooded cover of a majority of the pervious surfaces results in an SCS curve number (CN) of 73.

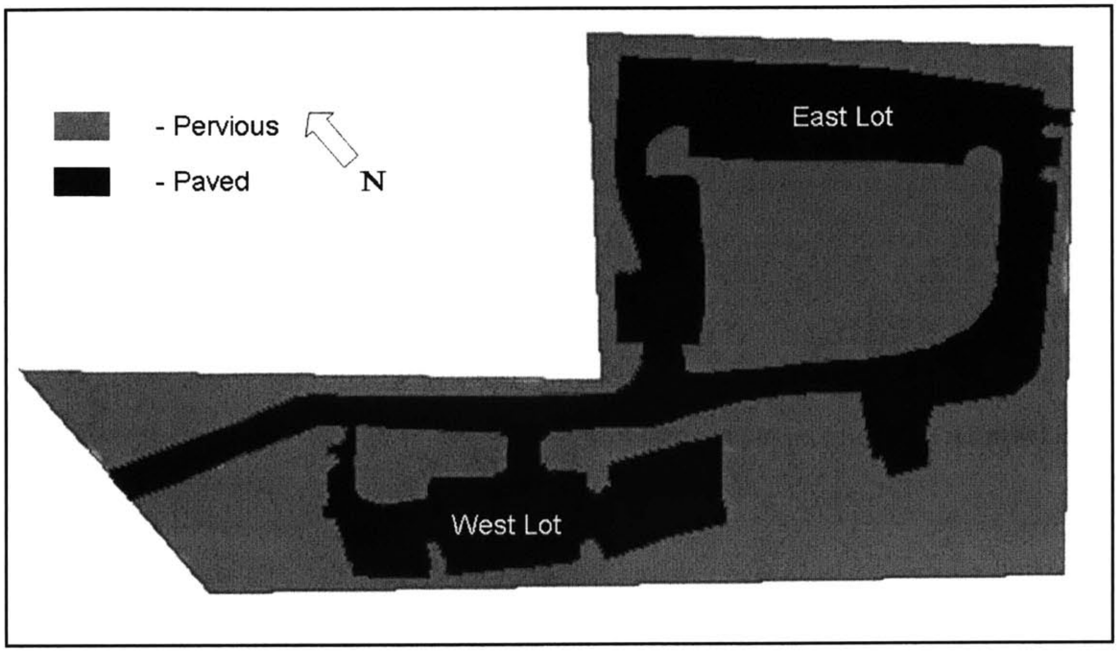


Figure 6: Existing paved and unpaved surfaces

The perimeter of the site is outlined by a stone wall, which delineates the property line. This method of property delineation is a typical for the New England region.

East lot - The center median of the east parking area is approximately 0.52 acres (22,000 sf) of naturally forested cover. The trees surrounding the lot and within the median area are a mixture of deciduous and evergreen. The two tool-sheds and solid waste dumpster shown in Figure 7 are located on the west side of the east lot median area. The east lot has seventy-one standard parking spaces and one handicap space.

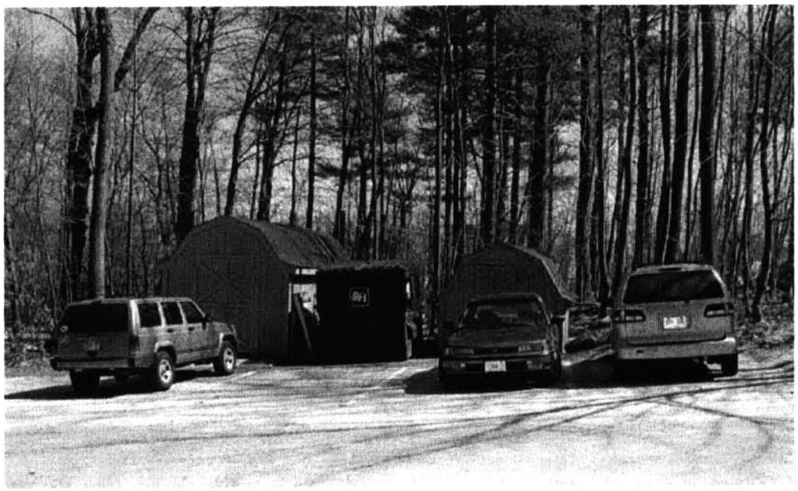


Figure 7: Discovery Museums tool and equipment sheds

West lot – The west lot is comprised of three small parking cells with opposing peninsula garden areas creating entrances to each cell. There are twenty-three standard spaces, two handicap spaces, and three undesignated spaces in the cell closest to the Children's Museum structure. A leach field supporting the Science Museum's septic system is located beneath the center parking cell and extends into the entrance driveway. A 3,400 square foot garden area with a small nature trail, shown in Figure 8, forms the northeast boundary of the center and lower parking cells.

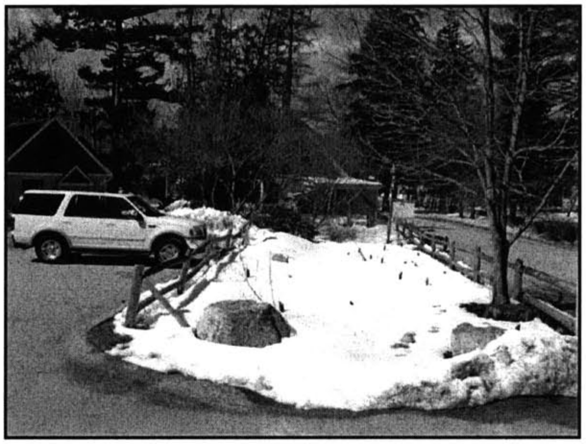


Figure 8: West lot garden and nature trail

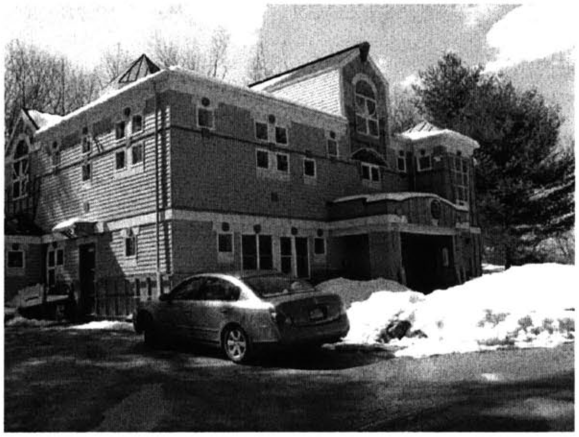


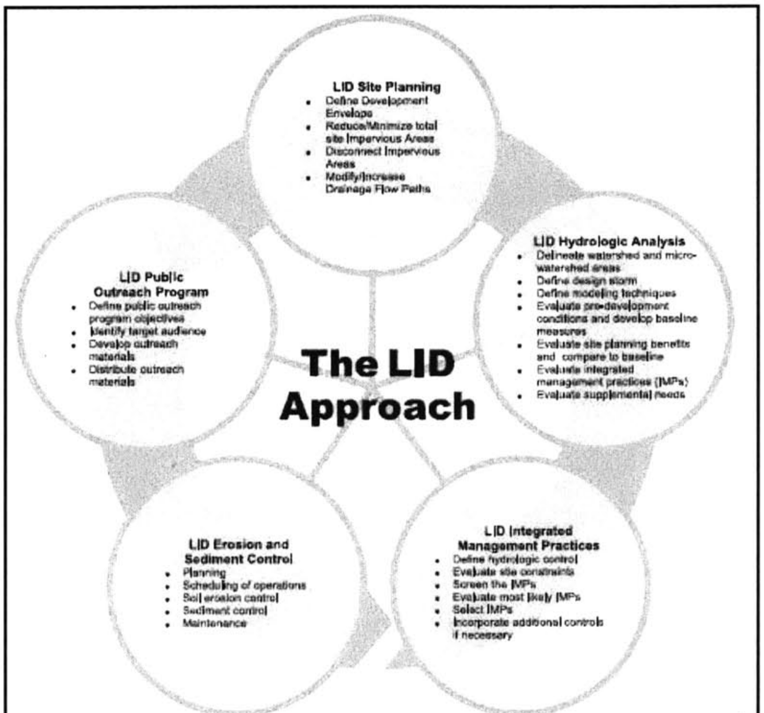
Figure 9: Children's Science Museum front elevation

The Science Museum building, shown in Figure 9 and located on the southern corner of the lot, has a 3,600 square-foot footprint and a three-story front exposure. The structure is placed into a hillside with a resulting two-story rear elevation. The floor plan of the museum's second level includes a group meeting/classroom space with doors leading to an outdoor picnic area in the back of the museum. There is also a third floor rear exit that steps out onto a 12-ft-by-12-ft elevated deck.

6.3 *Site Redevelopment*

The EPA's Low-Impact Development Design Strategies manual was used to guide the Discovery Museums' site planning and design development. There are five major components of the LID approach, which are illustrated in Figure 10 (PG County DER 2000). Four of the five major components were addressed within the scope of the Discovery Museums' redevelopment design.

The only component not specifically addressed is construction sediment and erosion control (SEC). This is an important component, but does not have a major impact on the final design. The construction/engineering firm chosen to perform the construction and site work will be required to submit SEC plans and comply with the runoff and erosion control requirements detailed in the Acton Subdivision Regulations.



Source: EPA: Low-ImpactDevelopment Design Strategies Manual

Figure 10: Low-Impact Development strategic approach diagram

The EPA LID design manual is primarily geared toward multi-lot subdivision development. However, its concepts are easily refined and can be applied to lot-level application.

Site Planning- A comprehensive assessment of the site was performed to ensure all key site features and characteristics are included in the final design decisions. Major components of the site assessment include:

- Recording key topographic features
- Reviewing current utility and subsurface infrastructure
- Evaluating current site impervious surface area
- Assessing site impervious connectivity/continuity
- Identifying key landscape resources – trees, shrubs, soil, slopes, etc.
- Evaluating/quantifying key hydrologic functions for pre-developed and current site condition

- Identifying applicable zoning, land use, subdivision, and other local regulations

Information was gathered to complete the initial site assessment. Property plat and utility drawings were obtained from town records. Engineering reports and drawings were acquired from GeoSyntec Consultants who designed the Discovery Museums' first aquifer recharge project. The Massachusetts Geographic Information System (MGIS 2005) database was used to obtain information on land use, topographic features, and significant hydrologic detail for the region. A survey was conducted, as shown in Figure 11 to collect key elevation and location data. The Discovery Museums' facilities director was also interviewed for historical data and site maintenance information.

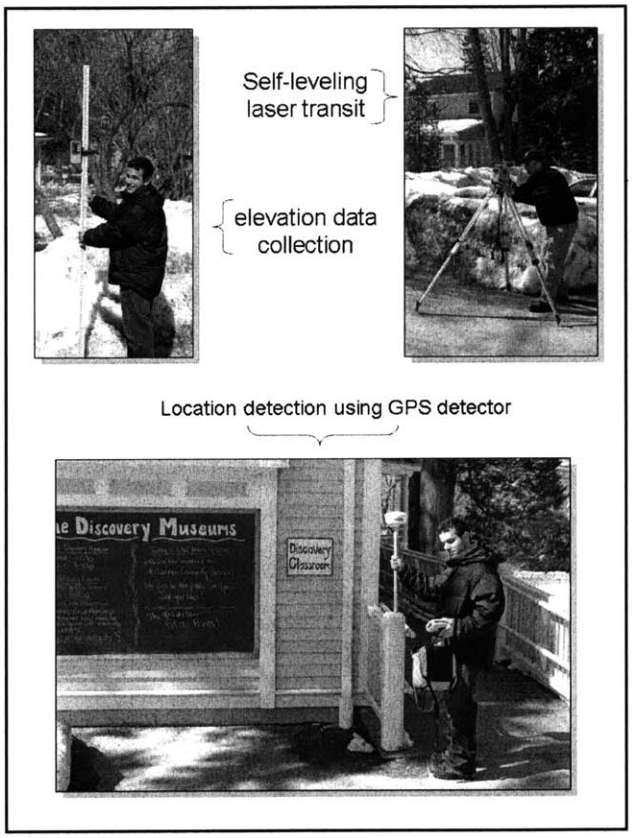


Figure 11: Discovery Museums site survey

East lot – The east lot is reconfigured to absorb all of the displaced west lot spaces. The goal of the reconfiguration is to reuse as much of the existing paved surfaces as practicable. However, a portion of the forested center median must be cleared and paved to increase the parking capacity of this lot and to do so in compliance with zoning bylaw dimension, setback, and landscape requirements. The specific location of forested area clearance was carefully selected to ensure preservation of the maximum amount of large and old growth trees. Further, no rare or endangered flora or fauna are located in the proposed clearance area. The final design layout for the east lot is shown in Figure 12.

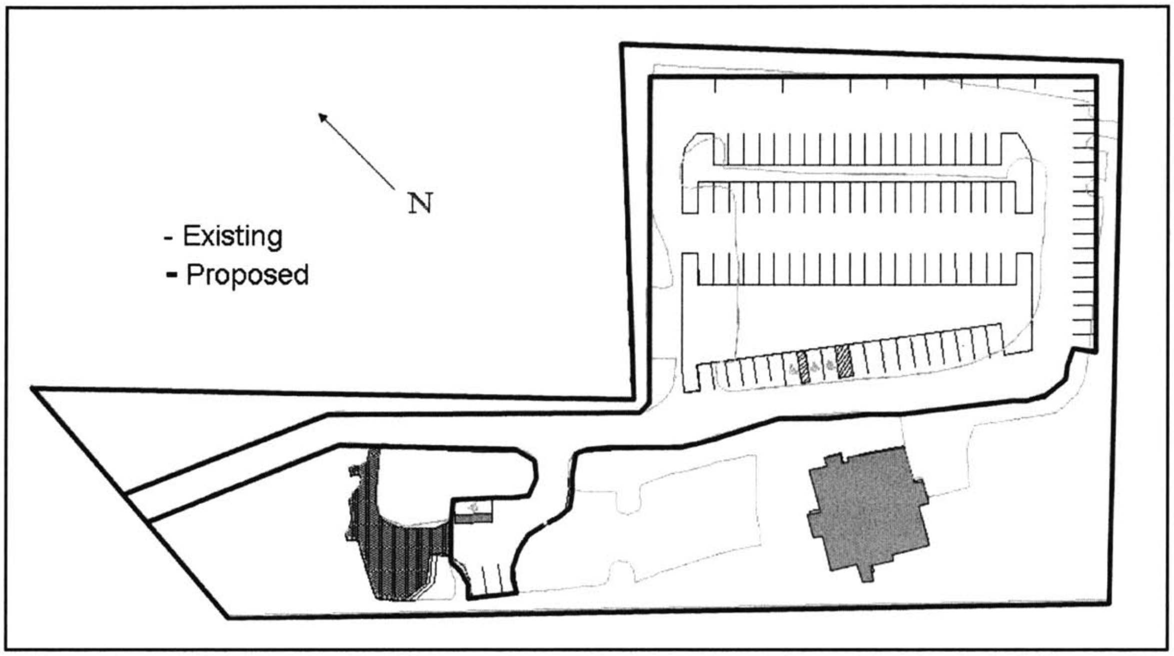


Figure 12: Proposed versus existing lot layout

<u>West lot</u> – The majority of the existing east lot paved surface will be removed and replaced with porous landscape. Selection of specific landscape detail for the reclaimed section of the southern half of this lot is beyond the scope of this design and has been left for the Museum to select. The site's hydrologic analysis treats this area as porous media and has been modeled as if it were natural ground cover similar to ground cover on the rest of the site. The existing entrance shown in Figure 12 and a small portion of the center parking cell will remain to provide employee parking and required handicap parking for the Children's Museum.

Once the existing pavement is lifted, a landscape design option such as that shown in Figure 13 can be constructed in the upper cell of the existing lot. This design includes a small playground area, a gazebo pavilion, and a picnic area.

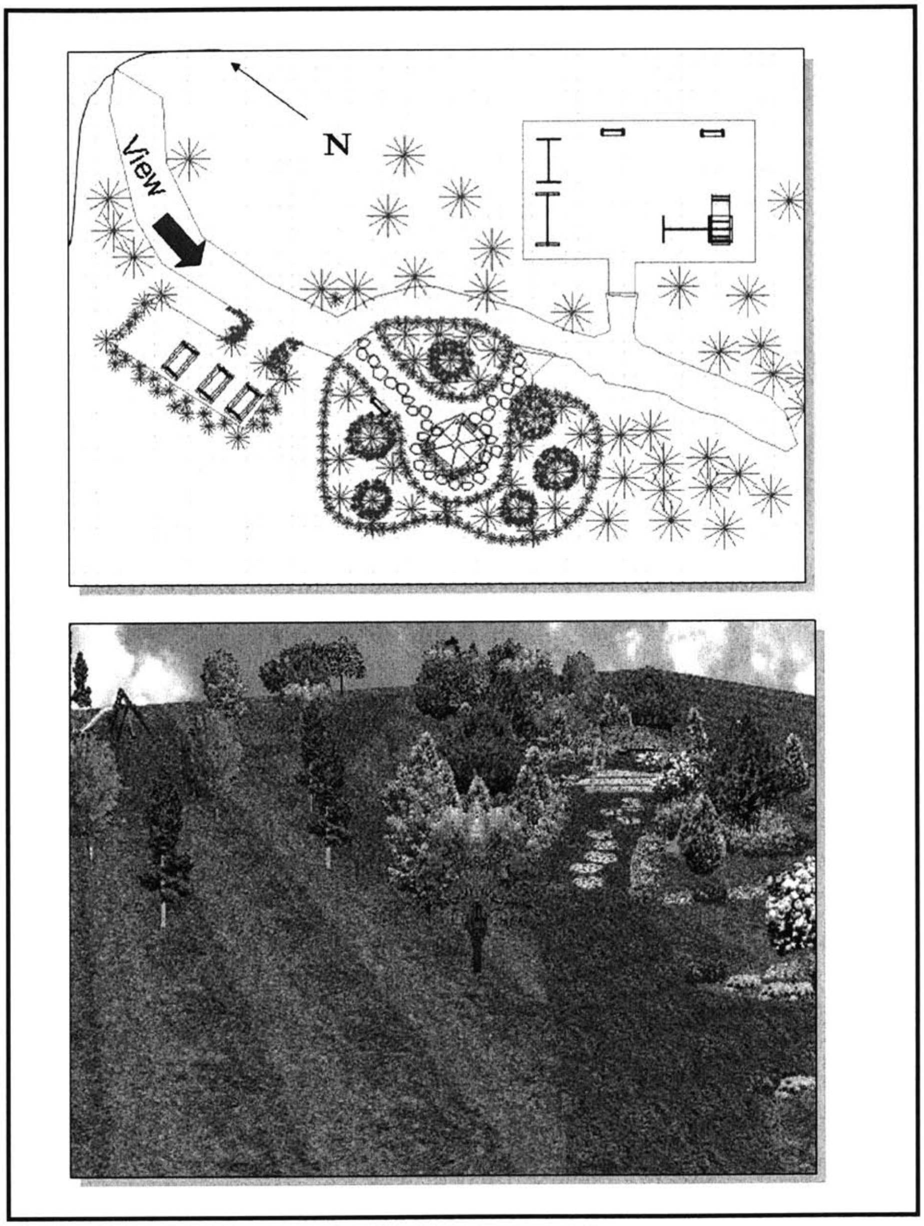
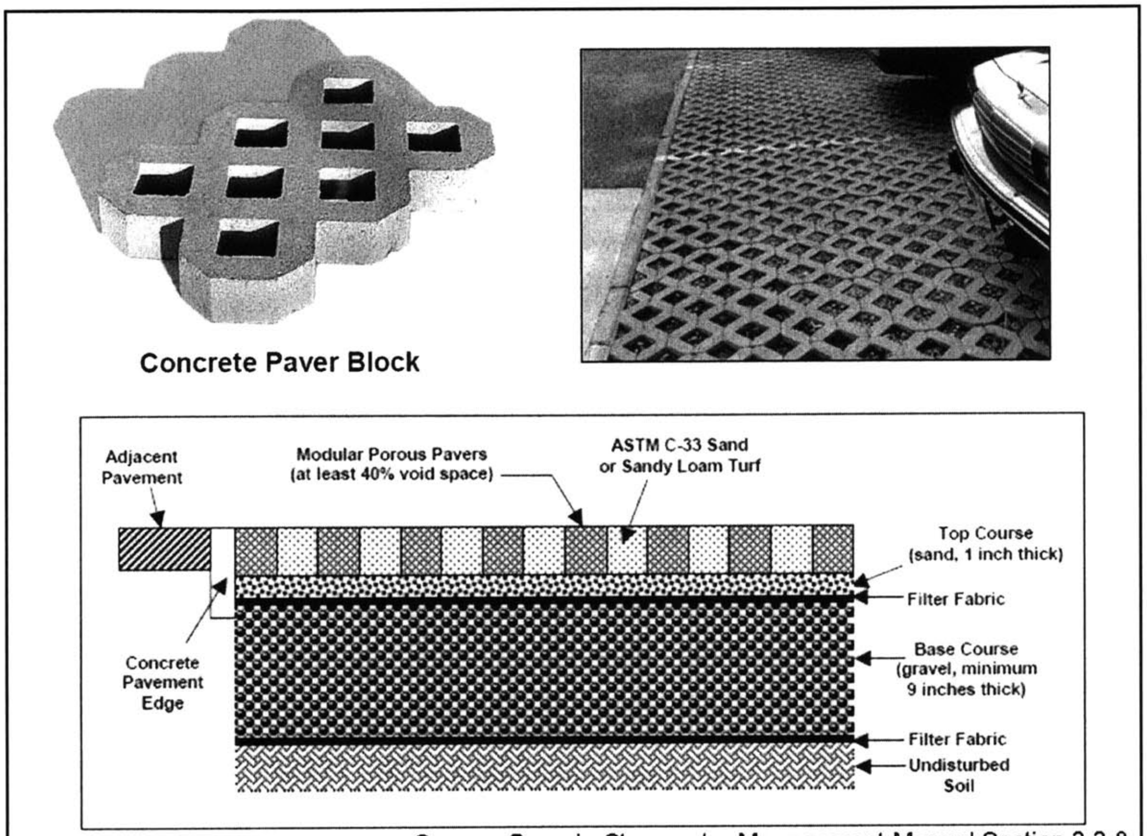


Figure 13: West lot landscape layout

All paved surfaces in the western cell (closest to the two Children's Museum structures) will be lifted and replaced with porous pavers. A typical porous paver system is shown in Figure 14. It is engineered to provide a firm surface for pedestrian traffic and has a high hydraulic conductivity to promote stormwater infiltration.



Source: Georgia Stormwater Management Manual Section 3.3.8

Figure 14: Typical porous paver section

Architectural renderings of the proposed lot design are shown in Figure 15 and Figure 16.

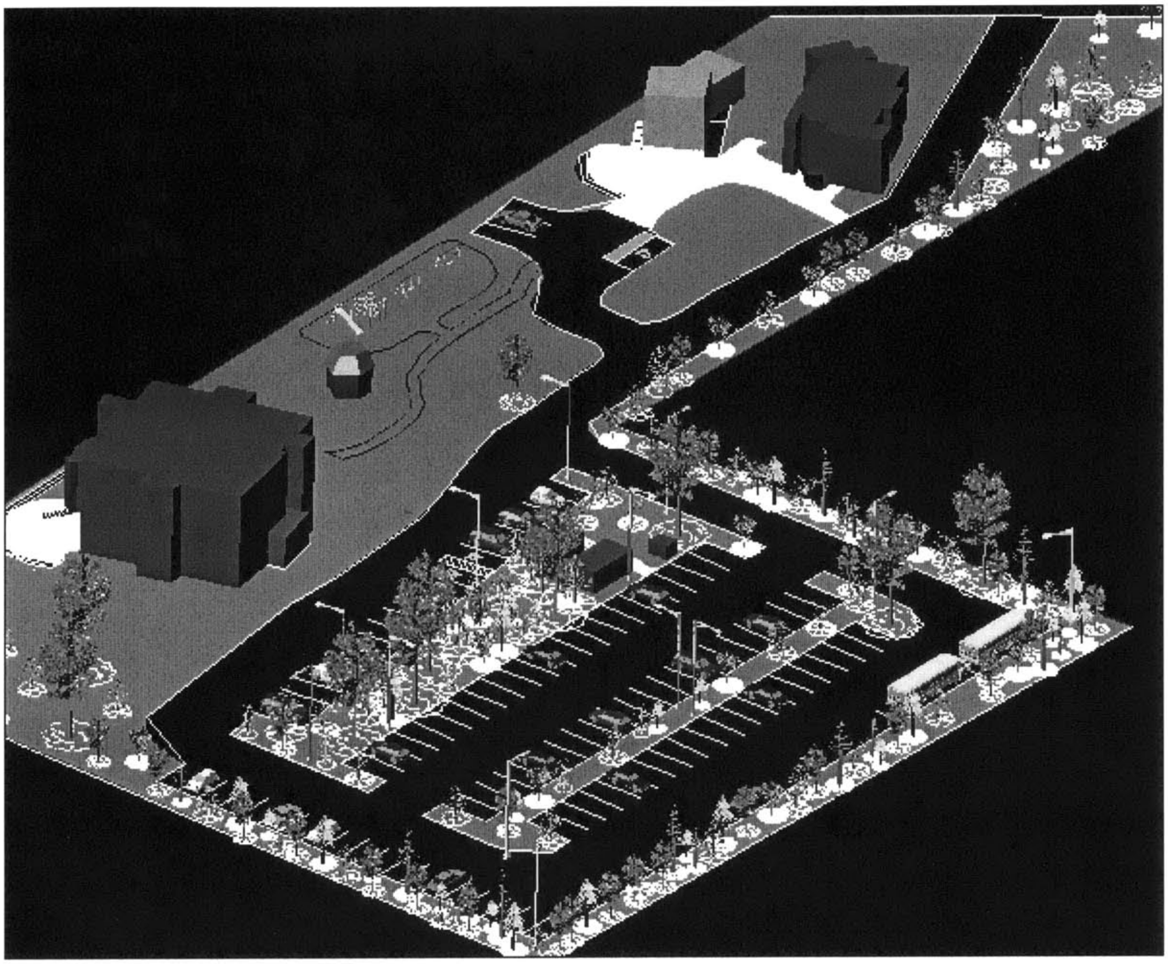


Figure 15: The Discovery Museums aerial rendering

Figure 16: The Discovery Museums east lot rendering

Using this conceptual design, I sized and analyzed LID features on the site to mimic natural hydrology. The following chapter explains the approaches that I took to the hydrologic site design and analysis, and the results that I found.

7 Site Hydrologic Design

7.1 *Basic Runoff Volume Model (SCS Curve Number Method)*

The runoff volume from the site is a key parameter in a stormwater management design. The Natural Resources Conservation Service or NRCS (formerly the Soil Conservation Service or SCS) developed a simple model for calculating runoff from the land surface that has become one of the most wisely used stormwater management tools. The SCS method calculates runoff based on a precipitation event, hydrologic soil group, and surface cover.

A parameter called the curve number (CN) accounts for both the hydrologic soil group and the surface cover. CN values have been tabulated in many publications, such as the manual for the NRCS TR-55 Model. An example of a curve number table is shown in Table 1 (NRCS 1986).

Table 1: Example of an SCS curve number table

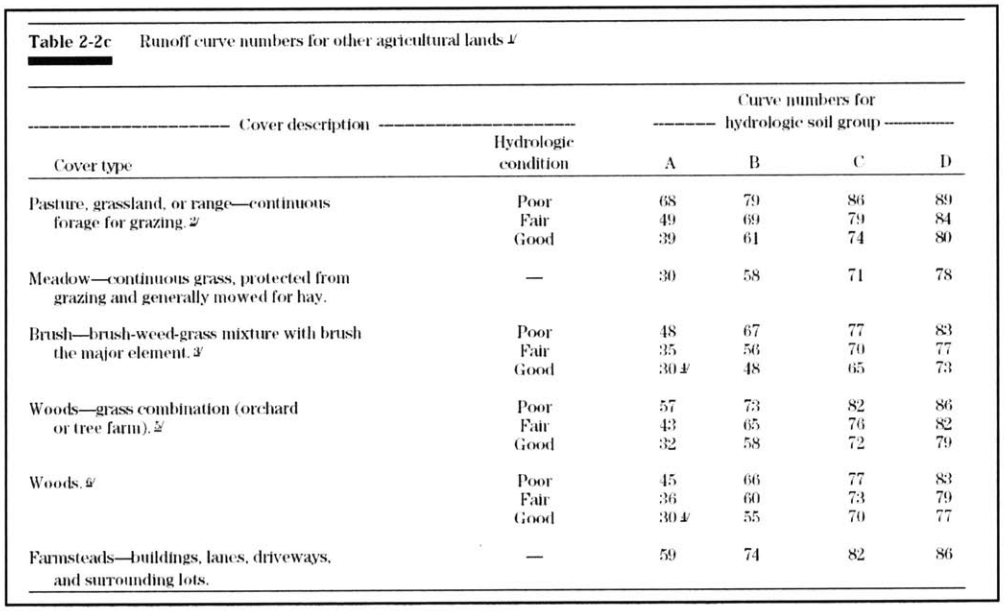


Table 2-2c Runoff curve numbers for other agricultural lands [1]

Cover description		Curve numbers for hydrologic soil group			
Cover type	Hydrologic condition	A	B	C	D
Pasture, grassland, or range—continuous forage for grazing. [2]	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow—continuous grass, protected from grazing and generally mowed for hay.	—	30	58	71	78
Brush—brush-weed-grass mixture with brush the major element. [3]	Poor	48	67	77	83
	Fair	35	56	70	77
	Good	30 [4]	48	65	73
Woods—grass combination (orchard or tree farm). [5]	Poor	57	73	82	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods. [6]	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	30 [4]	55	70	77
Farmsteads—buildings, lanes, driveways, and surrounding lots.	—	59	74	82	86

Curve numbers range from 0 to 100. A curve number of 0 implies no runoff, while a curve number of 100 implies that all rainfall contributes to runoff.

The SCS curve number equations can be used to calculate the total runoff from an area given the total precipitation of the event according to the following equations:

Equation 1: Runoff volume per unit area given a precipitation event, P

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}$$

Equation 2: Parameter S – Function of curve number

$$S = \frac{1000}{CN} - 10$$

The value, (0.2 * S) is equivalent to the initial abstraction that occurs at the beginning of an event. In other words, when P is equivalent to (0.2*S), the numerator of Equation 1 and runoff volume are zero. When P exceeds the initial abstraction value, runoff volume begins to be seen. The magnitude of the initial abstraction is dependent on S and therefore on the curve number as shown in Equation 2 . Q in Equation 1 represents the volume of water runoff per unit area of site. Therefore the total runoff volume can be found by multiplying Q times the area. Figure 17 (NRCS 1986) shows how runoff volume varies with curve number and precipitation.

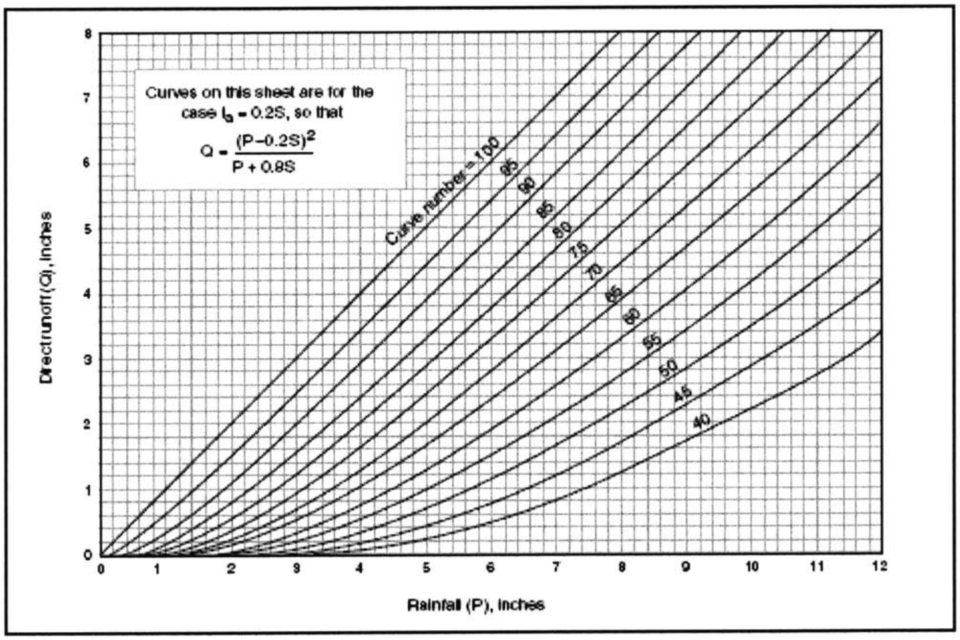


Figure 17: Solution of SCS runoff volume equation

7.2 *Runoff Rate – The Hydrograph*

The runoff rate is also very important for managing stormwater. Traditionally, models such as TR-55 have been used to generate runoff hydrographs, which illustrate runoff versus time. The model uses a parameter called the time of concentration to calculate the timing of water as it moves through a watershed. The time of concentration is defined as the travel time from the hydraulically most distant point in a watershed to the outlet. Figure 18 (RiverSmart undated) shows this concept pictorially.

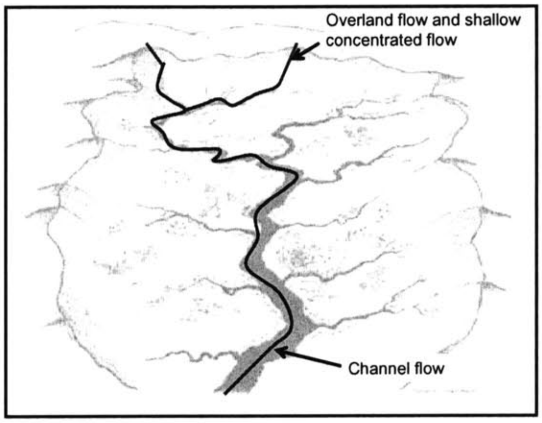


Figure 18: Graphic representation of time of concentration

As shown, flow starts at the upland part of the watershed as overland flow and then becomes shallow concentrated flow and channel flow as it reaches the outlet. TR-55 was designed for larger watersheds and has been shown to be less useful for smaller watersheds. In fact, research has suggested that TR-20 peak runoff rate estimates and time of concentration methods "should not be used to model wooded watersheds less than 20 acres" (Fennessey et al. 2001). Many developed sites in urban areas are part of very small catchments. The Discovery Museums are no exception. The time of concentration at the site was calculated to be less than 5 minutes. For this reason, I have focused on runoff volume and assumed the time of concentration to be instantaneous. As a result, I have implemented a simplified model of runoff rate for very small watersheds.

The simplified model for runoff rate is based on the SCS curve number method for runoff volume. To produce a runoff hydrograph, a time series of precipitation values and the SCS curve number method equations are used to calculate a time series of runoff volumes. One complication that arises is that the SCS method is designed for single events. With a time series of precipitation values that comprise an event, the initial abstraction term (0.2*S) cannot be subtracted out at every time step. Consequently, a cumulative method must be used. First, at each time step during a storm, the cumulative rainfall is calculated. Next, the cumulative runoff volume is calculated based on the cumulative rainfall. Finally, the runoff volume at time step, t, is calculated as the cumulative runoff at time step, t, minus the cumulative runoff at time step, t – 1. This method is described in more detail in Chapter 10 of the National Engineering Handbook (NEH) for Hydrology (Mockus 1964).

A runoff hydrograph can be produced after the time series of runoff volumes is calculated. The hydrograph shows the runoff rate versus time. Conventionally, stormwater management devices have been designed by matching the peak of the post-development hydrograph to the peak of the pre-development hydrograph. While this controls peak discharge, it does not address runoff volume, which is equal to the area under the runoff hydrograph. Typical hydrographs of pre-development, conventional, and LID design are shown in Figure 19 (PG County DER 2000).

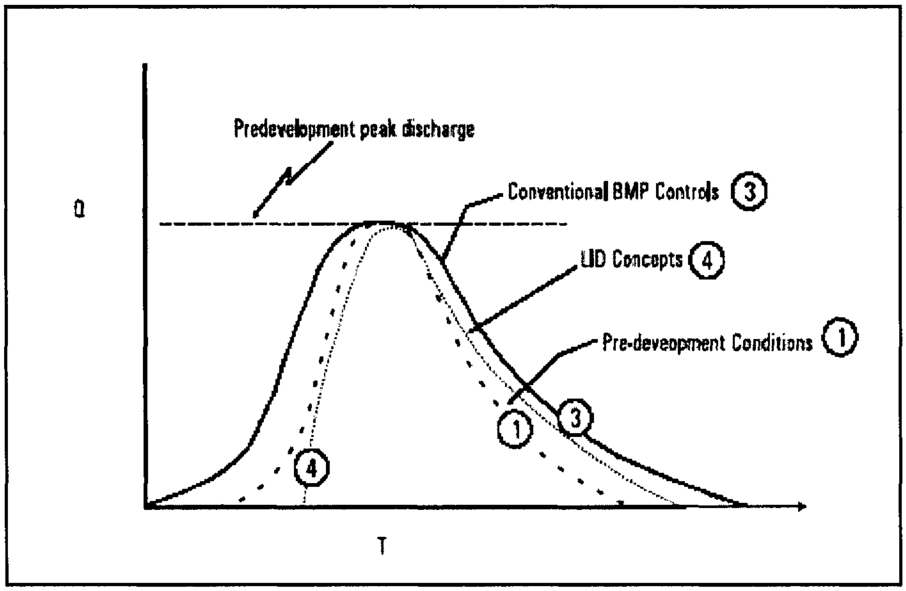


Figure 19: Typical hydrographs for pre-development, conventional, and LID sites

7.3 *The Design Storm and Rainfall Distribution*

Design storms have been conventionally used in the design of stormwater management devices. The principal reason is ease of use. Regulations usually specify the design storm or storms to be used to analyze and size the device. Acton specifies a

24-hour storm with a 10-year return period (the rainfall that occurs in a 24-hr period on average once every 10 years) (Town of Acton Planning Board 2004). For Acton, this storm is equivalent to 4.25 inches (Wilks and Cember 1993).

The rainfall distribution is used to describe *how* the rain falls during the 24-hour period. As shown in Figure 20 (NRCS 1986), Massachusetts is said to experience Type III rainfall distribution.

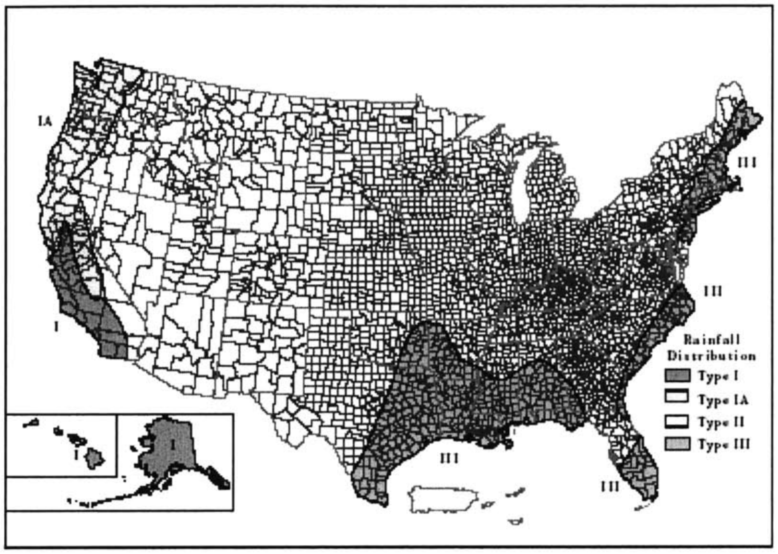


Figure 20: Approximate geographic boundaries for SCS rainfall distributions

A rainfall hyetograph is a plot of rainfall versus time. Figure 21 shows a rainfall hyetograph for a type III rainfall distribution and a design storm of 4.25 inches.

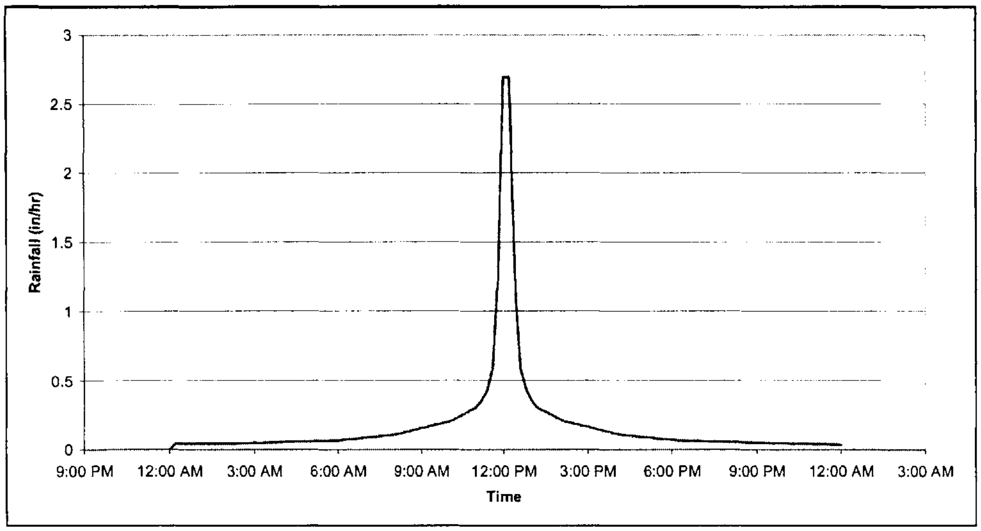


Figure 21: Rainfall hyetograph for a 4.25 inch design storm

7.4 *Basic Site Hydrology*

Before analyzing runoff from the site, a general understanding of the basic hydrology is critical. ArcGIS, a Geographic Information System (GIS) mapping program, was used to model how water flows across the site.

7.4.1 *Site Details and Elevation Contours*

Different GIS layers were taken from MassGIS (MGIS 2005) and the Town of Acton GIS database. I imported the land use and site boundary data for the Museums site. In addition, an aerial photo was imported. The elevations of the site were taken from MassGIS. This baseline data is shown on Figure 22.

7.4.2 *Finding the Direction of Runoff Flow*

The GIS layer that contains the elevation data is called a grid. Using this data, GIS is able to analyze the following hydrologic aspects of the area:

- Flow Direction
- Flow Accumulation
- Stream Network

The flow direction and stream network were used to find the site divide. The site divide is the line at which everything to one side flows in one direction, and everything to the other side flows in a different direction. In the case of the Discovery Museums, water flows either west towards Main Street or northwest to the Great Hill Conservation Area. The site divide is shown on Figure 23. The stream network is marked as runoff direction (away from the hill).

7.5 *Analysis of the Pre-Developed Site*

The pre-development state of the site was assumed to be all woods. The entire site also contains hydrologic group C soils. The curve number was found to be 73 from tabulated values in TR-55 (NRCS 1986). Because the curve number was the same across the site, the runoff volume could be calculated from a single simple basin. The total runoff volume for the 10-year design storm was 540 m^3.

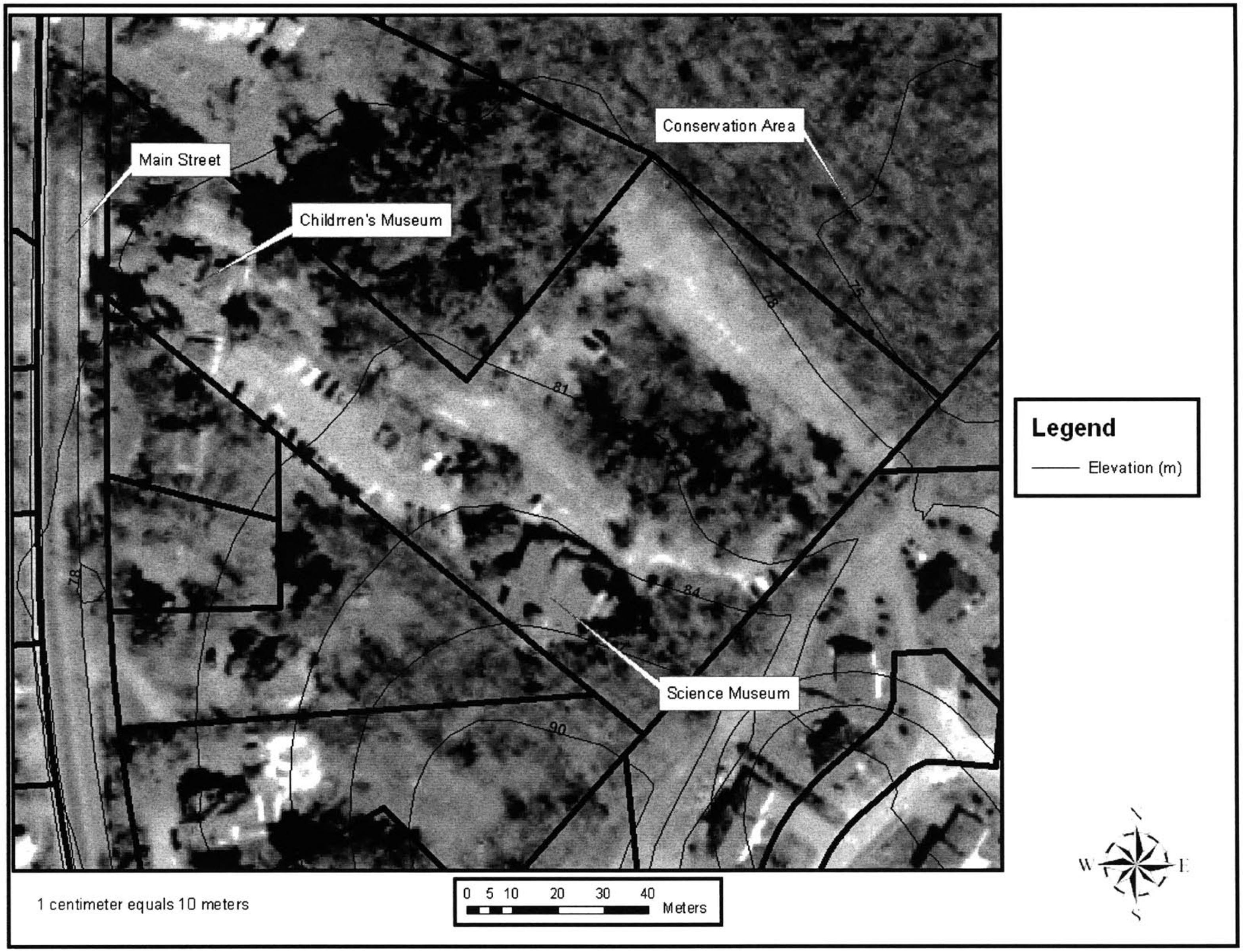


Figure 22: Discovery Museums site

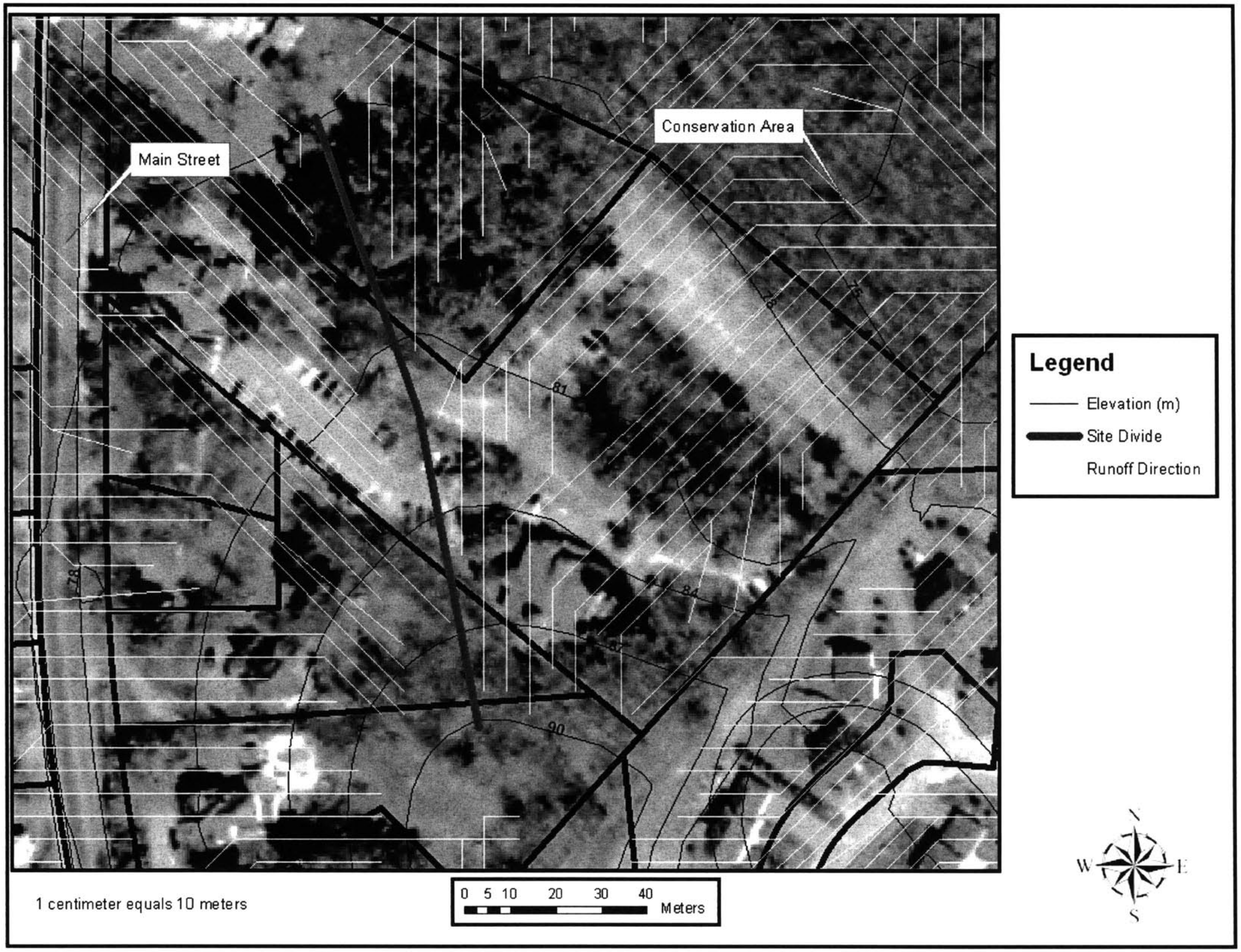


Figure 23: Discovery Museums hydrologic surface model

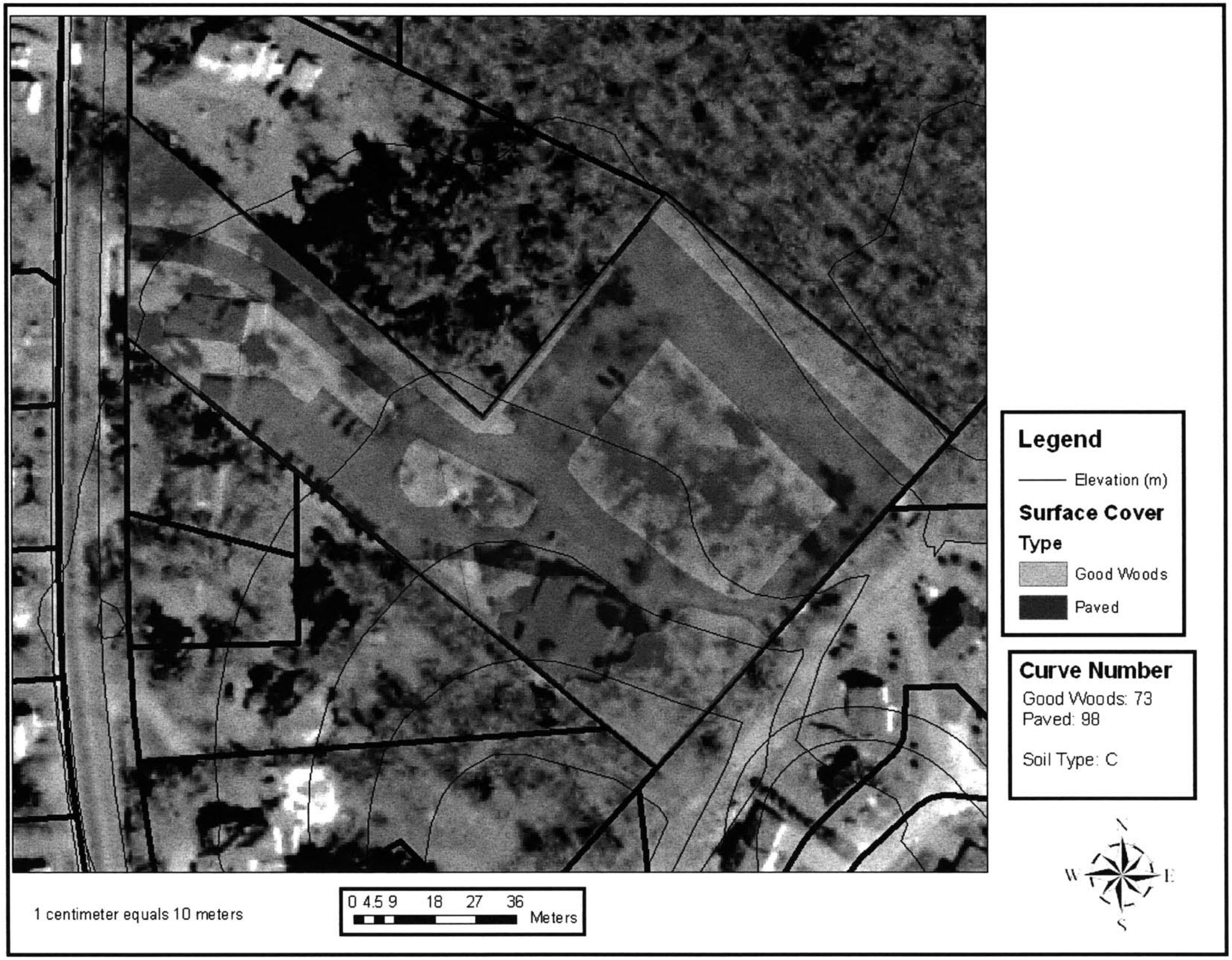


Figure 24: Land use differentiation for existing site

7.6 *Analysis of the Existing Site*

The analysis of the existing site was more challenging because of the heterogeneity of the land use on the site. The site was divided into areas of pervious and impervious surfaces. Figure 30 shows how this was done on ArcGIS, though more accurate values for the areas were calculated using AutoCad. I assigned a curve number of 73 to the pervious areas and 98 to the impervious areas. The effective curve number was calculated by weighting the two curve numbers based on area. Table 2 shows the parameters that were calculated for both the pre-developed and existing site.

Table 2: Pre-developed and current site conditions

Parameter	Pre-Developed	Existing
Surface Cover	Fair Woods	Fair Woods, Impervious Surface, Grass
% Imperviousness	0%	39%
Effective Curve Number	73	85
Soil Type	C	C

While the effective curve number has been cited as a reasonable way to calculate runoff volume from heterogeneous sites (NRCS 1986), I have found that large discrepancies occur between the total runoff volume calculated with the effective curve number and total runoff volume calculated as the sum of each individual area. The reason for the discrepancy is that the curve number and runoff volume are not directly related as shown by equations 1 and 2. As a result, the total runoff volume was calculated as the sum of the runoff volumes from each sub-area having a different curve number. Table 3 shows the total runoff volume for the pre-developed and existing site for four different design storms.

Table 3: Total runoff results for various design storms

Rainfall Event	Rainfall (in)	Pre-Developed Total Runoff (m^3)	Existing Total Runoff (m^3)
2 yr Rainfall Event	2.75	247	530
10 yr Rainfall Event	4.25	596	958
50 yr Rainfall Event	6.25	1150	1576
100 yr Rainfall Event	7.1	1402	1848

The total runoff for the existing site is much greater than the pre-developed conditions for all rainfall events. Figure 25 illustrates how runoff changes versus rainfall for the pre-developed and existing sites.

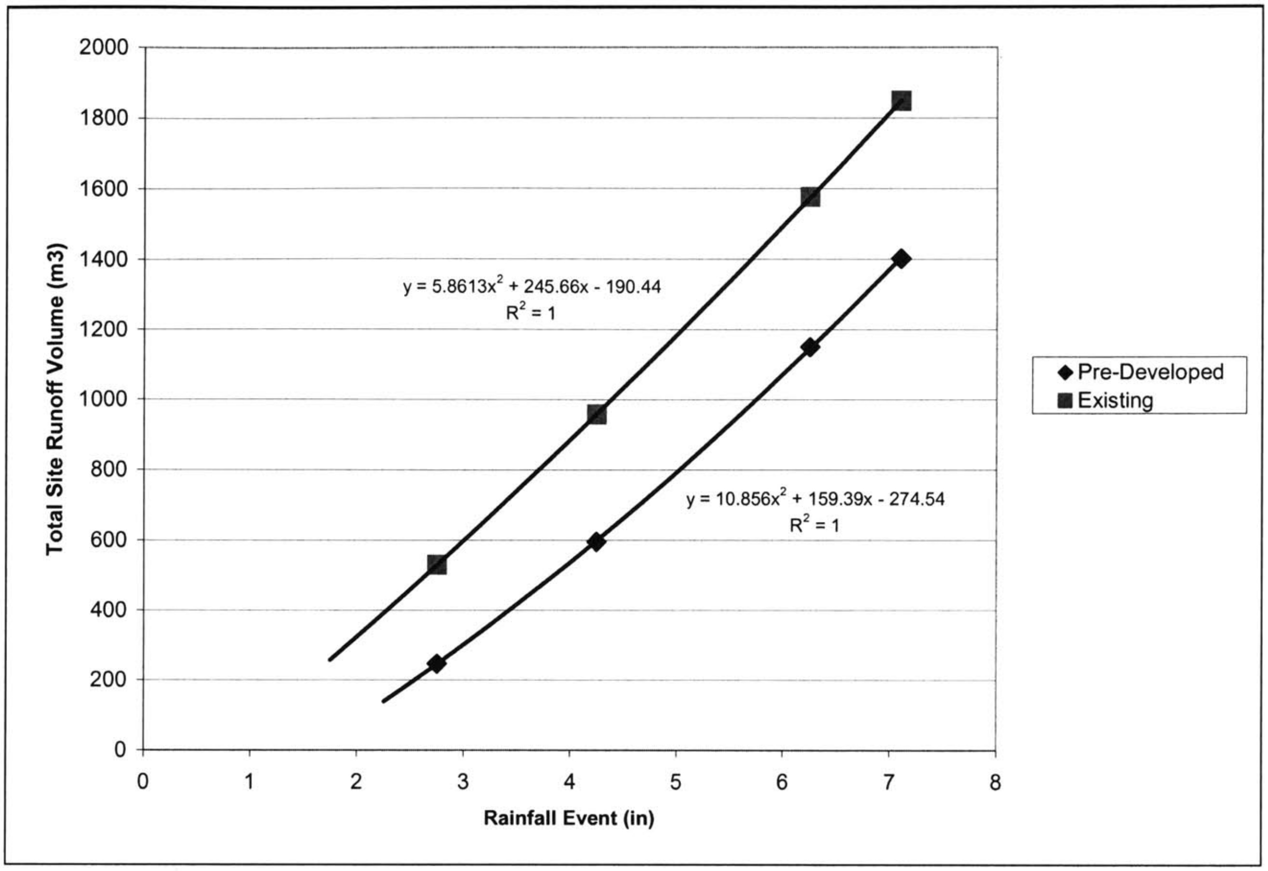


Figure 25: Total site runoff versus rainfall for pre-developed and existing site

7.7 *Analysis and Sizing of the LID Design*

The LID design is intended to decrease the runoff volume and peak discharge of the existing site to pre-development levels. The following section describes the procedure used to analyze the site with LID controls and the iterative process of sizing the LID features. While the analysis of the pre-developed and existing site was relatively simple, the analysis of the LID design poses some new challenges. One of the biggest challenges in analyzing the hydrology of a site designed with LID technologies is that hydrologic simulation programs that currently exist cannot implement the new stormwater BMPs, such as rain gardens and swales. For this reason, I wrote a source code in Visual Basic for Applications (VBA) to analyze a LID designed site. Although this model has the capability to route water and perform continuous water balances on storage areas, it is still based on the assumption that the time of concentration is instantaneous. For this reason, I only recommend its use for small catchments.

7.7.1 *Site Low-Impact Development Design Model (SLIDD)*

The source code of SLIDD is based on the SCS curve number method for runoff volume. Runoff is calculated using equations 1 and 2 from sub-basins (non-LID areas) and then routed to LID areas. Using a time series of precipitation and evaporation data, the program calculates a time series of runoff volumes by performing a water balance on each rain garden. Figure 26 illustrates the interaction between sub-areas and rain gardens in SLIDD.

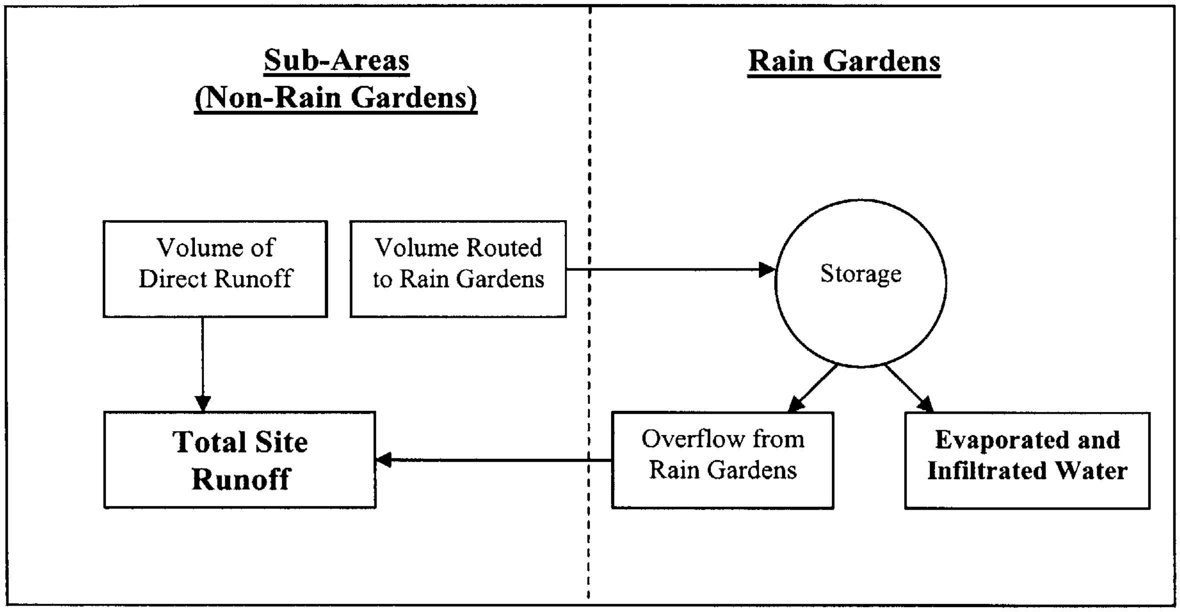


Figure 26: Interaction between sub-areas and rain gardens in SLIDD

The following sections describe in more detail the input and calculations of SLIDD.

7.7.1.1 Sub-Areas (Non-Rain Gardens)

Sub-Areas are defined as all areas that produce runoff. The user must input the surface area, percent routed (generally 100%), and curve number for each sub-area. The program uses these values to calculate runoff.

7.7.1.2 Calculating Runoff Produced from Sub-Areas during a Rainfall Event

The SCS equations are designed to be used for a single storm event. For a time series, multiple precipitation values can contribute to a single storm event. This presents a problem, because initial abstraction is subtracted from the total runoff volume at each time step, while it should only be subtracted once for the entire storm. To solve this problem, I use a cumulative approach for each storm, described in detail in Section 7.2.

7.7.1.3 Rain Gardens

Rain gardens are LID stormwater management features that accept water. The user enters the area, depth, porosity, and infiltration rate of the rain garden. The porosity should be entered as the average porosity of the rain garden. For instance, if water is able to pool on top of the rain garden, that area (porosity = 1) should be averaged with the subsurface soil volume.

Equation 3: Average porosity

$$\text{Average Porosity} = (\text{Total Void Volume}) / (\text{Total Volume})$$

The average porosity of our storage areas was approximately 0.38.

The infiltration rate was based on the infiltration rate of the underlying soil. For the Discovery Museums site, a value of 0.27 in/day was used, corresponding to silty loam (Maryland DEP 1984). For analyzing the design storm, I used the mean annual evaporation rate for the site. The evaporation from the rain gardens was estimated using a pan coefficient.

Equation 4: Empirical reference crop evaporation

$$E_{rc} = k_{pan} + E_{pan}$$

A value of 0.75 was used for k_{pan}, corresponding to light wind, medium relative humidity, and 10 meters of upwind fetch (Shuttleworth 1993). The type A pan evaporation is 33 inches/year (NOAA 1983). This corresponds to an average evaporation rate of 0.0017 m/d.

7.7.1.4 Water Balance of Rain Gardens

The user enters which sub-areas contribute water to which rain garden for each time step. Having this information, SLIDD performs a water balance on each rain garden. The water balance equation is:

Equation 5: Water balance for rain gardens

$$V_t = V_{t-1} + (P_t * A) + V_{sa} - (E_t * A * \Delta t) - (I * A * \Delta t)$$

Where: V_t = Volume of water at current time step (m^3)

V_{t-1} = Volume of water at previous time step (m^3)

P_t = Precipitation at current time step (m)

A = Surface area of rain garden (m^2)

V_{sa} = Volume contributed by sub-areas (m^3)

E_t = Evaporation rate (m/d)

Δt = time step (d)

I = Infiltration rate (m/d)

7.7.1.5 Water Routing

Water is routed in SLIDD from the sub-areas to the rain gardens. Also, water can be routed from an overflowing rain garden to the next downstream rain garden. This was utilized in the Discovery Museums site in creating a terracing effect. Water from sub-areas is routed to the uppermost rain gardens, and then overflow from these rain gardens is routed to lower elevation rain gardens. The source code used for routing water can be found in Appendix C.

7.7.1.6 Total Site Runoff

The program calculates total site runoff by adding the overflows (that are not routed to other rain gardens) and the direct runoff from sub-areas. The program outputs this value for every time step. A hydrograph (runoff volume vs. time) is produced.

7.7.2 *Sizing the LID Storage Features*

The sizing of the LID storage features was an iterative process. The goal was to match the pre-developed runoff volume and peak rate. The first step was to model the site using sub-areas that flow to the strategically placed rain gardens, as shown in Appendix A. Because the site contains a divide that separates flow to the street from flow to the conservation area (see Figure 23), the two sub-basins were modeled separately. I will refer to the area that flows to the conservation area as sub-basin 1 and the area that flows to the street sub-basin 2.

7.7.2.1 LID Design of Sub-Basin 1

Sub-basin 1 contains the expanded parking lot. There are three spots in the sub-basin that are designed for LID storage. The first is a rain garden next to the museum building that was previously constructed. A median in the parking lot and the northern border of the site were also designed as LID features. Refer to Figure 29, a map of the entire LID-designed site, for the locations of the LID features. The SLIDD model was run iteratively for the LID-designed sub-basin. As part of the LID design process, the amount of storage in the LID features was changed until the peak runoff matched the peak pre-developed runoff. Figure 27 shows the hydrographs for the pre-developed, existing, and LID-designed site.

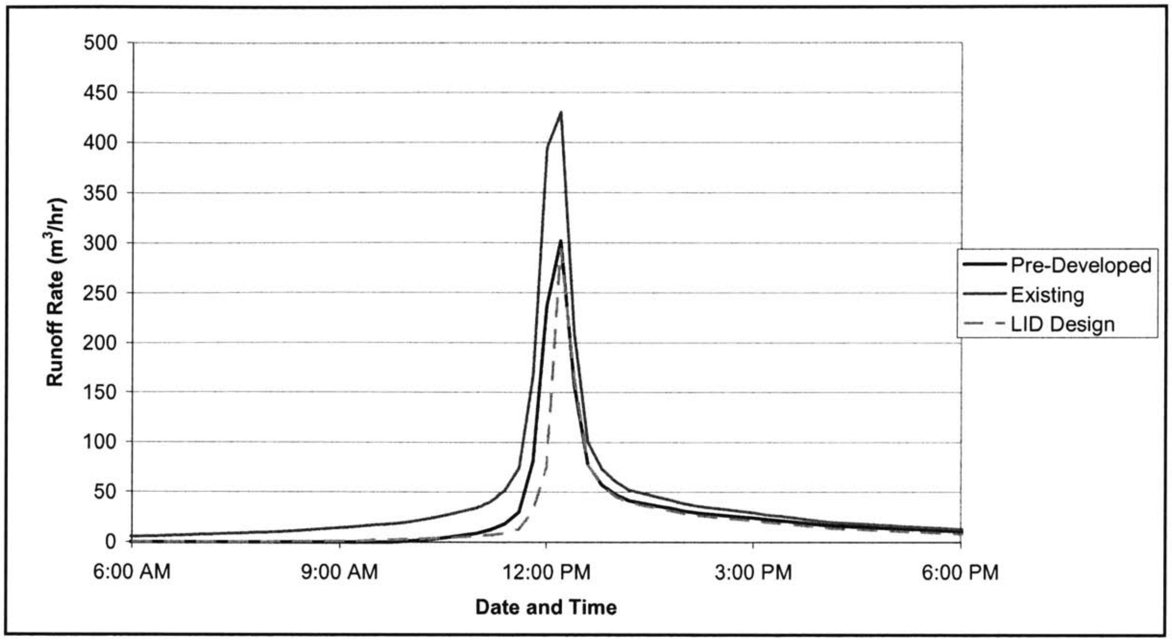


Figure 27: Runoff hydrographs for sub-basin 1

The final design for sub-basin 1 contained approximately 225 m^3 of storage and produced approximately 290 m^3 of runoff in the 10-year design storm.

7.7.2.2 LID Design of Sub-Basin 2

The same iterative procedure was used to size and analyze Sub-Basin 2. The basin was designed with LID features in two locations, both near the western border of the site. Again, please refer to Figure 29 for the exact location and size of the LID features. Figure 28 shows the runoff hydrographs for the pre-developed, existing, and LID-designed sub-basin.

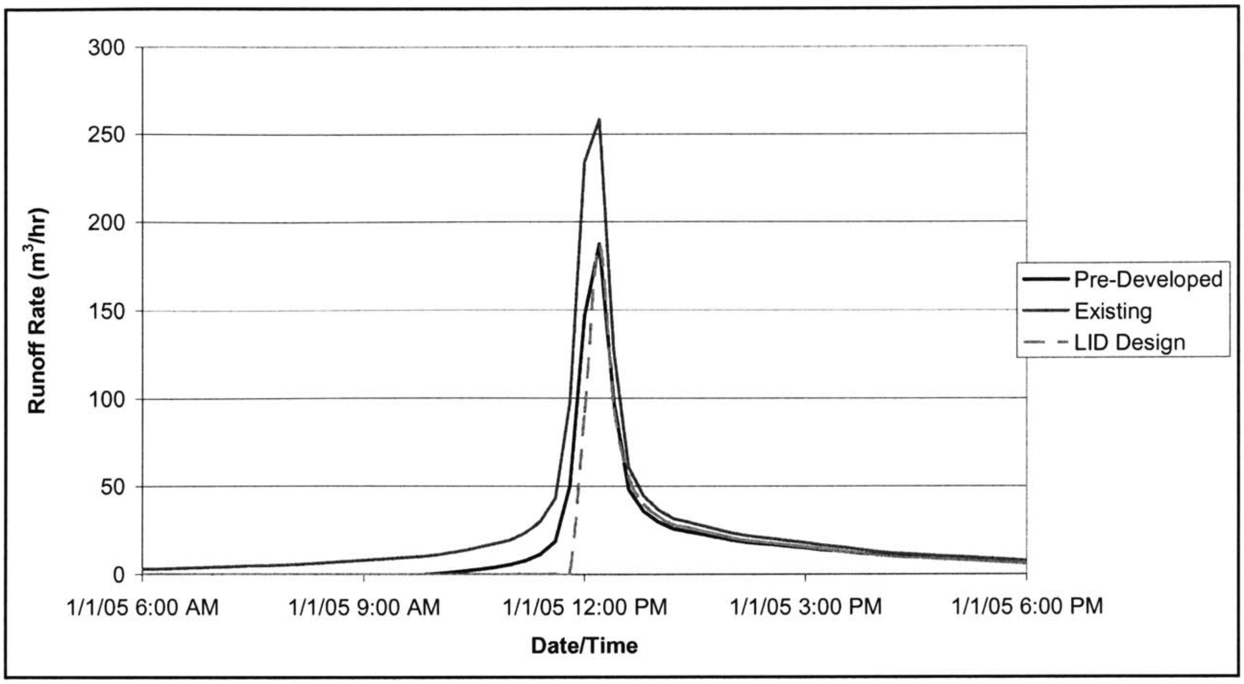


Figure 28: Runoff hydrographs for sub-basin 2

The final design for sub-basin 2 contained approximately 87 m^3 of storage and produced 195 m^3 of runoff in the 10-year design storm.

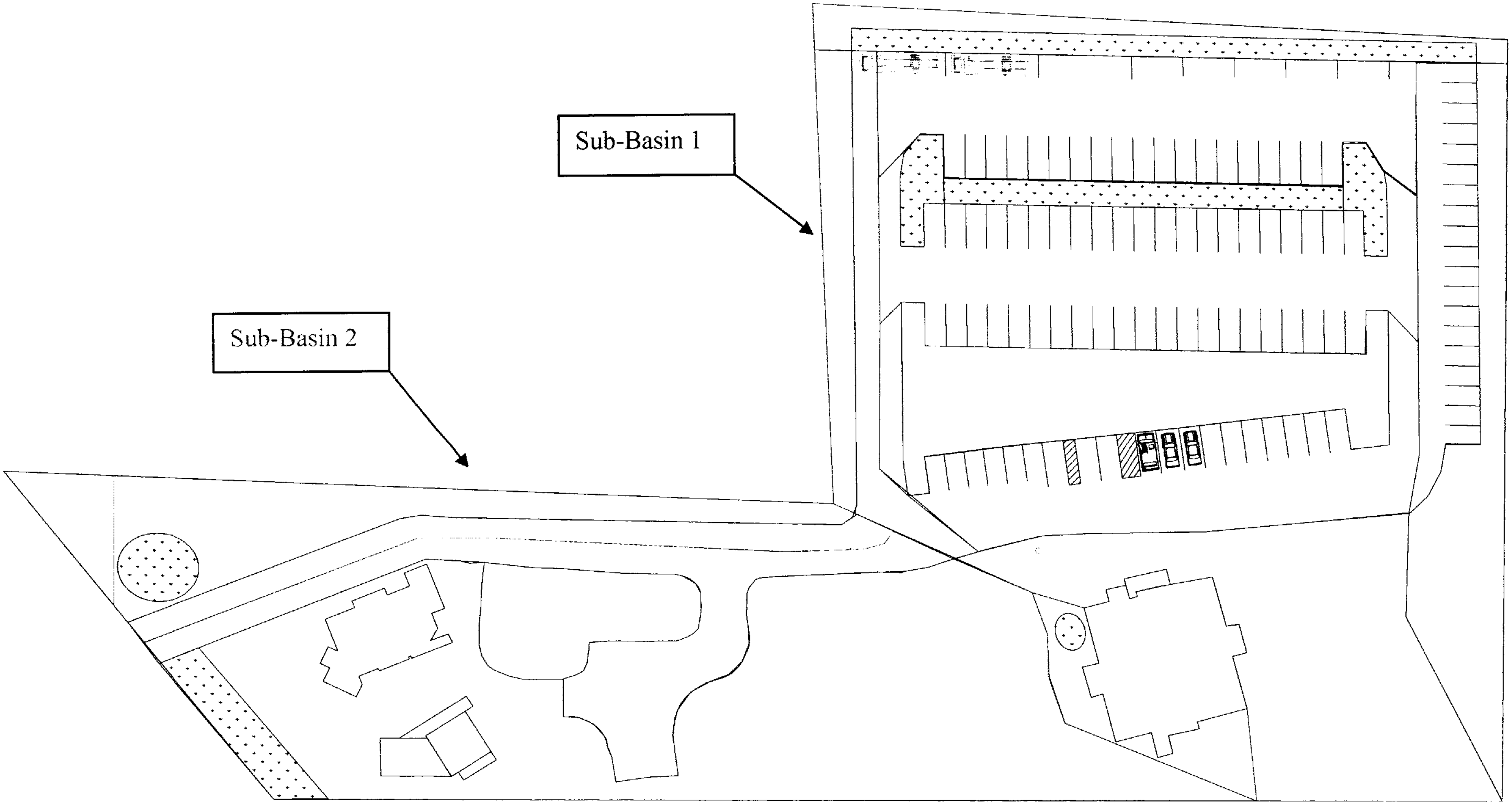


Figure 29: Map of both sub-basins and placement of LID features

7.7.2.3 Comparison of the Pre-Developed, Existing, and LID-Designed Site

After designing stormwater controls for the two sub-basins of the site, the results for the different development scenarios were compiled for comparison. Table 4 and Figure 30 summarize the results for the pre-developed, existing, and LID-designed site.

Table 4: Summary of results for the pre-developed, existing, and LID-designed site

Parameter	Pre-Developed	Existing	LID
Total Runoff Volume (m^3)	595	960	490
Peak Runoff (m^3/hr)	480	690	480

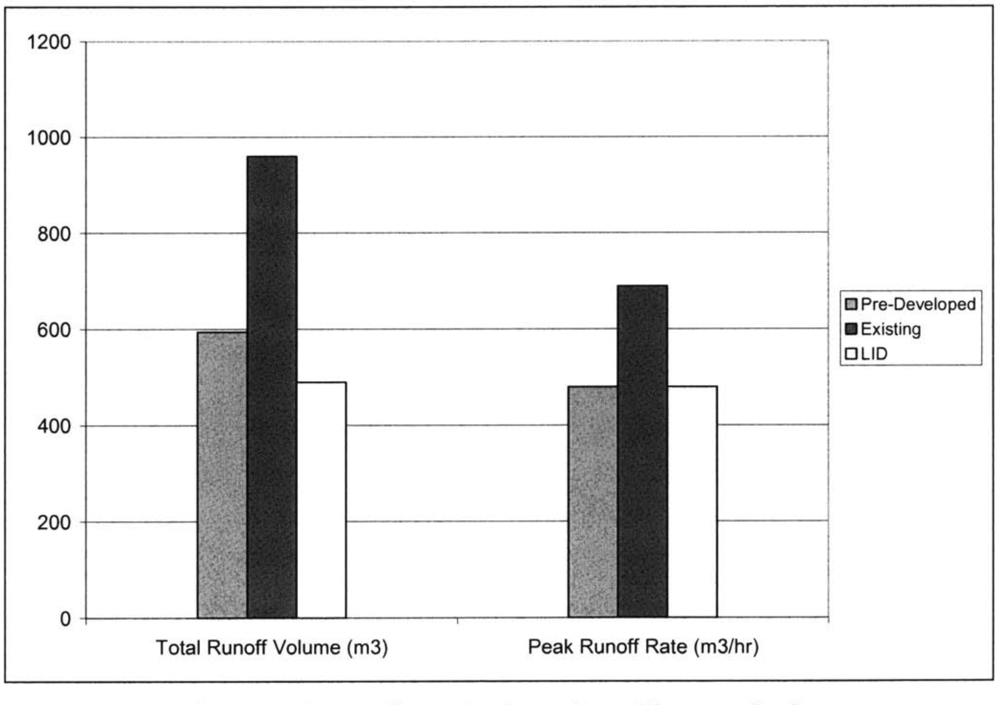


Figure 30: Bar chart of results based on 10-year design storm

The hydrographs for the entire site are shown in Figure 31.

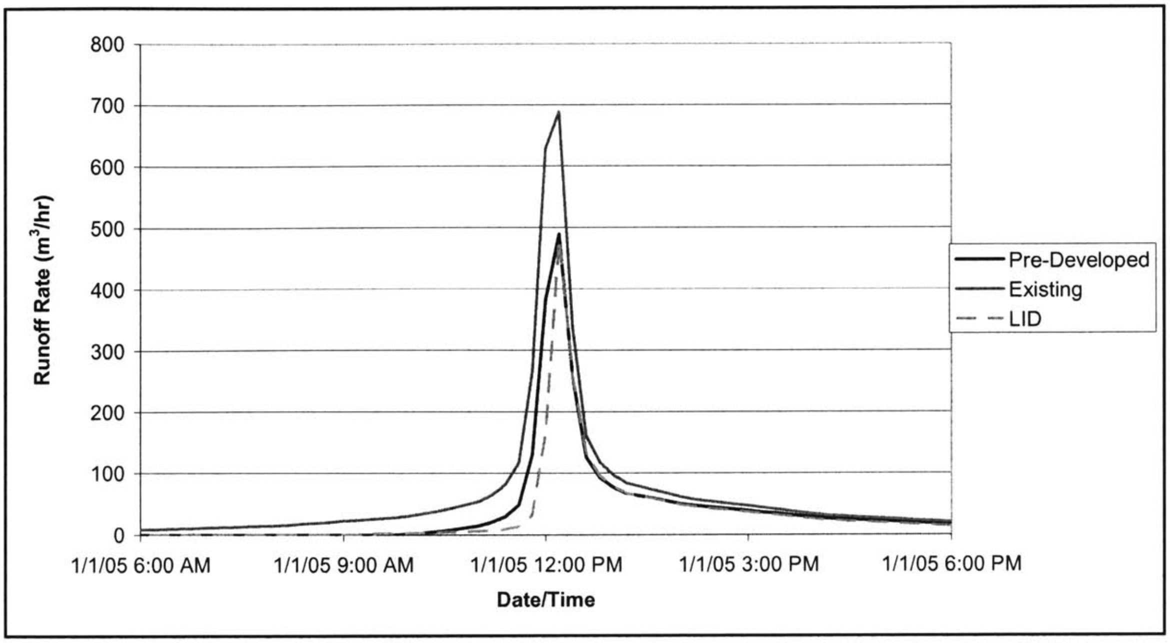


Figure 31: Runoff hydrographs for the entire site for 10-year design storm

The results show that the LID technologies are able to decrease both the peak and total runoff from the site. The total runoff actually decreased from the pre-developed to the LID-designed site. There is a sharper and later increase in the LID-designed scenario, which I attribute to the build up of stored water in the rain gardens. Once the capacity is reached, the hydrograph rises at the same rate as the existing site and the rain gardens are no longer effective. The difference between the existing and LID-designed hydrographs can be attributed to the water that is stored and then infiltrated or evapotranspired. The results suggest that landscape-based technologies can feasibly be used to manage stormwater on site. As shown in Figure 29, only a small fraction of the site was needed for the LID implementation. All SLIDD input pages used to obtain the results are shown in Appendix B.

7.8 *Performance Analysis of the LID-Design*

Although regulations require stormwater management designs to be based on individual storm events, more can be learned from a continuous time series. For this reason, I have run the LID-designed Discovery Museum site through the SLIDD Model with historical data. Hourly precipitation and temperature data was obtained from the

National Climatic Data Center (NCDC 2005). Monthly pan evaporation data was used to estimate evaporation from the rain gardens. In order to avoid complications associated with snowfall and snowmelt, I only modeled April through October. The modeled year was 2000.

Mean monthly evaporation rates based on long-term records were used to approximate the effects of evaporation. Evaporation data was taken from NOAA Technical Report NWS 33 (Farnsworth et al. 1982). I used percent of annual evaporation data from the Worcester, Massachusetts station for each month of interest. The annual mean pan evaporation for the site is approximately 33 inches (NOAA 1983). The rainfall and evaporation rates for the modeled months are shown in Figure 32.

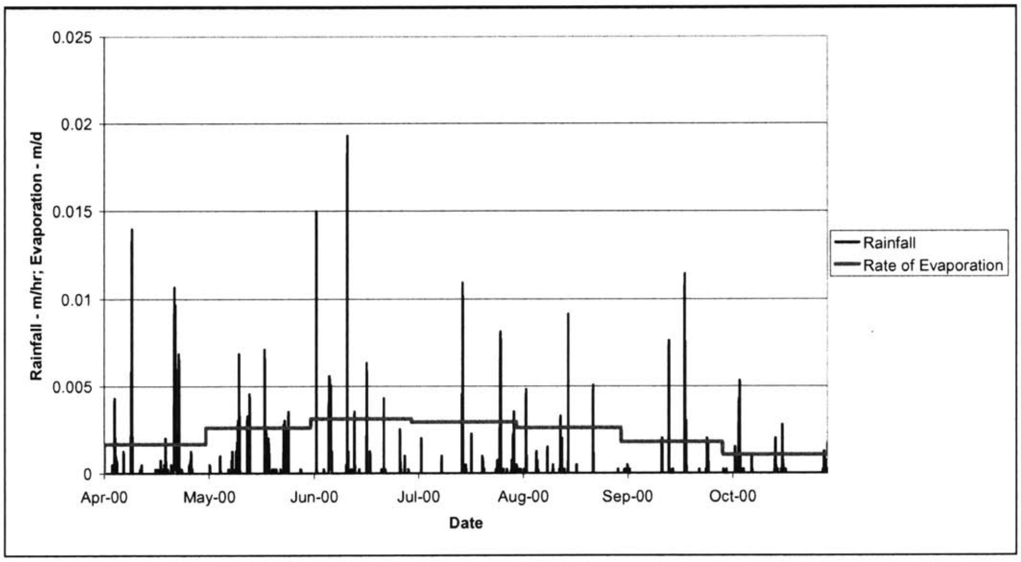


Figure 32: Rainfall and rate of evaporation used in SLIDD Model

The runoff during the model period for the pre-developed, existing, and LID-designed site is shown in Figure 33. Note that the scale of runoff rate (y-axis) varies for each plot.

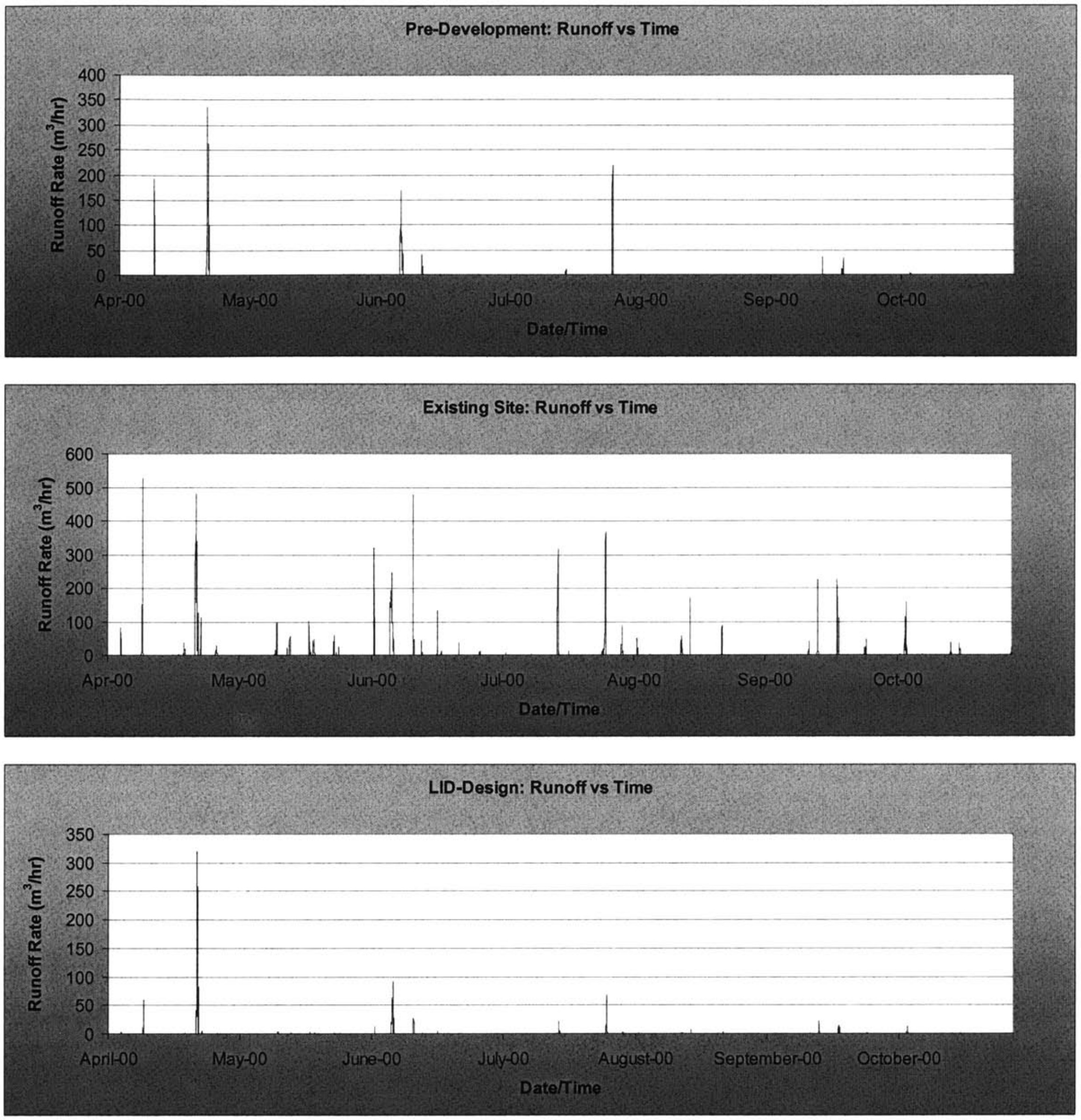


Figure 33: Runoff rate versus time for pre-developed, existing, and LID-designed site, April-Oct 2000

The results of total runoff volume and recharge plus evaporation for all three scenarios are shown in Table 5.

Table 5: Total runoff and recharge + evaporation for pre-developed, existing and LID-designed site, April-Oct 2000

Parameter	Pre-Developed	Existing	LID-Design
Precipitation (m^3)	9592	9592	9592
Total Runoff (m^3)	849	3347	528
Recharge+ET (m^3)	8743	6245	9064

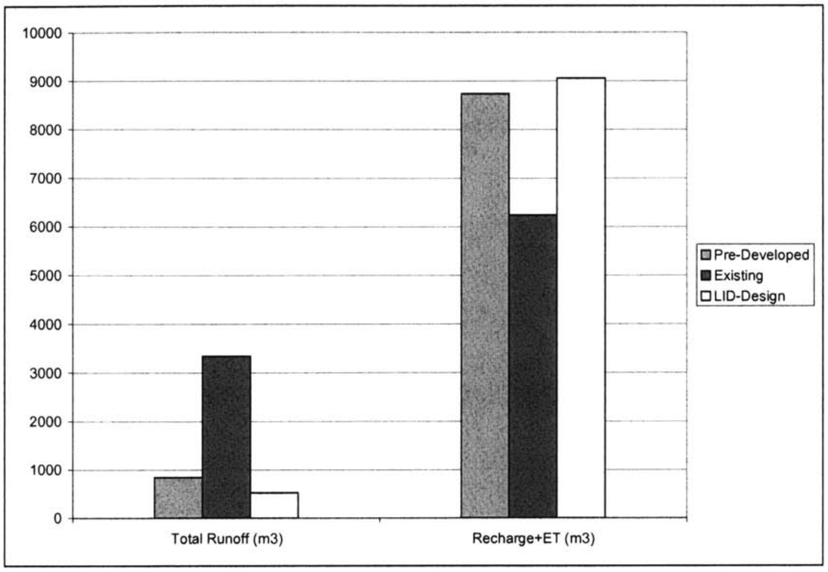


Figure 34: Bar chart of results based on historical data, April-Oct 2000

As Figure 34 shows, the sum of recharge and evapotranspiration is comparable for the pre-developed and LID-designed site. The existing site has substantially more runoff and less recharge and evapotranspiration. As discussed earlier, in order to match peak runoff, the LID design for the site actually decreases the total runoff volume from pre-developed conditions in the ten-year storm. In addition, because the site was designed for the ten-year storm, the LID-designed site tends to actually decrease the peaks of smaller storms (Figure 39). Interestingly enough, the number of runoff events increases in the LID-designed scenario. The pre-development site had approximately eight events, while the LID-designed site had approximately 20 smaller events. I attribute this to the fact that the pre-developed site has much higher initial abstraction. After a large storm, the LID features are at capacity. When smaller storms follow, the impervious areas still produce some runoff that must flow offsite. On the other hand, the pre-developed site, with a much lower curve number, will not produce any runoff during the smaller storms.

7.9 *Conclusions and Recommendations*

The LID design for the Discovery Museums in Acton would help to alleviate water quantity and quality problems in the area. As opposed to conventional technologies, the LID design addresses both the issue of total runoff volume and peak rate management. Decreasing total runoff volume is the next step in controlling flooding in downstream rivers (i.e. Assabet River). By decreasing runoff and increasing recharge, the LID technologies are able to increase groundwater storage and hence baseflow to rivers. This is of great importance in Acton, because of the town's reliance on groundwater as its primary drinking water source. I recommend that LID be strongly considered as a beneficial alternative to conventional stormwater management technologies.

8 Large-Scale Implications of Low-Impact Development in the Assabet Watershed

An understanding of the benefits and liabilities of LID is critical before implementing it on a large scale. As discussed earlier, LID is intended to reduce runoff and increase aquifer recharge. Increased recharge leads to increased baseflow, as the aquifer is able to discharge more water. Stream water quality benefits from increased baseflow, as dilution plays a critical role especially in low-flow conditions. In this section, I will first establish the current water balance for Acton's watershed. I will then evaluate to what degree LID can benefit water quantity and quality.

While LID is promising for effectively controlling flow and contaminant concentrations in runoff, there are potential negative impacts to groundwater. A number of conservative contaminants, such as salt, have the potential of entering aquifers at increased levels through LID technologies. Also, restoring groundwater to natural levels has the potential of increasing flooding in low lying areas. This section will discuss why these negative effects occur, the conditions in which they occur, and strategies to prevent them.

8.1 *Study Area*

A sub-basin of the Assabet Watershed, the Upper Nashoba Brook Watershed, was chosen as the study area because of its proximity to Acton, Massachusetts and availability of data. Sub-basins of the Assabet River are shown in Figure 35. The Upper Nashoba Watershed is shown in the small map in the upper left hand corner of the Figure. On the larger map, the Upper Nashoba Watershed is defined by all areas in the Nashoba Watershed upstream of the USGS stream gage.

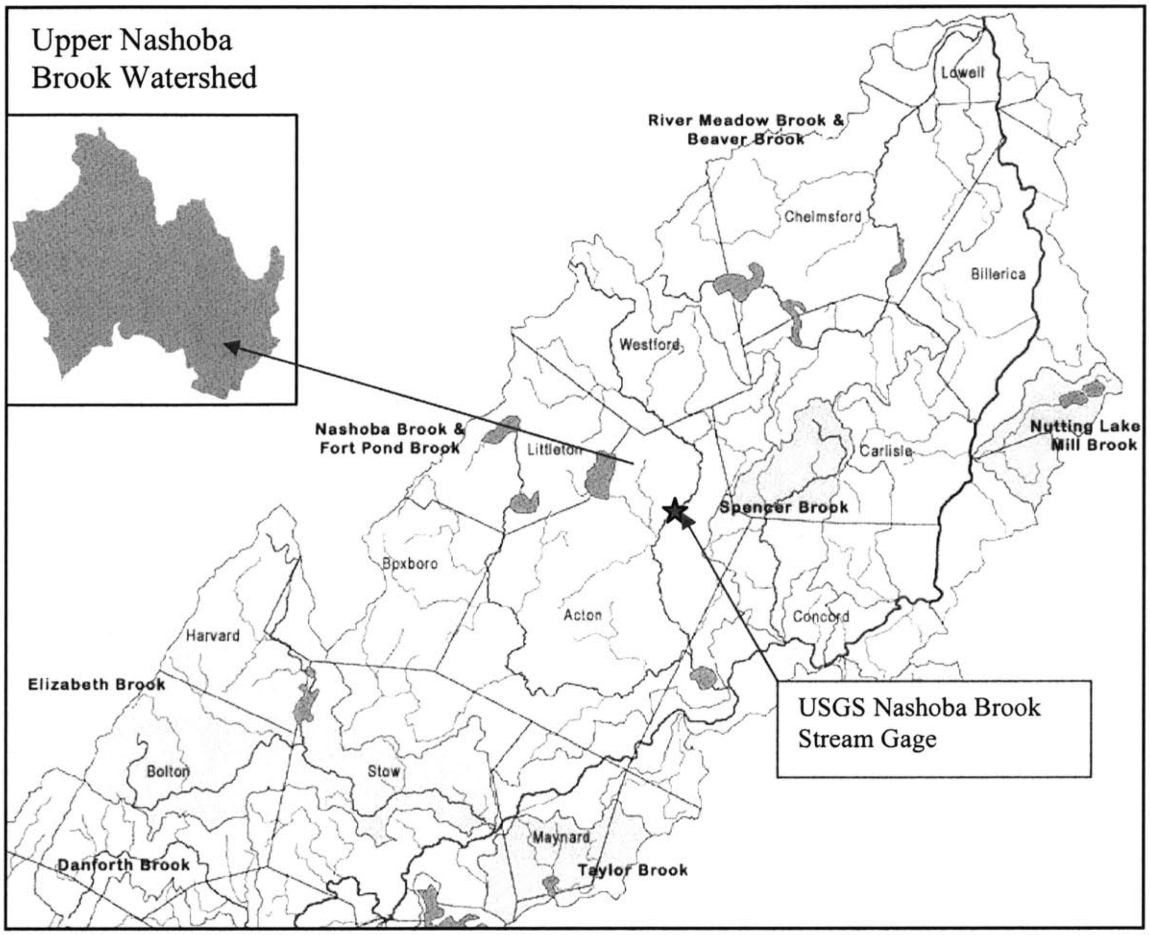


Figure 35: Map of Assabet River Sub-Watersheds

The land use of the watershed is largely forested, though residential, industrial and commercial uses exist. Figure 36 shows the land uses of the watershed. Although Acton is not entirely within the Upper Nashoba Watershed, the area is representative of soil types and land use throughout the region. This is an important feature because the analysis of the hydrologic processes will be linked to stormwater management policy recommendations. For the remainder of this report, the Upper Nashoba Watershed will be simply referred to as the Nashoba Watershed.

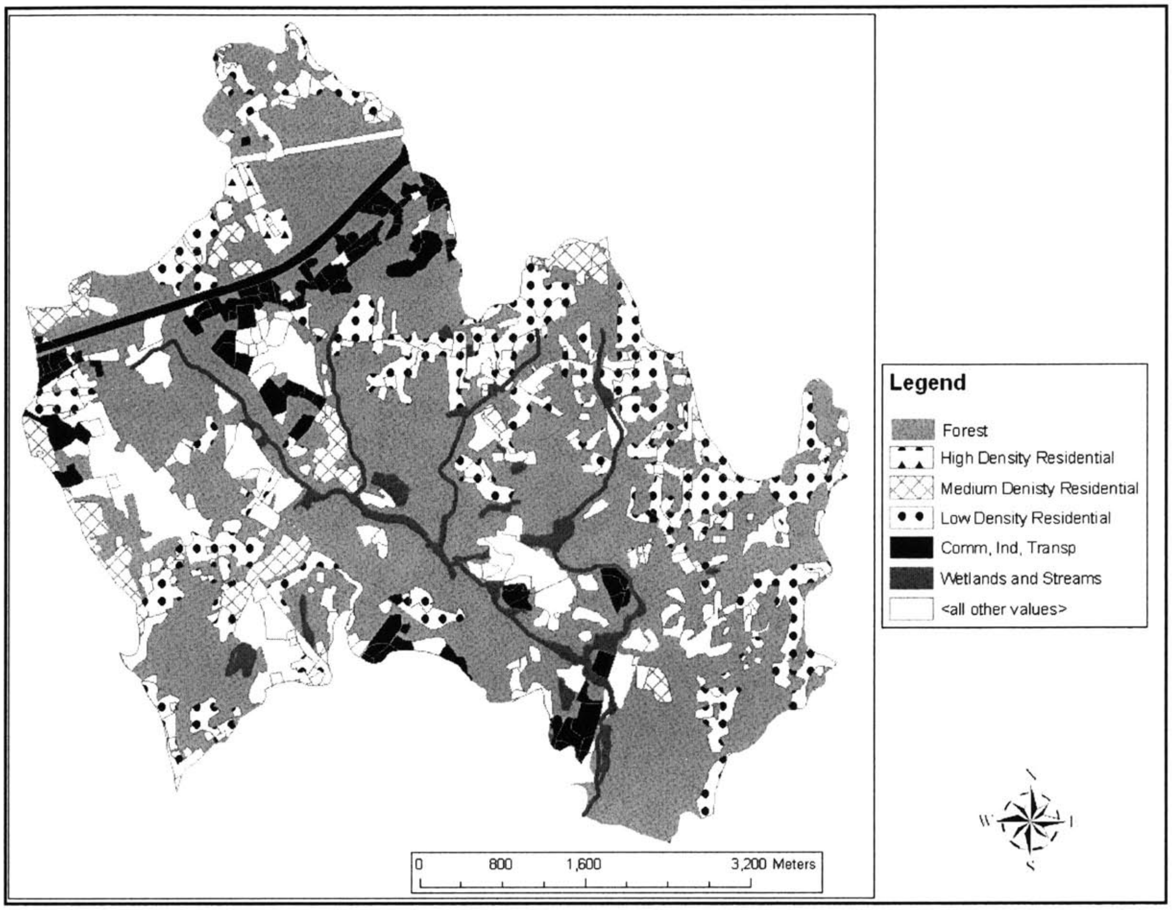


Figure 36: Land use map of the Nashoba Brook Watershed

8.2 *Water Balance*

A water balance was used to establish current hydrologic conditions in the study area. The primary objective was to estimate what percentage of rainfall infiltrated the soil and recharged the aquifer. To perform a water balance, good estimates of processes that drive water from one storage volume to another are critical. The following storage compartments were included in the balance:

- Groundwater
- Atmosphere
- Surface Water

Processes defining movement in the watershed included:

- Precipitation
- Evapotranspiration
- Groundwater Recharge

- Runoff
- Groundwater Extraction
- Groundwater Discharge to Surface Waters

Figure 37 (ISGS 2004) shows a diagram of water movement through the entire hydrologic system.

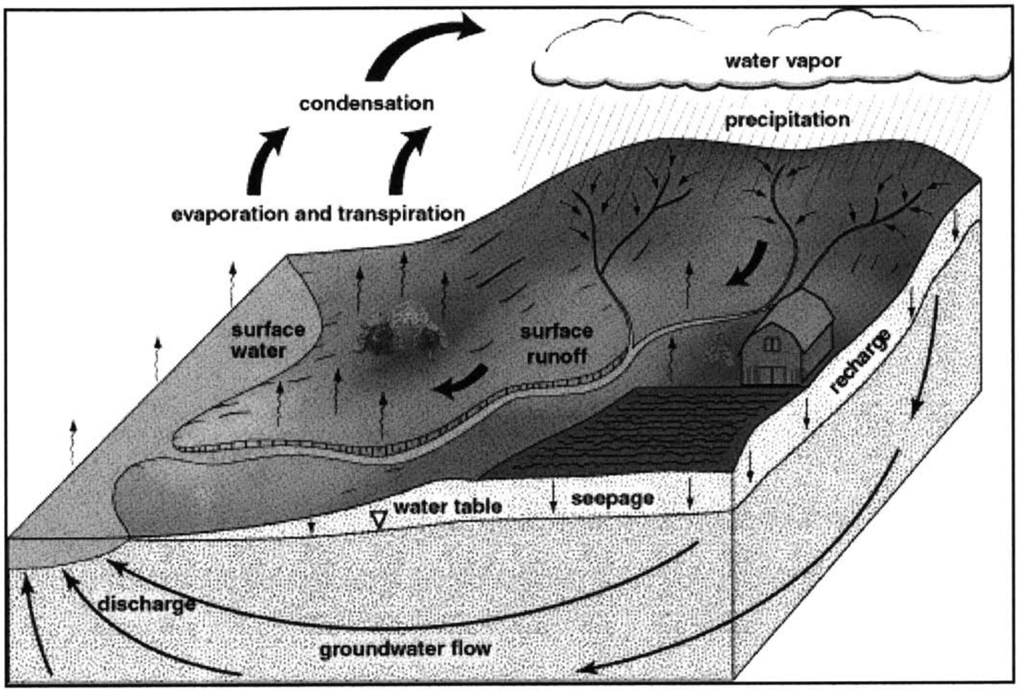


Figure 37: Hydrologic Cycle

8.2.1 *Available Data*

A study period of 1990 through 1999 was used because of availability of data and relevance to current hydrologic conditions. I collected temperature, precipitation, groundwater level, and streamflow data for the study period. The time series of the data set is shown in Figure 38.

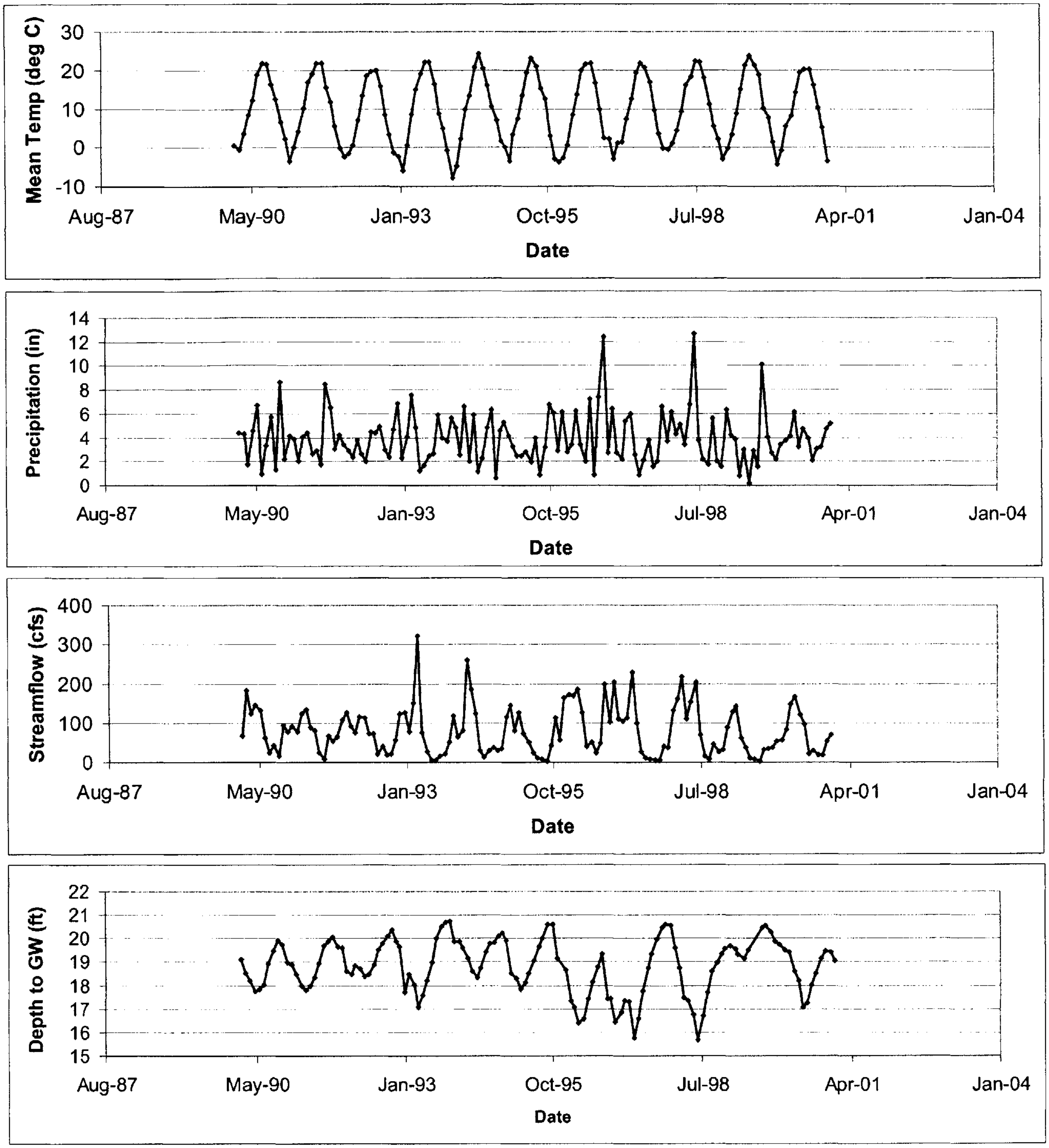


Figure 38: Available hydrologic data for the Nashoba Brook Watershed, 1990-1999

8.2.2 *Determining Evapotranspiration*

A Thornthwaite water balance was used to estimate evapotranspiration. This monthly climatic water balance uses inputs of site latitude, precipitation and temperature data. Variables for the runoff coefficient and soil moisture capacity are also needed. The following steps briefly outline the procedure and are adopted from "Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance"(Thornthwaite and Mather 1957):

1) Calculate the heat index based on temperature.
2) Determine unadjusted potential evapotranspiration (UPET) based on temperature and total annual heat index.
3) Determine mean possible monthly duration, r, of sunlight based on site latitude and month.
4) Calculate potential evapotranspiration (PE) as the multiple of UPET and r.
5) Determine value of infiltration (I) minus PE. Positive values indicate excess moisture available for infiltration and runoff, while negative values indicate potential water loss (PWL).
6) Determine soil moisture storage capacity (Cs). Eight inches was used as a typical value for the Nashoba Watershed.
7) Calculate storage (ST). Accumulated water loss decreases storage, while (I – PE) increases storage.
8) Calculate change in soil moisture (ΔST) based on the storage. Above ground storage (snow) is not taken into account.
9) Determine actual evapotranspiration (ET): when (I – PE) is greater than zero, then the soil remains full of water, and ET = PE. When (I – PE) is less than zero, $ET = I + |\Delta ST|$.

Following this procedure, I estimated monthly evapotranspiration for the Nashoba Watershed. The calculations are shown in Appendix D. The infiltration was estimated by using land use data from MassGIS (MGIS 2005), shown in Figure 34. Overland flow and infiltration were separated using a runoff coefficient (C). The runoff coefficient C, from the Rational Method, is loosely defined as the ratio of runoff to rainfall (Pilgrim and Cordery 1993). This value is widely tabulated for values of surface cover (land use) and soil group. An example table is shown in Table 6 (McCuen 2004).

Table 6: Runoff Coefficients for the rational method based on soil group, land use, and slope

	A			B			C			D		
Land Use	0–2%	2–6%	6%+	0–2%	2–6%	6%+	0–2%	2–6%	6%+	0–2%	2–6%	6%+
Cultivated land	0.08[a]	0.13	0.16	0.11	0.15	0.21	0.14	0.19	0.26	0.18	0.23	0.31
	0.14[b]	0.18	0.22	0.16	0.21	0.28	0.20	0.25	0.34	0.24	0.29	0.41
Pasture	0.12	0.20	0.30	0.18	0.28	0.37	0.24	0.34	0.44	0.30	0.40	0.50
	0.15	0.25	0.37	0.23	0.34	0.45	0.30	0.42	0.52	0.37	0.50	0.62
Meadow	0.10	0.16	0.25	0.14	0.22	0.30	0.20	0.28	0.36	0.24	0.30	0.40
	0.14	0.22	0.30	0.20	0.28	0.37	0.26	0.35	0.44	0.30	0.40	0.50
Forest	0.05	0.08	0.11	0.08	0.11	0.14	0.10	0.13	0.16	0.12	0.16	0.20
	0.08	0.11	0.14	0.10	0.14	0.18	0.12	0.16	0.20	0.15	0.20	0.25
Residential lot size 1/8 acre	0.25	0.28	0.31	0.27	0.30	0.35	0.30	0.33	0.38	0.33	0.36	0.42
	0.33	0.37	0.40	0.35	0.39	0.44	0.38	0.42	0.49	0.41	0.45	0.54
Residential lot size 1/4 acre	0.22	0.26	0.29	0.24	0.29	0.33	0.27	0.31	0.36	0.30	0.34	0.40
	0.30	0.34	0.37	0.33	0.37	0.42	0.36	0.40	0.47	0.38	0.42	0.52
Residential lot size 1/3 acre	0.19	0.23	0.26	0.22	0.26	0.30	0.25	0.29	0.34	0.28	0.32	0.39
	0.28	0.32	0.35	0.30	0.35	0.39	0.33	0.38	0.45	0.36	0.40	0.50
Residential lot size 1/2 acre	0.16	0.20	0.24	0.19	0.23	0.28	0.22	0.27	0.32	0.26	0.30	0.37
	0.25	0.29	0.32	0.28	0.32	0.36	0.31	0.35	0.42	0.34	0.38	0.48
Residential lot size 1 acre	0.14	0.19	0.22	0.17	0.21	0.26	0.20	0.25	0.31	0.24	0.29	0.35
	0.22	0.26	0.29	0.24	0.28	0.34	0.28	0.32	0.40	0.31	0.35	0.46
Industrial	0.67	0.68	0.68	0.68	0.68	0.69	0.68	0.69	0.69	0.69	0.69	0.70
	0.85	0.85	0.86	0.85	0.86	0.86	0.86	0.86	0.87	0.86	0.86	0.88
Commercial	0.71	0.71	0.72	0.71	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
	0.88	0.88	0.89	0.89	0.89	0.89	0.89	0.89	0.90	0.89	0.89	0.90
Streets	0.70	0.71	0.72	0.71	0.72	0.74	0.72	0.73	0.76	0.73	0.75	0.78
	0.76	0.77	0.79	0.80	0.82	0.84	0.84	0.85	0.89	0.89	0.91	0.95
Open space	0.05	0.10	0.14	0.08	0.13	0.19	0.12	0.17	0.24	0.15	0.21	0.28
	0.11	0.16	0.20	0.14	0.19	0.26	0.18	0.23	0.32	0.22	0.27	0.39
Parking	0.85	0.86	0.87	0.85	0.86	0.87	0.85	0.86	0.87	0.85	0.86	0.87
	0.95	0.96	0.97	0.95	0.96	0.97	0.95	0.96	0.97	0.95	0.96	0.97

[a] Runoff coefficients for storm recurrence intervals less than 25 years.

[b] Runoff coefficients for storm recurrence intervals of 25 years or longer.

The watershed contains mainly hydrologic group C soils, with more permeable soils near the river basins. For the purpose of the water balance, I assumed a mixture of group B and C soils. The average runoff coefficient was then calculated by weighting the different runoff coefficients of each. A summary table of the average runoff coefficient calculation is shown in Table 7.

Table 7: Average runoff coefficient calculation

Land Use:	Forest	< 1/4 Acre Residential (LID)	1/3 Acre Residential (LID)	> 1/2 Acre Residential (LID)	Commercial, Industrial, Transportation	Other
Percent of Total Area	58%	1%	4%	18%	7%	12%
Tabulated Runoff Coef.	0.09	0.285	0.235	0.185	0.70	0.10
Average Runoff Coef.	**0.16**					

Rainfall interception can be significant in forested regions. I assumed that 10 percent of the rainfall during the months of March through October was intercepted. This value is based on a typical forested interception value of 20 percent (Shuttleworth 1993), and dividing by 2 because only about half of the watershed is forested. Infiltration was then calculated using Equation 6.

Equation 6: Infiltration calculation

$I = [(1 - C) * P * (1 - f_i)]$ where: f_i = fraction intercepted

C = runoff coefficient

Using the monthly calculated infiltration, and other Thornthwaite parameters, I calculated the mean monthly evaporation over the study period (1990-1999). The results are shown in Figure 39. The evapotranspiration peaks in July. The average annual evapotranspiration was calculated as 23.2 inches. The summer months of June through August experience a water deficit, calculated as potential evapotranspiration minus actual evapotranspiration. During this period, soil moisture declines. The soil water is then replenished during September and October. During months of positive (P – PE), surplus is calculated as $(I - PE - \Delta ST)$. Because January and February experience below freezing temperatures, precipitation is assumed to form snow and no surplus is created.

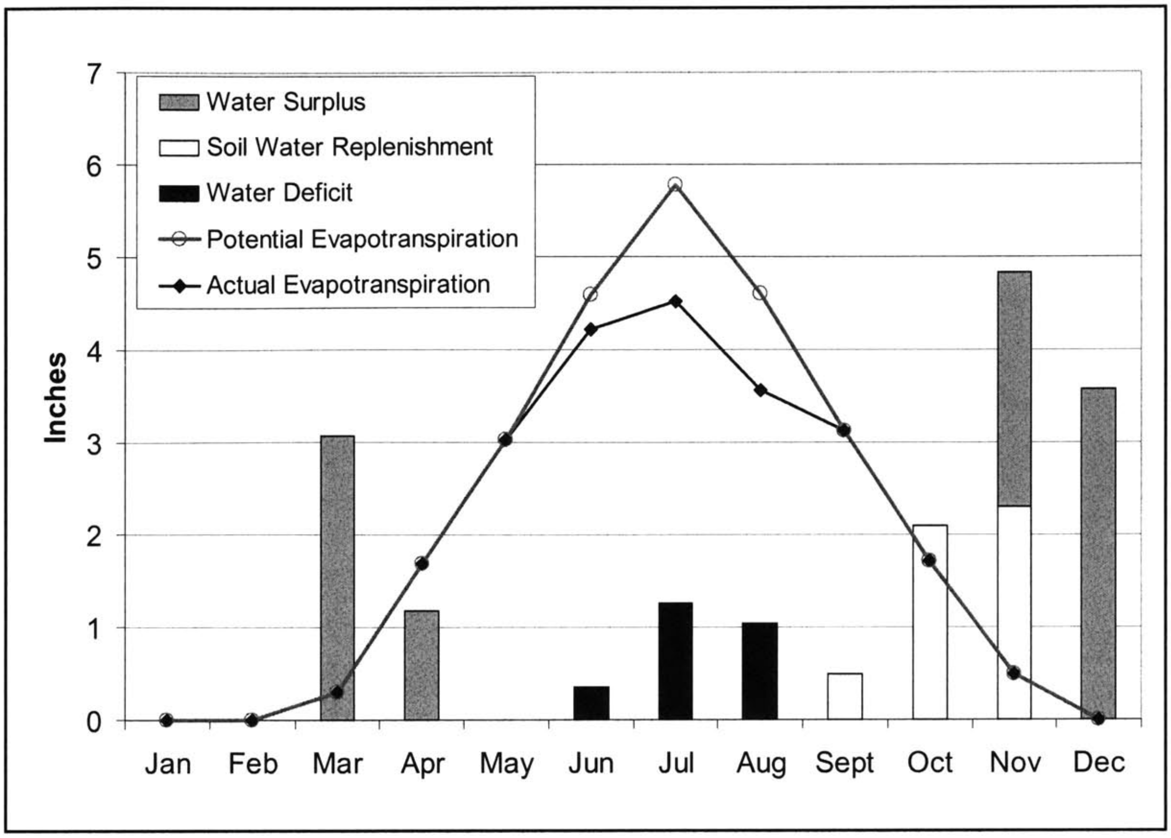


Figure 39: Thornthwaite water balance results, 1990-1999 data

8.2.3 *Baseflow Separation*

Streamflow can be formed in three major ways: surface runoff, interflow, and baseflow. Surface runoff is perhaps the easiest to understand, and is defined as the water that flows overland directly into streams. The two mechanisms that cause surface runoff are rainfall in excess of the infiltration capacity of soils and saturation excess. Interflow is subsurface flow that is facilitated by macropores in the soil. Macropores can be caused by tree roots or the burrowing animals and insects. Both interflow and surface runoff occur in short time scales (hours and days) after a rainfall event. For the purpose of this water balance, surface runoff and interflow were lumped together to form "fastflow". Baseflow is the discharge of groundwater to streams and does not respond to rainfall events as much as fastflow. The baseflow is the most critical parameter to stream water quality in the summer months, because it is a source of relatively clean water that can dilute pollution. A USGS-supported program called PART (Rutledge 2005) was used to analyze the streamflow record (1990-1999) at the Nashoba Brook gage. PART implements a baseflow separation algorithm to distinguish surface runoff and interflow from baseflow. The algorithm is based on estimating the time of streamflow recession. The time after a streamflow peak during which surface runoff and interflow are significant can be estimated from Equation 7 (Rutledge 1998).

Equation 7: Recession Period

$$N = A^{0.2}$$

Where:

N = number of days after the peak, and

A = drainage area in square miles

The program searches the streamflow array for days that meet an antecedent recession requirement. The requirement is given by Equation 7 and is the number of decreasing streamflow days after a peak. During these days, the measured streamflow discharge is presumed to represent baseflow unless there is a 0.1 log cycle or greater decline in streamflow the following day. A decline of this magnitude is assumed in the method to indicate flow produced by interflow or surface flow and thus flow that is not strictly baseflow. Baseflow is linearly interpolated for days that do not meet the antecedent recession requirement. The search procedure is repeated three times. First, the program uses the largest integer smaller than the result of Equation 7 for the recession requirement. Then the procedure is repeated twice using the next two largest integers. From these three approximations, PART finds the exact value of baseflow by using a second-order polynomial regression of the three PART approximations. Figure 40 shows the streamflow and one approximation of baseflow for the Nashoba Brook stream gage during the study period.

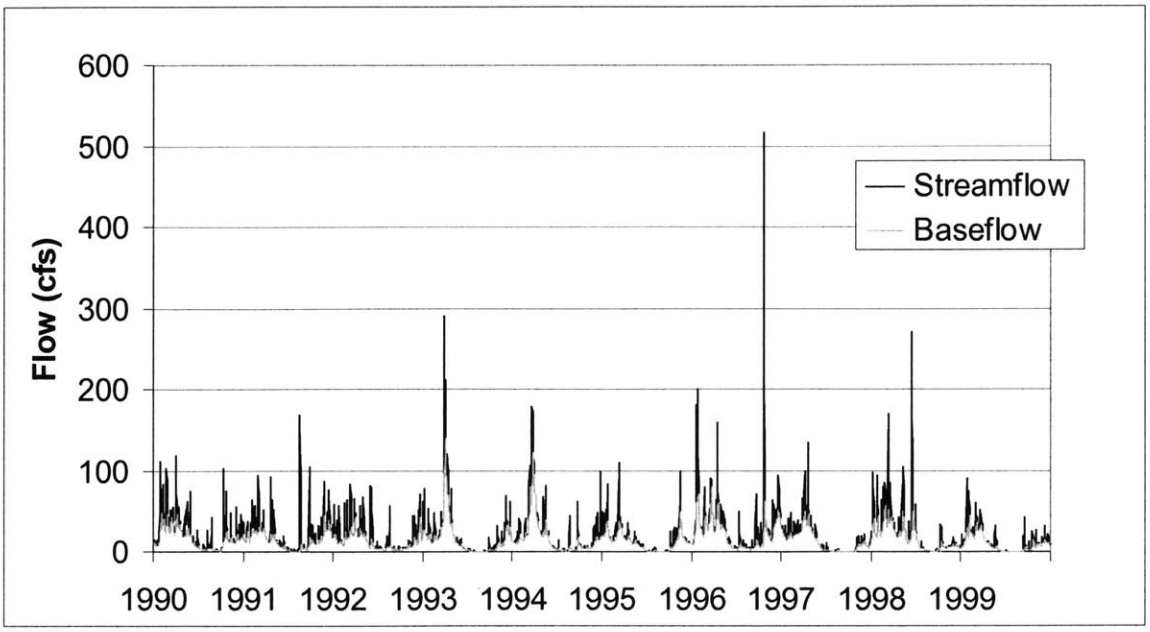


Figure 40: PART baseflow approximation

The "fastflow" contribution to streamflow can be calculated as the difference between the total streamflow and the baseflow. A runoff coefficient can be calculated for each month as the fraction of rainfall that becomes fastflow. Table 8 shows these values.

Table 8: Average monthly runoff coefficients for the Nashoba Watershed, 1990-1999

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	**Year**
Precipitation (inches)	4.4	3.2	4.4	3.7	3.7	2.9	3.4	3.6	4.7	4.9	4.0	4.2	**47.2**
Fastflow (inches)	0.76	0.42	0.62	0.45	0.42	0.36	0.11	0.30	0.25	0.71	0.33	0.50	**5.22**
Runoff Coeff	0.17	0.13	0.14	0.12	0.11	0.13	0.03	0.08	0.05	0.14	0.08	0.12	**0.11**

Interestingly, the runoff coefficient fluctuates between 0.03 and 0.17. The lower values are observed in the summertime, most likely because of a lower groundwater table and increased infiltration capacity.

8.2.4 *Infiltration*

Infiltration is the remainder of the effective precipitation that does not form fastflow, Q_f. The effective precipitation, P_e, is calculated by subtracting the fraction of rainfall that is intercepted from the total rainfall. The rainfall interception term is discussed in more detail in Section 8.2.5.

Equation 8: Infiltration

$$\text{Infiltration (I)} = P_e - Q_f$$

8.2.5 *Recharge*

Infiltration characterizes the total sum of water that flows into the subsurface. Recharge is different from infiltration in that it is only the portion of water that penetrates to the groundwater aquifer. A mass balance on the sub-surface soil can be used to estimate the recharge in a particular month.

Equation 9: Recharge estimation

$$\text{Recharge} = I - ET$$

The amount of evapotranspiration in this equation is equal to the Thornthwaite evapotranspiration over natural areas. Impervious surfaces produce direct runoff and move water to natural areas or surface waters. Evaporation over impervious surfaces is included in the interception term and does not play a role in the soil water balance. The average percent imperviousness for the watershed was calculated based on land use. Table 9 shows how imperviousness changes with land use (CDM 1993).

Table 9: Percent imperviousness for various land uses

WWM Land Use	% Impervious
Forest/Open	5
Agricultural/Pasture	5
Cropland	5
Low Density Residential	10
Medium Density Residential/Institutional	25
High Density Residential	45
Commercial	90
Office/Light Industrial	65
Heavy Industrial	80
Water	100
Wetlands	100
Major Highway	90

These values were taken from the Watershed Management Model (WMM), developed by Camp Dresser and McKee. The calculation for the percent imperviousness of the watershed is shown in Table 10.

Table 10: Average percent imperviousness in the Nashoba Watershed

Land Use:	Forest	< 1/4 Acre Residential (LID)	1/3 Acre Residential (LID)	> 1/2 Acre Residential (LID)	Commercial, Industrial, Transportation	Other
Percent of Total Area	58%	1%	4%	18%	7%	12%
% Impervious	5	45	25	10	80	5
Average % Impervious	**12**					

The average percent impervious was calculated to be 12 percent. Therefore, the evapotranspiration used in Equation 9 was equal to 0.88 times the Thornthwaite evapotranspiration. Recharge, on an annual basis, should be equivalent to baseflow. The fraction intercepted was optimized so that this criterion was met. Equation 6 shows that an increased fraction intercepted leads to less infiltration and therefore recharge. The result was 0.13, or 13 percent intercepted. Table 11 shows a summary of the average monthly results for baseflow, fastflow, infiltration, and recharge over the study period.

Table 11: Average monthly baseflow, fastflow, infiltration, and recharge, 1990-1999

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Year
Effective Precip (inches)	4.4	3.2	4.4	3.7	3.7	2.9	3.4	3.6	4.7	4.9	4.0	4.2	47.2
Thornthwaite ET (inches)	0.0	0.0	0.3	1.7	3.0	4.2	4.5	3.6	3.1	1.7	0.5	0.0	22.6
Baseflow (inches)	1.7	2.0	3.2	2.8	1.6	0.7	0.3	0.2	0.2	0.6	1.1	1.7	16.0
Fastflow (inches)	0.8	0.4	0.6	0.4	0.4	0.4	0.1	0.3	0.3	0.7	0.3	0.5	5.2
Infiltration (inches)	3.1	2.4	3.2	2.8	2.8	2.2	2.9	2.8	3.9	3.6	3.1	3.2	36.0
Recharge (inches)	3.1	2.4	3.0	1.3	0.1	-1.6	-1.1	-0.3	1.1	2.1	2.7	3.2	16.0

One interesting outcome is that recharge actually becomes negative in the summer months. The reason for this is that the evapotranspiration exceeds the water that is able to infiltrate the soils. The physical result of negative values of recharge is a flux of water from the groundwater up to the vadose zone or to the atmosphere. This is seen in transpiration in riparian zones (where trees have access directly to groundwater) and in capillary action driven by tree root suction. The annual recharge calculated of 16 inches is typical of other investigations of this area (DeSimone 2004).

8.2.6 *Groundwater Storage*

Change in groundwater storage is a simple function of baseflow (G) and recharge (Re).

Equation 10: Water balance of groundwater storage

$$\Delta S_g = Re - G$$

Because groundwater data is available, change in groundwater storage can be used as a check for the water balance. Figure 41 shows actual and estimated monthly values of change in groundwater storage.

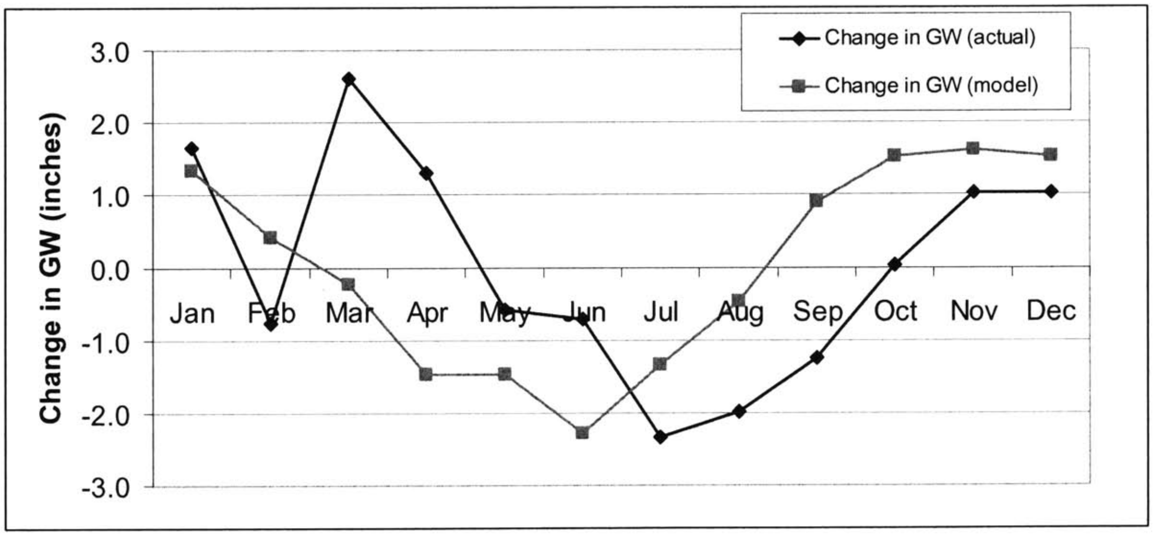


Figure 41: Comparison of modeled and actual change in groundwater storage, 1990-1999 data

The modeled and actual changes in groundwater show the same sort of trends. The spike from snowmelt is observed in March in the actual data, while the model did not account for this phenomenon. The downward trend in storage during the summer months is seen in both scenarios. Differences in estimated and actual values can be attributed to both errors in the model and temporal resolution in the data. The model does not account for anthropogenic fluxes, including increased groundwater withdrawals in the summertime. The data was taken from the USGS monitoring well in Acton, Massachusetts, which only records once a month. Therefore, the average annual data shown only reflects ten points during the 1990-1999 study period. It is possible that the average of these points do not reflect the true average monthly groundwater levels. Interestingly, the actual values of change in groundwater storage for July through November are very well matched by the predicted values for June through October. One explanation for this one-month shift is a lag in groundwater storage response. Typically, subsurface vertical flows can be very slow, especially in glacial till. The model assumes that the groundwater reaches a steady-state with the inflows and outflows within each month, while there may in fact be a lag.

The groundwater levels are theoretically related to baseflow. High groundwater levels should yield higher baseflows. This trend was examined using the modeled data. A logarithmic trend line was fit to the data. Figure 42 shows the correlation.

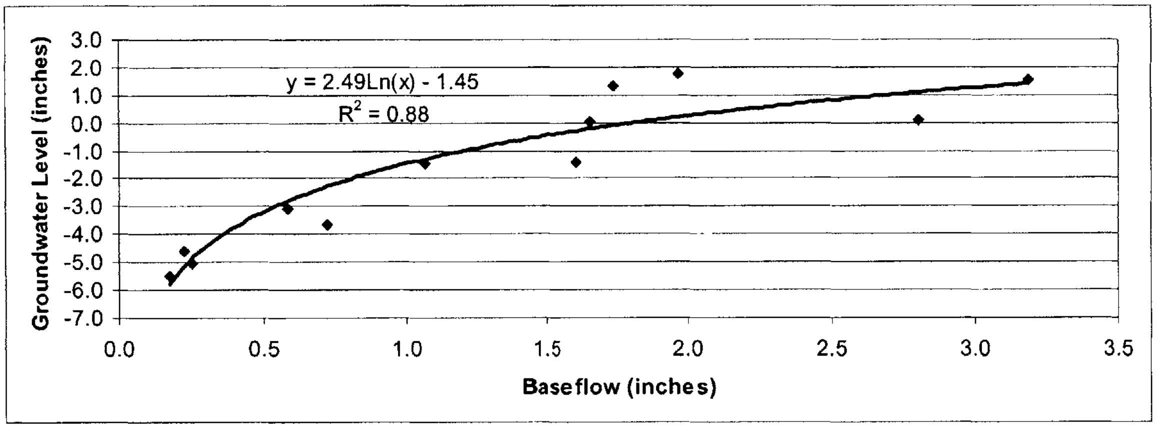


Figure 42: Relationship between modeled groundwater level and baseflow

All average monthly data for the water balance is shown in Appendix E. The averaged data for the 1990s in the Nashoba Brook Watershed show a seasonal trend in groundwater levels and baseflow. Because LID returns land to a natural hydrologic state, I hypothesize that increased infiltration and decreased runoff from LID implementation would lead to higher baseflow and therefore stream water quality. The following section investigates and quantifies this hypothesis using the same water balance model.

8.3 *Potential Benefits of LID*

The town of Acton has experienced the environmental impacts of groundwater extraction and urban development first hand. Seasonal variability in groundwater storage has proven to be detrimental to stream water quality. The following quote is taken from the Assabet River Stream Watch (ARSW 2002):

> Most Assabet communities use water from ground water sources and discharge into the river, failing to replenish the local aquifers. These aquifers supply the clean, pure groundwater "baseflow" that is essential to keep the smaller streams flowing during the summer dry season. As the groundwater levels drop, the streams also dry up, and there is less baseflow available to the Assabet River to dilute the wastewater treatment effluent. During dry summers most of the Assabet watershed communities have needed to institute water-use restrictions of some type.

In addition to stream water quality, water supply is an issue that Acton may face in the future. Acton relies fully on groundwater as their supply source. As population and imperviousness increase, both demand and recharge decrease. If nothing is done to stop this trend, future generations may see a higher demand than supply of groundwater during dry summers. Finally, increased flooding is an obvious and long-understood effect of urban development. LID is a potential remedy to all of these problems.

8.3.1 *Analysis of Hydrologic Data*

The water balance provides an excellent picture of the seasonal variability of the hydrologic cycle in the Nashoba Watershed. A shift in the availability of water occurs during the summer. While all other months experience a surplus of water ($P - PE > 0$), June, July, and August all experience a deficit. This phenomenon is seen in the Thornthwaite analysis (Figure 39), as well as the groundwater storage and streamflow data. The change in storage is negative during summer months and depth to groundwater increases throughout the summer. The results of this seasonality are low summer baseflows. The hydrologic evidence shows that declines in groundwater storage are linked to the dramatic decrease in baseflow and therefore streamflow during summer months. Figure 42 shows the relationship between modeled groundwater level and baseflow.

The baseflow and low-flows have decreased in recent years. The flow duration curve (FDC) is a tool used to observe the distribution of flow during a given period. The FDC plots the log discharge on the y-axis and the percent exceeded on the x-axis. Figure 43 shows flow duration curves using daily flow at the USGS Nashoba Brook gage during the 1980s and 1990s.

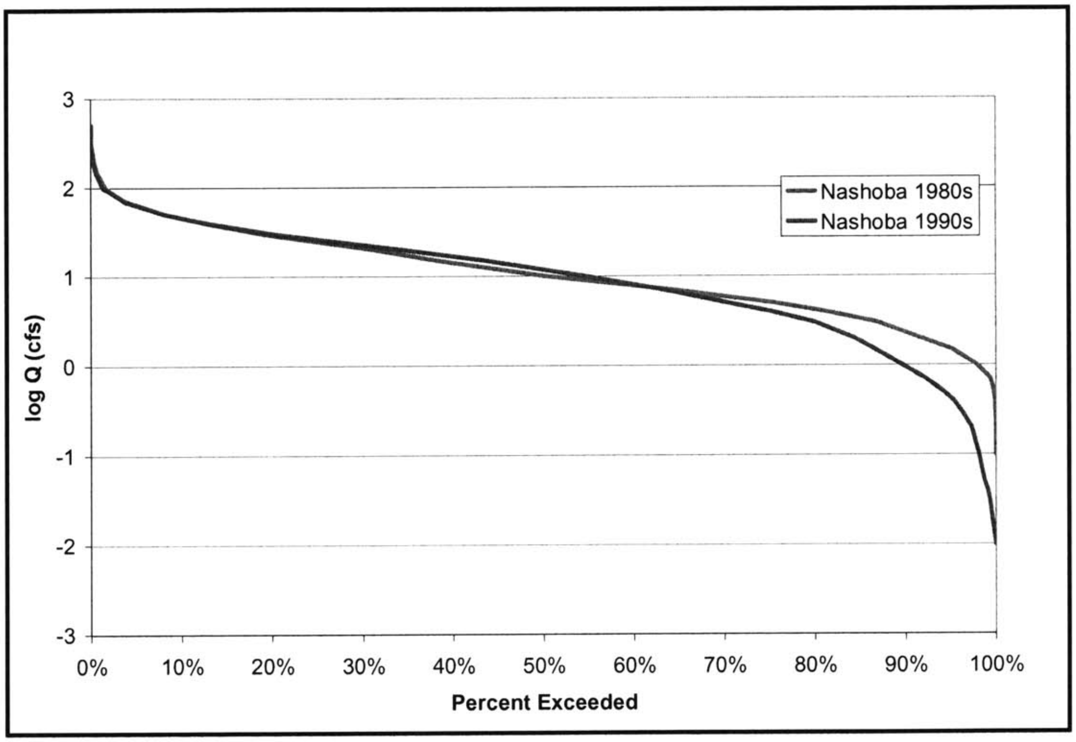


Figure 43: Flow duration curves for the USGS Nashoba Brook gage – 1980s and 1990s

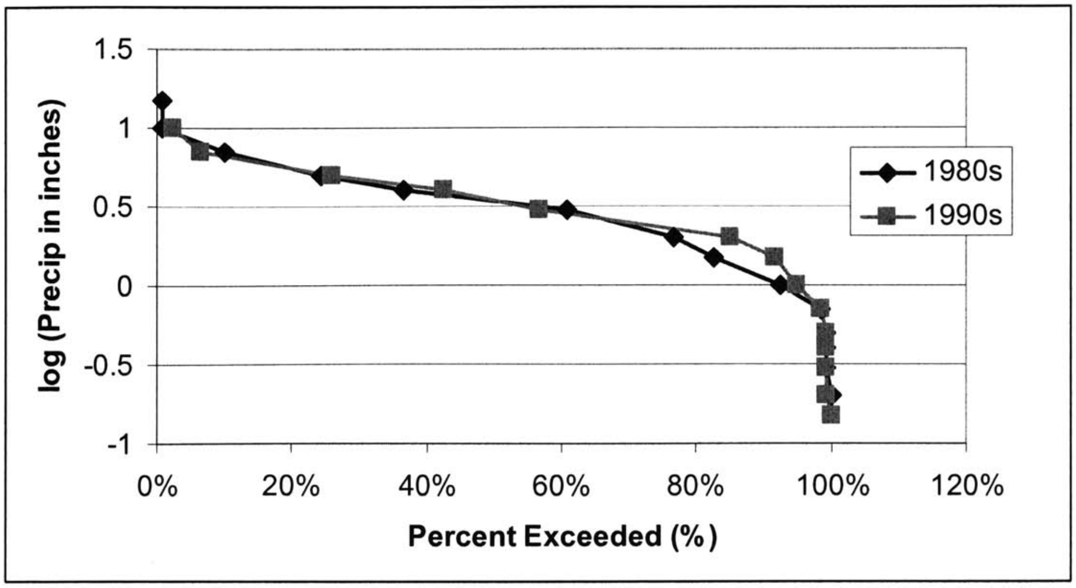


Figure 44: Percent exceedence of monthly rainfall at the Bedford, MA station – 1980s and 1990s

Figure 44 shows the percent exceedence of monthly rainfall for the 1980s and 1990s. The rainfall for the 1990s is not less than the 1980s. The average monthly rainfall actually increased in the 1990s. On the other hand, the FDC for the 1990s has significantly lower flows at the high end of the percent exceeded scale. This shows that the low-flow events, governed by baseflow, have decreased. One determining factor is the surface cover in the watershed. The area had large amounts of population growth and development, increasing imperviousness and decreasing forest cover. From a hydrologic standpoint, this shift affects the runoff coefficient, and therefore the percentage of streamflow coming from either runoff or baseflow.

8.3.2 *Watershed Monthly Runoff Model*

A watershed runoff model was produced based on the water balance discussed previously. The main goal was to observe how the hydrologic cycle was affected by changes in surface cover. Land use affects both the runoff coefficient and percent imperviousness. For this model, it was assumed that increases in runoff coefficient would be a result of the replacement of forest with medium density residential land. Recall the current runoff coefficients using the water balance from Table 8. A multiplicative factor was applied to the coefficients to simulate the gradual development of the land. By using the land use and rational method runoff coefficient data (Table 7), I approximated that an 18.5% decrease in forests (compared to present land use) leads to a 10% increase in runoff coefficient. The developed forests were replaced with medium density residential land. It was also calculated that the same 18.5% decrease in forests leads to a 17.5% increase in impervious surface (compared to present impervious surface). This data was used to calculate how incremental 10 percent increases in the runoff coefficient (equivalent to 18.5% decrease in forests) would affect baseflow and groundwater levels.

The simulation uses the same principles as the water balance, although the runoff coefficient determines the baseflow instead of the baseflow determining the runoff coefficient. Groundwater levels were estimated using the relationship shown in Figure 42. All other parameters follow the same assumptions. Evapotranspiration is assumed to be unchanged by development.

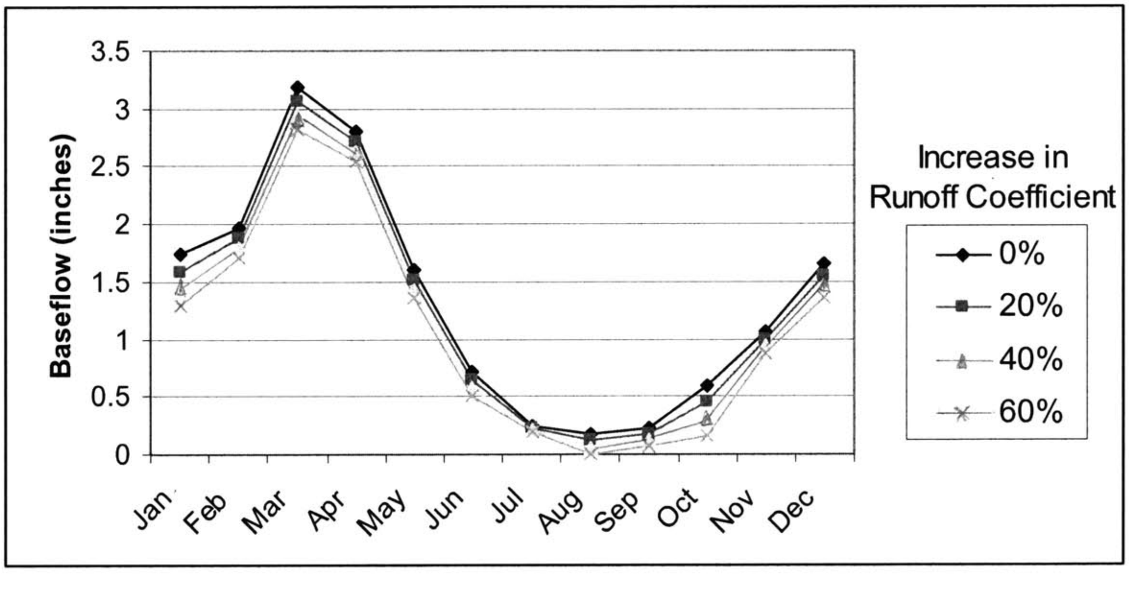


Figure 45: Baseflow response to residential development

As development increases, and the runoff coefficient increases due to impervious cover, the baseflow steadily drops. Figure 45 indicates that baseflow to the Nashoba in summer months may even go to zero if a substantial amount of forested land is developed. Remember, a 10% increase in runoff coefficient is approximately equal to an 18.5% decrease in forests due to residential development. This issue is the most troublesome from an environmental standpoint, and requires the most attention from stormwater management authorities. While a replacement of 18.5% of the forests with residential areas is a large amount, the results show the potential negative effects of heavy development.

Flood control during high flow storms is the other major hydrologic concern in the Assabet River Watershed. Runoff from heavy storms is the main cause of flooding. The average monthly streamflow values are shown in Figure 46.

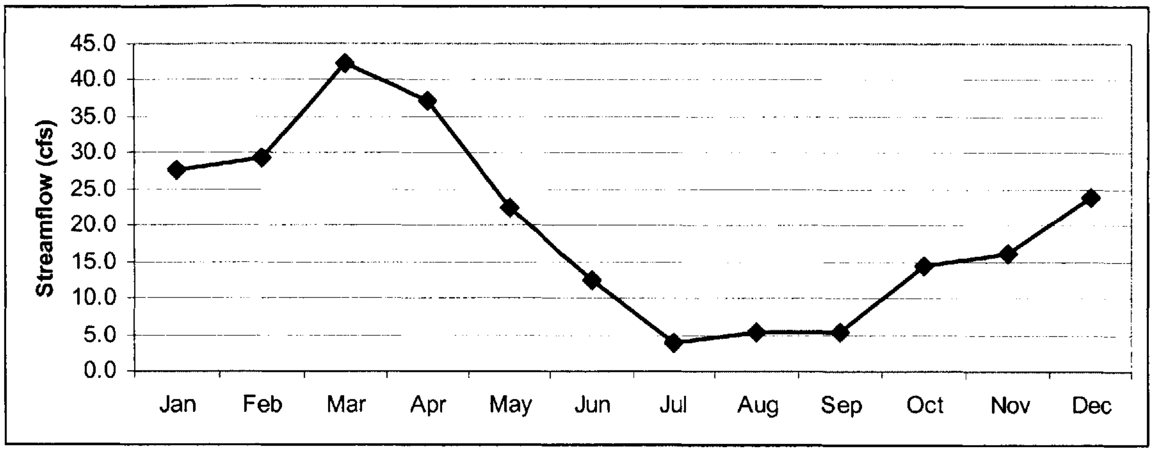


Figure 46: Monthly average streamflow at the USGS Nashoba Brook gage, 1990-1999

The streamflow peaks in the spring, causing increased flooding. In fact, while writing this report (2005), the Assabet River, which Nashoba Brook empties into, experienced a number of flood warnings. What cannot be seen from average monthly data is the role of fastflow. Also referred to as stormflow, fastflow causes quick surges of storm water that cause flooding. Fastflow, as with baseflow, is governed by the runoff coefficient. Developed land leads to a larger percentage of fastflow and increased flooding.

8.3.3 *The Role of LID*

As previously discussed, LID works to increase infiltration and recharge and decrease runoff in developed areas. These characteristics make LID a feasible technology for increasing baseflow and decreasing flooding. Increasing infiltration and recharge throughout the year increases baseflow to streams, as demonstrated by the water balance. This increase in recharge and baseflow is crucial to the water quality in surface waters during the low-flow summer months. Common sense also shows that increasing recharge through LID will have a direct impact on the availability of groundwater as a water source. The very principle of LID is to store and infiltrate water, and in effect increase groundwater storage.

In order to quantify the potential impacts of LID, I have used the land use data of the Nashoba Watershed to model how the runoff coefficient would change. In theory, LID restores developed areas to a natural state (forested) through storage, infiltration, and evaporation. Recall that the existing average runoff coefficient using land use data for the watershed is 0.16. Using the same approach, I calculated the average runoff coefficient with LID implementation in all residential areas. Table 12 shows this calculation.

Table 12: Average runoff coefficient calculation with LID implementation

Land Use:	Forest	< 1/4 Acre Residential (LID)	1/3 Acre Residential (LID)	> 1/2 Acre Residential (LID)	Commercial, Industrial, Transportation	Other
Percent of Total Area	54%	2%	8%	18%	5%	13%
Tabulated Runoff Coeff.	0.09	0.09	0.09	0.09	0.70	0.10
Average Runoff Coeff.	**0.12**					

The resulting average runoff coefficient is 0.12, a 25 percent decrease from the current state. I decreased the runoff coefficients in the model by the same percentage and found the lowest average baseflow (during August), to be 0.25 inches, compared to 0.18 inches for the existing basin. The result is modest numerically, but accounts for a 40 percent increase. The importance is that implementing LID technologies ensures substantial baseflow during the low-flow months. Figure 47 compares baseflow for the existing and LID-implemented watershed.

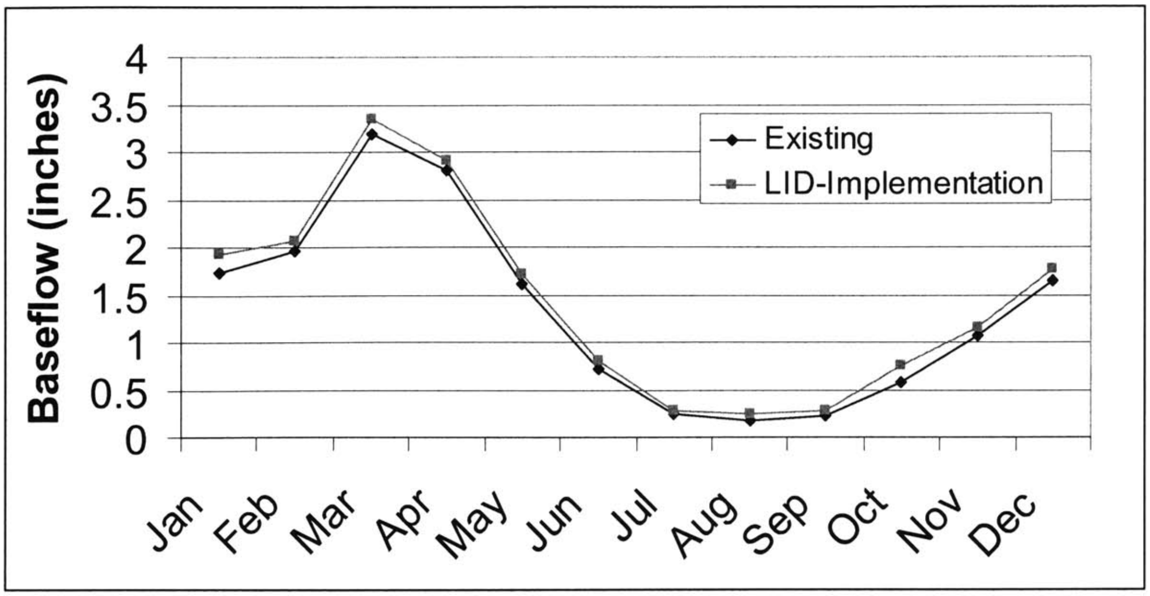


Figure 47: Effect of LID-implementation on baseflow

Stormwater management practices that reduce runoff and increase infiltration are especially important in new development. The watershed cannot afford loss of forest and increased impervious surfaces that jeopardize baseflow. While LID retrofits can be quite costly, I strongly recommend the consideration of such practices in the further development of Acton and the surrounding towns.

Runoff control can also be mitigated using LID technologies. The spring season experiences very high runoff and flooding events. It has been shown that increased river flow is mostly due to direct runoff, as opposed to increased baseflow (Pilgrim and Cordery 1993). The high volumes of runoff produced on impervious surfaces can be controlled using LID storage areas that can infiltrate and evapotranspire water. Although no watershed-scale analysis was done to quantify the effects of LID implementation, the small-scale design in Chapter 7 of this report shows the impressive benefits of LID to control runoff and decrease flooding.

8.4 *Potential Liabilities of LID*

Although LID seems like a very beneficial tool, there are some potential problems and liabilities. No analyses were done on the liabilities of LID. Rather, this section is designed to bring up several issues that should be considered before implementing LID on a large scale.

The benefits of LID are rooted in the property of increased infiltration of rain water. Technologies such as rain gardens store and infiltrate water that would otherwise run off a property. This same feature is also the focus of one of my largest concerns. Salt contamination has long been cited as a problematic contaminant in groundwater drinking-water sources. Acton, Massachusetts relies completely on groundwater as its water supply. Additionally, areas that receive large amounts of snowfall, like the Assabet River Watershed, are especially susceptible to salt contamination due to the application of deicing road salts. As early as the 1970s, this issue was recognized in eastern Massachusetts. "There is little doubt that these (groundwater) concentrations of sodium and chloride are due to the increased use of highway deicing compounds" (Gelhar and Wilson 1974). The concentration of NaCl in groundwater is a function of natural recharge, street density, and the application rate. Also, Gelhar and Wilson noted that the fraction of salt that reaches the water table decreases with development. LID strives to return developed areas to hydrologically undeveloped states. The problem is that potentially heavily polluted stormwater is able to infiltrate and recharge the aquifer at higher rates. While compounds like phosphates and suspended solids tend to be taken up and filtered out in the soil, other chemicals, like salt, nitrates, and some pesticides are conserved. As a result, I advise the use of caution in implementing LID technologies where groundwater is a drinking water source. Some potentially prohibitive conditions for LID with regard to groundwater quality include:

- Transportation – heavily salted roads and highways
- Highly urbanized
- Agricultural lands
- Livestock operations

I hypothesize that water quality problems associated with LID would be localized to the treatment technologies. Before implementing an LID design in a prohibitive condition, an environmental impact analysis should be performed in regard to local groundwater supply. LID can be modified to prevent groundwater recharge by lining the devices with impermeable materials. While infiltration is not increased, polluted runoff is stored and processed. The main outflow in these modified technologies is evapotranspiration. Besides ceasing to use or modifying LID technologies on these land types, the other obvious solution (which is often forgotten about) is minimizing the use of chemicals in the first place. Concord, Massachusetts has ceased to use salts for deicing roads. There are also a number of alternative chemical deicers that are less harmful to groundwater quality. Regardless, it is clear that ground water quality is an important "side-effect" of LID, and requires further research and analysis.

The other potential liability of LID stems from a hydrologic perspective. The concept is very simple. Humans have changed the landscape, and consequently the hydrologic processes across the world. LID attempts to restore hydrologic processes back to "natural" conditions. These conditions may be problematic. For example, development may have lowered groundwater in wetlands and floodplains to a point where they can be built on. If LID restores the area to natural conditions, rising groundwater levels may cause flooding in and around buildings. This very situation was analyzed by Gobel et al. (2004) who state "Higher groundwater surface can cause wet basements and parts of buildings or may cause damage to buildings through buoyancy...Although stormwater infiltration should be regarded as a reasonable measure of near-natural stormwater management, it is now clear that the adverse economic and logical consequences in particular have not yet been adequately estimated". In general low-lying areas, such as floodplains and wetlands, would be most susceptible to flooding. As opposed to water quality concerns, changes in groundwater levels from stormwater management practices could potentially be regional in scale, especially with large-scale implementations. As with water quality concerns, these potential hydrologic liabilities of LID need to be further addressed. I foresee decisions with regard to these concerns having to be made on a case-by-case basis because of site-specific factors, such as soil type, climate, and land use.

9 Conclusion

Runoff control has been used for decades to control flooding in rivers and streams. Traditionally, stormwater detention facilities have been used to control peak flows, but little attention has been given to actually decreasing the total runoff volume from developed land. Nonpoint source pollution has become an additional concern for runoff control. It is now recognized as a major, if not the most important, water quality problem facing the United States. Runoff from urban and agricultural land carries with it nutrients and toxics that degrade water quality.

Low-Impact Development provides solutions to these problems. By increasing recharge and decreasing runoff, LID, if designed properly, can return developed areas to pre-developed conditions. The result is a lower volume of runoff that can better control flooding downstream. Also, as the water balance reveals, LID practices increase baseflow during critical low-flow times of the year. The surface waters benefit in two ways; the diffuse runoff nutrient load is decreased and the purer baseflow is increased. While the results are promising, the methods used in this thesis are all based on modeled data. The logical next step is to test the performance of LID in the field at site and watershed levels.

The benefits of LID may not be realized without consequences. Negative effects to groundwater quality are possible, especially in areas with extremely polluted runoff. While many contaminants are taken up by soils before they reach the groundwater, some, such as salt and nitrates, can potentially contaminate groundwater. Additionally, changes in ground water levels from increased recharge have potential economic and logistic consequences, such as flooding in low-lying areas. More analysis is required in this area to better assess these concerns.

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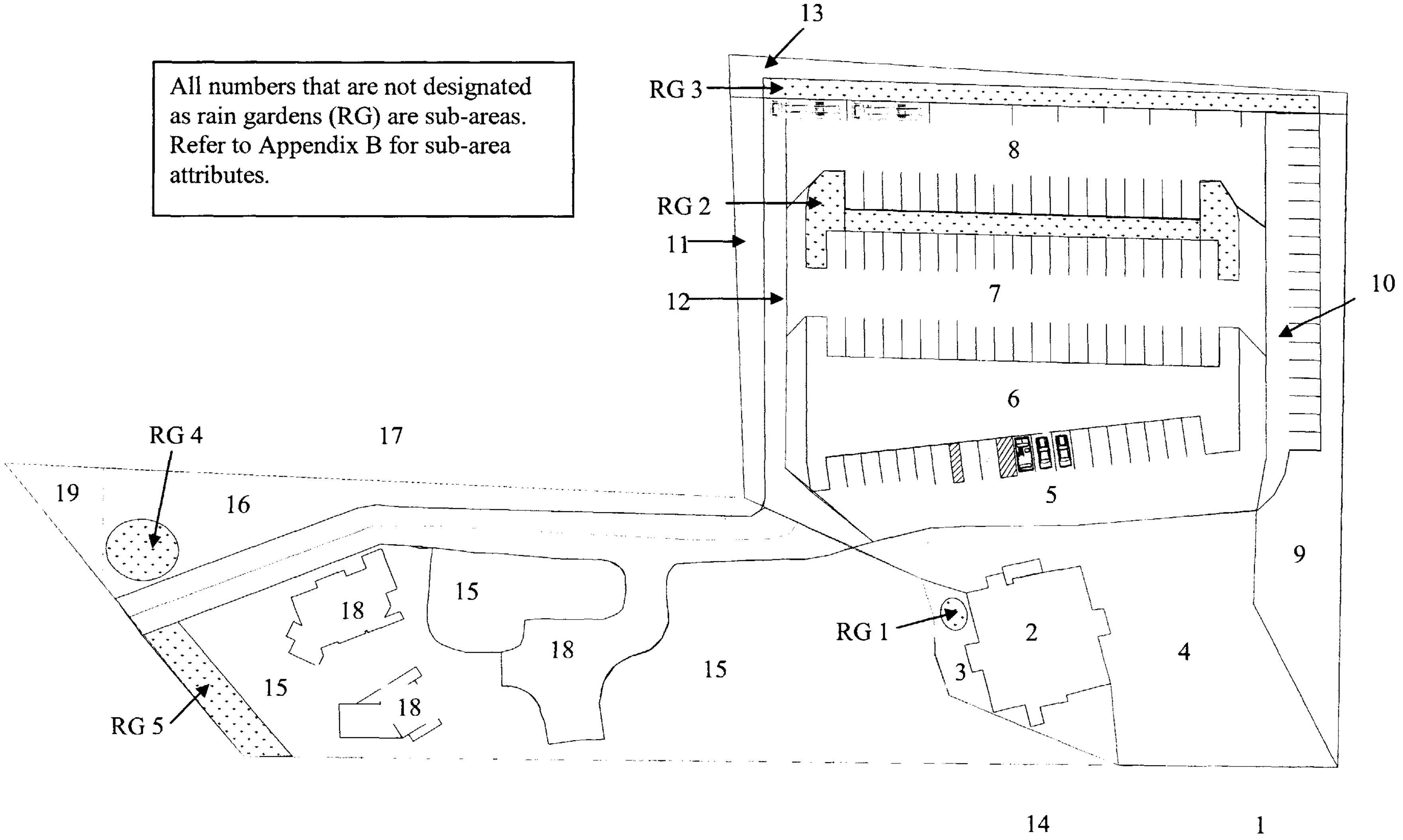
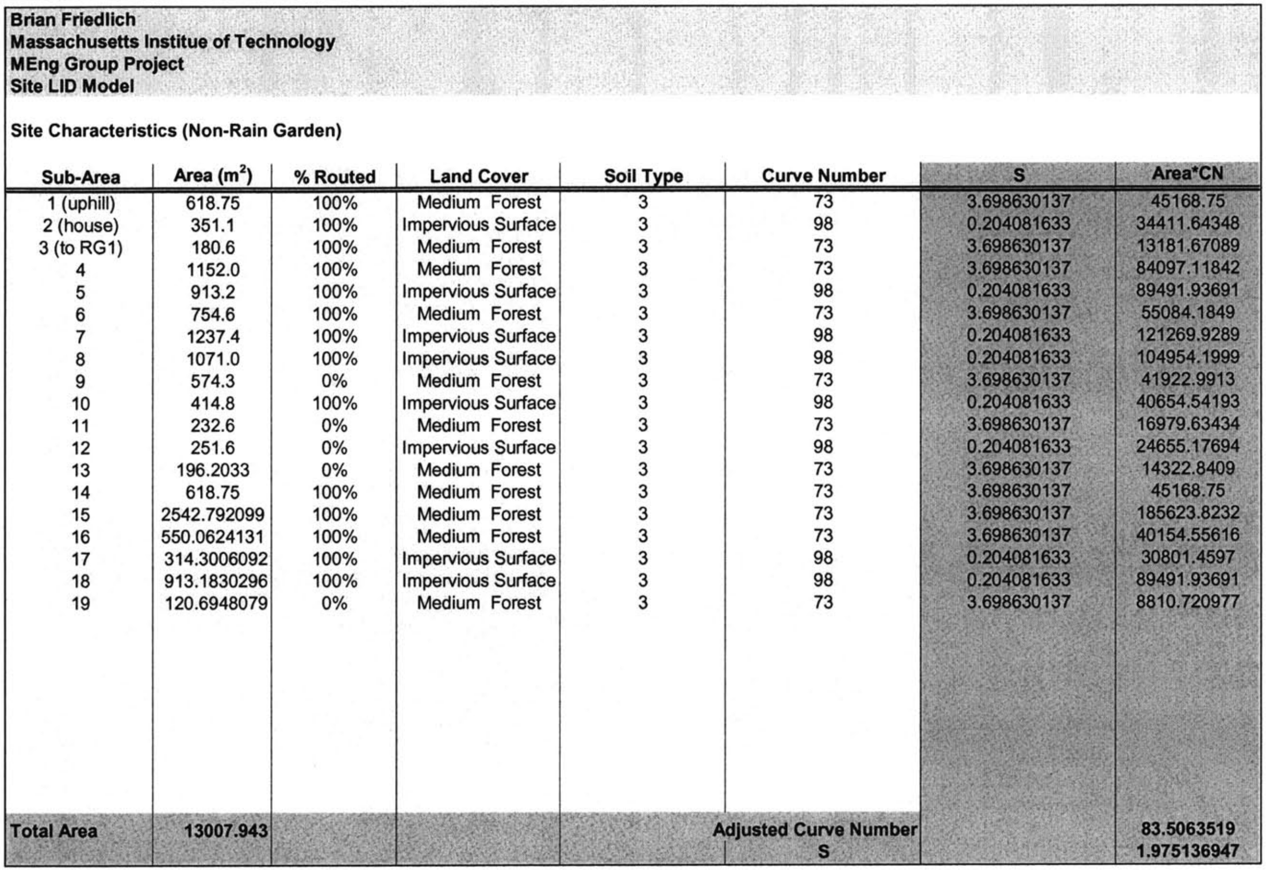
Appendix A. Map of LID Design Sub-Areas and Rain Garden

All numbers that are not designated as rain gardens (RG) are sub-areas. Refer to Appendix B for sub-area attributes.



Appendix B. SLIDD Input Pages for LID Design



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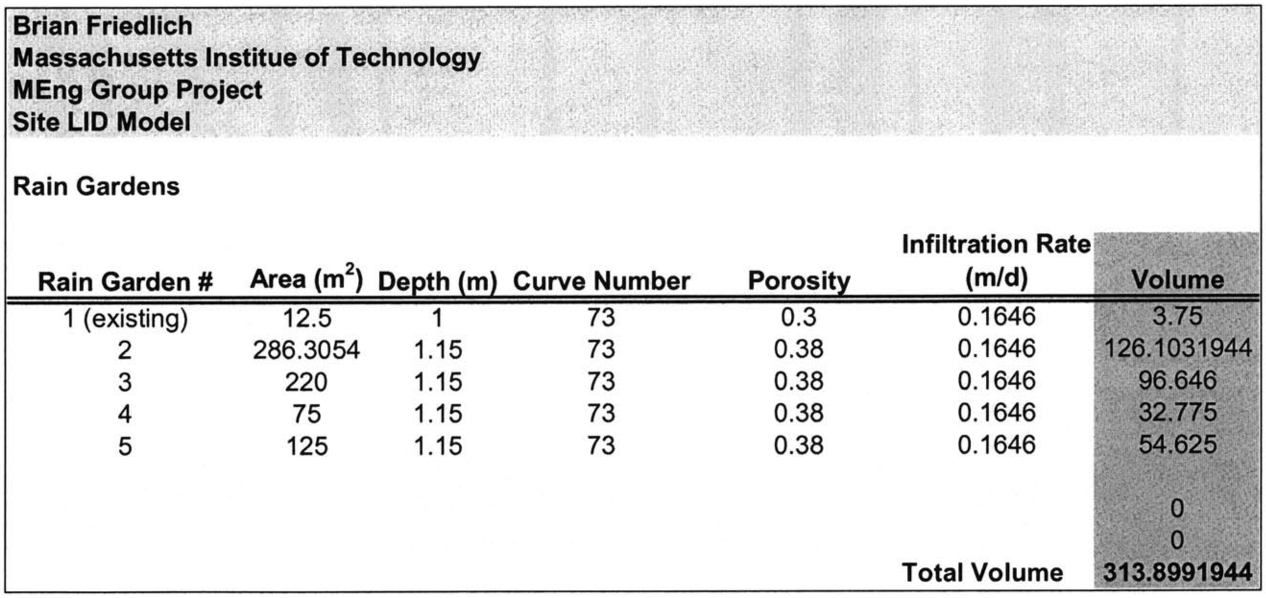
Site LID Model

Site Characteristics (Non-Rain Garden)

Sub-Area	Area (m^2)	% Routed	Land Cover	Soil Type	Curve Number	S	Area*CN
1 (uphill)	618.75	100%	Medium Forest	3	73	3.698630137	45168.75
2 (house)	351.1	100%	Impervious Surface	3	98	0.204081633	34411.64348
3 (to RG1)	180.6	100%	Medium Forest	3	73	3.698630137	13181.67089
4	1152.0	100%	Medium Forest	3	73	3.698630137	84097.11842
5	913.2	100%	Impervious Surface	3	98	0.204081633	89491.93691
6	754.6	100%	Medium Forest	3	73	3.698630137	55084.1849
7	1237.4	100%	Impervious Surface	3	98	0.204081633	121269.9289
8	1071.0	100%	Impervious Surface	3	98	0.204081633	104954.1999
9	574.3	0%	Medium Forest	3	73	3.698630137	41922.9913
10	414.8	100%	Impervious Surface	3	98	0.204081633	40654.54193
11	232.6	0%	Medium Forest	3	73	3.698630137	16979.63434
12	251.6	0%	Impervious Surface	3	98	0.204081633	24655.17694
13	196.2033	0%	Medium Forest	3	73	3.698630137	14322.8409
14	618.75	100%	Medium Forest	3	73	3.698630137	45168.75
15	2542.792099	100%	Medium Forest	3	73	3.698630137	185623.8232
16	550.0624131	100%	Medium Forest	3	73	3.698630137	40154.55616
17	314.3006092	100%	Impervious Surface	3	98	0.204081633	30801.4597
18	913.1830296	100%	Impervious Surface	3	98	0.204081633	89491.93691
19	120.6948079	0%	Medium Forest	3	73	3.698630137	8810.720977
Total Area	**13007.943**				**Adjusted Curve Number**		**83.5063519**
					S		**1.975136947**



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Site LID Model

Rain Gardens

Rain Garden #	Area (m^2)	Depth (m)	Curve Number	Porosity	Infiltration Rate (m/d)	Volume
1 (existing)	12.5	1	73	0.3	0.1646	3.75
2	286.3054	1.15	73	0.38	0.1646	126.1031944
3	220	1.15	73	0.38	0.1646	96.646
4	75	1.15	73	0.38	0.1646	32.775
5	125	1.15	73	0.38	0.1646	54.625
						0
						0
					Total Volume	**313.8991944**

Appendix C. SLIDD Overview and Source Code

SLIDD was written in Visual Basic for Applications (VBA). The program has the capabilities of simulating runoff from land and a distributed network of rain gardens or storage areas. Water from sub-areas, or non-rain gardens, is routed either to contribute to site runoff or to rain gardens. The model performs a water balance for the rain garden, processing inputs of direct rainfall and routed runoff, and outputs of evapotranspiration and infiltration. In the case of rain garden overflow water can be routed to another rain garden. Otherwise, overflow contributes to total site runoff. The final output of the code is total site runoff per time step.

The three major components of the program are the input of data, runoff and storage calculations, and output of results. In the source code, I have outlined the major program tasks in italic text. While most of these are straightforward, some require explanation.

The calculation of runoff from sub-areas is complicated because the SCS runoff method used in this program is based on a single event, while SLIDD models an entire time series of rainfall data. The model sets the criterion for a new rainfall event. In the simulation of the Discovery Museums, a criterion of two hours was assumed to be reasonable (Resource Analysis 1975). A dummy variable, IWET is turned on when a rainfall event begins. Another dummy variable, IDRY, is used to count the number of consecutive dry days during an event. If IDRY exceeds the criterion, both IWET and IDRY are set back to zero indicating the end of an event. During the event, a cumulative approach to calculating runoff from sub areas is used, discussed in more detail in Section 7.2 of the main text.

Overflow calculations are repeated the same number of times as there are rain gardens. This is to ensure that overflow is routed fully. In other words, if overflow from rain garden 1 is routed to rain garden 2, the calculation repetition allows the continued routing to a potential third rain garden if rain garden 2 is full as well.

A number of variables in the source code require definition. The following figure defines all of the variables.

Number of parameters

Nts	# of times series data points
Nrg	# of rain gardens
Nsa	# of sub areas
step	time step

Sub Area Data

Asa	area of sub area
PRsa	perecent routed
CNsa	curve number of sub area
S	SCS parameter for sub area

Time Series Data

Tts	time
Pts	precipitation
TEMPts	temperature
Ets	evaporation rate

Rain Garden Data

Arg	area
CNrg	curve number
RECrg	recharge/infiltration rate

Sub Area Runoff Volumes

VolP	Runoff volume produced by sub area
Pacc	accumulated rainfall
VolPAcc	Event cumulative runoff produced by a sub area
VolPAccL	Runoff volume produced by sub area at last time step
VolSA	Sub area runoff volume routed to a particular rain garden
VolDR	Volume of direct runoff produced by a sub area

Rain Garden Volumes

VolC	volume capacity of a rain garden
VolRG	actual volume in a rain garden at a given time
VolOV	overflow volume at a given time
TotalVol	Total Runoff Volume at each time step

```
Option Explicit
Sub SLID()

Dim nts As Integer, Tend As Date, Nrg As Integer, Nsa As Integer, step As Date, IDRYC As Double
Dim IDRY As Integer, IWET As Integer, Pacc As Double
Dim t As Integer, sa As Integer, rg As Integer, i As Integer, RGO As Integer

Dim Tts(10000) As Date, Pts(10000) As Double, TEMPts(10000) As Double, Ets(10000) As Double, TotalVol(10000) As Double
Dim Arg(50) As Double, CNrg(50) As Double, RECrg(50) As Double, VolC(50) As Double
Dim Asa(50) As Double, PRsa(50) As Double, CNsa(50) As Double, S(50) As Double
Dim VolP(50) As Double, VolPAcc(50) As Double, VolPAccL(50) As Double, VolSA(50) As Double, VolRG(50) As Double, VolOV(50) As Double, VolDR(50) As Double
```

```
Application.ScreenUpdating = False

Inputs

'Determine # of Time Series Segments
Sheets("Time Series").Select
Range("A9").Select
If ActiveCell.Value = "" Then
  MsgBox "Time Series must have values"
  End
End If
nts = ActiveCell.Row
Selection.End(xlDown).Select
Tend = ActiveCell.Value
nts = ActiveCell.Row - nts

'Input Time Series Data
Range("A9").Select

For i = 1 To nts + 1
  Tts(i) = ActiveCell.Value
  ActiveCell.Offset(0, 1).Select
  Pts(i) = ActiveCell.Value
  ActiveCell.Offset(0, 2).Select
  TEMPts(i) = ActiveCell.Value
  ActiveCell.Offset(0, 1).Select
  Ets(i) = ActiveCell.Value
  ActiveCell.Offset(1, -4).Select
Next i

'Determine # of Rain Gardens

Sheets("Rain Gardens").Select
Range("A9").Select
If ActiveCell.Value = "" Then
  MsgBox "Rain Gardens must have values"
  End
End If
Nrg = ActiveCell.Row
Selection.End(xlDown).Select
Nrg = ActiveCell.Row - Nrg

'Input Rain Garden Data
Range("B9").Select
```

```
For i = 1 To Nrg + 1
  Arg(i) = ActiveCell.Value
  ActiveCell.Offset(0, 2).Select
  CNrg(i) = ActiveCell.Value
  ActiveCell.Offset(0, 2).Select
  RECrg(i) = ActiveCell.Value
  ActiveCell.Offset(0, 1).Select
  VolC(i) = ActiveCell.Value
  ActiveCell.Offset(1, -5).Select
Next i

'Determine Number of Sub-Areas
Sheets("Sub Areas").Select
Range("A9").Select
If ActiveCell.Value = "" Then
  MsgBox "Sub-Areas must have values"
  End
End If
Nsa = ActiveCell.Row
Selection.End(xlDown).Select
Nsa = ActiveCell.Row - Nsa


'Input Sub-Area Data
Range("B9").Select
For i = 1 To Nsa + 1
  Asa(i) = ActiveCell.Value
  ActiveCell.Offset(0, 1).Select
  PRsa(i) = ActiveCell.Value
  ActiveCell.Offset(0, 3).Select
  CNsa(i) = ActiveCell.Value
  ActiveCell.Offset(0, 1).Select
  S(i) = ActiveCell.Value
  ActiveCell.Offset(1, -5).Select
Next i

'Runoff/Storage Calcs

step = Tts(2) - Tts(1)
IDRYC = (2 / 24) / step
If IDRYC < 1 Then
  IDRYC = 1
End If
```

```
'Rain Garden Initial Conditions
For rg = 1 To Nrg + 1
 VolRG(rg) = 0
Next rg

For t = 1 To nts + 1
 'Calculate Volume off Sub-Areas
 If IWET = 0 Then
  If Pts(t) > 0 Then
   IWET = 1
  End If
 Else
  If Pts(t) > 0 Then
   IDRY = 0
  Else
   IDRY = IDRY + 1
   If IDRY > IDRYC - 1 Then
    IWET = 0
    IDRY = 0
    Pacc = 0
    For sa = 1 To Nsa + 1
     VolPAcc(sa) = 0
     VolPAccL(sa) = 0
    Next sa
   End If
  End If
 End If

 Pacc = Pacc + Pts(t)
 For sa = 1 To Nsa + 1
   If Pacc <= 0.2 * (1000 / CNsa(sa) - 10) Then
    VolP(sa) = 0
    Else
    VolPAcc(sa) = ((Pacc - 0.2 * S(sa)) ^ 2 / (Pacc + 0.8 * S(sa))) * 0.0254 * Asa(sa)
    VolP(sa) = VolPAcc(sa) - VolPAccL(sa)
    VolPAccL(sa) = VolPAcc(sa)
   End If
 Next sa
 'Calculate Direct Runoff
 For sa = 1 To Nsa + 1
  VolDR(sa) = (1 - PRsa(sa)) * VolP(sa)
 Next sa
 'Rout Sub-Area Volume to Rain Gardens
 Sheets("Routing").Select
```

```
 Range("B10").Select
 For rg = 1 To Nrg + 1
  VolSA(rg) = 0
  For sa = 1 To 10
   VolSA(rg) = VolSA(rg) + PRsa(ActiveCell.Value) * VolP(ActiveCell.Value)
   ActiveCell.Offset(1, 0).Select
  Next sa
  ActiveCell.Offset(-10, 1).Select
 Next rg
 'Water Balance Calc on Rain Garden
 For rg = 1 To Nrg + 1
  VolRG(rg) = VolRG(rg) + Pts(t) * Arg(rg) * 0.0254 + VolSA(rg) - Ets(t) * Arg(rg) * step -
RECrg(rg) * Arg(rg) * step
  If VolRG(rg) < 0 Then
   VolRG(rg) = 0
  End If
  'Overflow Calc on Rain Garden
  If VolRG(rg) > VolC(rg) Then
   VolOV(rg) = VolRG(rg) - VolC(rg)
   VolRG(rg) = VolC(rg)
   Else
   VolOV(rg) = 0
  End If
 Next rg
 'Overflow Routing
 Sheets("Routing").Select
 Range("B29").Select
 For i = 1 To 2
  For rg = 1 To Nrg + 1
   For RGO = 1 To 10
    If Not ActiveCell.Value = "" Then
     VolRG(rg) = VolRG(rg) + VolOV(ActiveCell.Value)
     VolOV(ActiveCell.Value) = 0
    End If
    ActiveCell.Offset(1, 0).Select
   Next RGO
   ActiveCell.Offset(-10, 1).Select
  Next rg
  ActiveCell.Offset(0, -Nrg - 1).Select
  'Recalculate Overflows
  For rg = 1 To Nrg + 1
   If VolRG(rg) > VolC(rg) Then
    VolOV(rg) = VolRG(rg) - VolC(rg)
    VolRG(rg) = VolC(rg)
```

```
    End If
   Next rg
  Next i
  'Calc Total Site Runoff Volume
  TotalVol(t) = 0
  For sa = 1 To Nsa + 1
   TotalVol(t) = TotalVol(t) + VolDR(sa)
  Next sa
  For rg = 1 To Nrg + 1
   TotalVol(t) = TotalVol(t) + VolOV(rg)
  Next rg
Next t
```

Outputs

```
'Display Results
Sheets("Time Series Output").Select
Range("A9", "B10009").ClearContents
Range("A9").Select
For t = 1 To nts + 1
 ActiveCell.Value = Tts(t)
 ActiveCell.Offset(0, 1).Select
 ActiveCell.Value = TotalVol(t)
 ActiveCell.Offset(1, -1).Select
Next t
End Sub
```

Appendix D. Thornthwaite Calculations

Thornthwaite Water Balance for Acton, Massachusetts
1990s

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Year
T, Air temperature (F)	27.6	28.6	36.1	47.2	57.0	67.2	72.2	70.2	62.1	50.8	40.9	32.9	
T, Air temperature (C)	-2.5	-1.9	2.3	8.4	13.9	19.5	22.3	21.2	16.7	10.4	4.9	0.5	
i, Heat index	0	0	0.3	2.21	4.69	7.89	9.64	8.92	6.22	3.06	0.98	0.03	43.9
UPET, Unadjusted PE (inches)	0	0	0.01	0.05	0.08	0.12	0.15	0.13	0.1	0.06	0.02	0	
r, PE Adjustment factor	24.5	24.6	30.8	33.6	37.8	38.2	38.5	35.4	31.2	28.5	24.6	23.4	
PET, Potential Evapotranspiration (inches)	0	0.0	0.3	1.7	3.0	4.6	5.8	4.6	3.1	1.7	0.5	0.0	**25.3**
P, Precipitation (inches)	4.4	3.2	4.4	3.7	3.7	2.9	3.4	3.6	4.7	4.9	4.0	4.2	**47.2**
Infiltration	3.7	2.7	3.4	2.9	2.8	2.2	2.6	2.8	3.6	3.8	3.4	3.6	
I - PE (in)	3.74	2.73	3.07	1.18	-0.20	-2.37	-3.15	-1.85	0.48	2.07	2.54	3.58	11.8
Acc Pot WL					-0.2	-2.6	-5.7	-7.6					
Storage	8.0	8.0	8.0	8.0	7.8	5.8	3.9	3.1	3.6	5.7	8.0	8.0	
ΔST, Change in Storage (inches)	0.0	0.0	0.0	0.0	-0.2	-2.0	-1.9	-0.8	0.5	2.1	2.3	0.0	
Actual Evapotranspiration	0.0	0.0	0.3	1.7	3.0	4.2	4.5	3.6	3.1	1.7	0.5	0.0	**22.6**
Deficit (inches)	0.0	0.0	0.0	0.0	0.0	0.4	1.3	1.0	0.0	0.0	0.0	0.0	
Moisture Surplus (inches)	**0.0**	**0.0**	**3.1**	**1.2**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**2.5**	**3.6**	**10.4**
Runoff Coeff.	**0.15**	**0.15**	**0.15**	**0.15**	**0.15**	**0.15**	**0.15**	**0.15**	**0.15**	**0.15**	**0.15**	**0.15**	**0.15**
Overland Flow	**0.66**	**0.48**	**0.66**	**0.56**	**0.55**	**0.43**	**0.51**	**0.54**	**0.71**	**0.74**	**0.59**	**0.63**	**7.08**
Soil Water Replenishment									0.5	2.1	2.3		

Appendix E. Water Balance Calculations

WATER BALANCE	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	YEAR
P (in)	4.4	3.2	4.4	3.7	3.7	2.9	3.4	3.6	4.7	4.9	4.0	4.2	47.2
P (mm)	111.8	81.6	112.0	94.9	93.9	73.6	87.2	91.5	119.6	125.6	100.7	107.0	1199.4
PET (in)	0.0	0.0	0.3	1.7	3.0	4.6	5.8	4.6	3.1	1.7	0.5	0.0	25.3
ET (in)	0.0	0.0	0.3	1.7	3.0	4.2	4.5	3.6	3.1	1.7	0.5	0.0	22.6
Q (cfs)	27.7	29.2	42.3	37.3	22.5	12.5	4.0	5.3	5.4	14.3	16.1	23.9	20.0
Q (in)	2.5	2.4	3.8	3.2	2.0	1.1	0.4	0.5	0.5	1.3	1.4	2.2	21.2
Q+ET (in)	2.5	2.4	3.8	3.2	2.0	1.1	0.4	0.5	0.5	1.3	1.4	2.2	
Baseflow (in)	1.7	2.0	3.2	2.8	1.6	0.7	0.3	0.2	0.2	0.6	1.1	1.7	16.0
Fastflow (in)	0.8	0.4	0.6	0.4	0.4	0.4	0.1	0.3	0.3	0.7	0.3	0.5	5.2
Rc	0.172	0.130	0.140	0.120	0.115	0.126	0.032	0.082	0.053	0.143	0.084	0.118	0.11
Infiltration (in)	3.1	2.4	3.2	2.8	2.8	2.2	2.9	2.8	3.9	3.6	3.1	3.2	35.911
Recharge (in)	3.1	2.4	3.0	1.3	0.1	-1.6	-1.1	-0.3	1.1	2.1	2.7	3.2	16.0
Change in GW (act)	1.6	-0.8	2.6	1.3	-0.6	-0.7	-2.3	-2.0	-1.2	0.0	1.0	1.0	0.0
Change in GW (model)	1.3	0.4	-0.2	-1.5	-1.5	-2.3	-1.3	-0.5	0.9	1.5	1.6	1.5	0.0