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An Economic approach to the ecological issues of urban stormwater runoff: A Case study of the Allen Creek Watershed in Monroe County, New York

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An Economic Approach to the Ecological Issues of Urban Stormwater Runoff: A Case Study of the Allen Creek Watershed in Monroe County, New York

by:

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A thesis submitted in partial fulfillment
of the requirements for the degree
of Master of Science

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ABSTRACT

Urban stormwater runoff is excess runoff created by increased imperviousness in an urbanized watershed and can have significant impacts on both water quantity and quality. Natural communities and human communities are faced with damages that occur as a result of the change in the type and magnitude of stormwater runoff flows, including but not limited to increased flooding and degradation of natural aquatic systems. Therefore, from both an economic and ecological perspective, it is important that urban planners effectively manage excess stormwater runoff. This paper details the development of an ecological-economic model that can be used to guide urban planners in the implementation of cost-effective abatement solutions for a given watershed. The model can be used on a large-scale to guide stormwater management policies in entire counties, watersheds, etc., but can also be applied on a smaller scale, which is demonstrated by a case study in a sub-section of the Allen Creek watershed located primarily in the Town of Brighton, NY. The case study is focused on the impact of a potential development project in Brighton on the downstream residential properties and uses a hedonic price model to estimate the marginal damage cost of additional average annual stormwater runoff as a result of the new development project. This marginal damage cost is compared to the marginal cost of residential abatement technologies to determine the optimal volume of abatement in the Town of Brighton. Though focused primarily on the cost of increased water quantity, the preliminary results indicate that the marginal damage cost of runoff in this community is larger than the marginal abatement independent of the existing volume of average annual runoff experienced by the community. Therefore, in its current state, the Town of Brighton needs to encourage the abatement of all stormwater runoff in the community and any additional development would require additional abatement measures that must extend beyond strictly residential abatement.

INTRODUCTION

Hydrologic Background

Stormwater runoff occurs as a natural result of snowmelts and precipitation events and, along with subsurface and groundwater flow, provides the essential environmental service of recharging stream channels within watersheds. Channel recharge via stormwater runoff can occur as a consequence of two different flow patterns: stormflow and baseflow. Stormflow, also known as direct runoff, travels along the ground surface and is the most immediate source of recharge for a stream, reaching a channel within a day or two of the precipitation event. In contrast, stormwater that infiltrates into the ground becomes baseflow, stored in the soil until it is needed to sustain stream flow during dry periods (Dunne and Leopold 1978, 257). Like many natural processes, however, the process of stormwater flow can be affected by human activities. Changes in land use, specifically the conversion of natural landscapes to urbanized areas, have been found to significantly impact stormwater flow. Increase in impervious surface area (such as roofs and pavement) in urbanized watersheds has been linked to changes in both the type and magnitude of stormwater flow.

Watersheds dominated by a subsurface stormflow regime pre-urbanization experience an increase in runoff generated by Horton overland flow or saturation overland flow due to increased imperviousness (Dunne and Leopold 1978, 275). Subsurface stormflow is dominant in humid areas where soil infiltration capacity is high as a result of high porosity and/or the existence of abundant vegetation. Most stormwater is able to infiltrate the ground surface and will vertically percolate through the soil. Because the soil is most saturated near the stream channel, subsurface stormflow will deliver stormwater to the base of the stream, effectively raising the water level in the stream and recharging the water table so that its level remains relatively unchanged (Dunne and Leopold 1978, 262-264). In this manner, the stream volume is steadily maintained by baseflow that has been filtered by the soil.

The processes of Horton overland flow and saturation overland flow, however, recharge stream channels primarily though stormflow. Horton overland flow and saturation overland flow occur when both soil infiltration capacity and depression storage along the land surface have been exhausted. Then the remaining stormflow must flow over the ground surface downslope into the stream channel. Both overland flow regimes result in a greater quantity of water being delivered to the stream channel over a short period of time and less baseflow storage as compared to a subsurface stormflow regime (Dunne and Leopold 1978, 258-267). Even in arid regions, where overland stormflow may dominate pre-development due to low infiltration capacity of the soil, overland flow can still increase as paved surfaces can lower infiltration capacity of the land to near zero. (Dunne and Leopold 1978, 275).

Reduction of soil infiltration capacity in arid or humid regions can also occur as a result of vegetation clearing and soil compaction, although the infiltration capacity of the soil should not be completely lowered to zero. Soil compaction decreases the porosity of the soil and the clearing of vegetation reduces infiltration along the root boundary, thereby increasing the amount of water infiltrating the soil. Therefore, urbanization of any region, dry or humid, generates a greater volume of direct stormwater runoff than land left in its natural state (Booth and Jackson 1997, 1078).   Such a change in the mechanism of runoff formation leads to increased channel recharge by stormflow and creates higher flows levels during storm events and turbidity (Coon 2008, 6).

An increase in direct stormwater runoff means stream channels receive more water in shorter time periods and therefore experience a higher frequency of peak flows than would naturally occur (Booth and Jackson 1997, 1078). When very large storm events occur, it is common for the precipitation rate to exceed the infiltration rate in areas dominated by subsurface flow, causing overland stormwater flow that creates the major peak flows in streams. Because urbanization decreases the infiltration capacity of the soil, assuming the precipitation rate remains unchanged, this difference between the rate of precipitation and infiltration is increased, leading to the creation of greater and flashier volumes of direct stormwater runoff during large storm events. Additionally, smaller storms that may have generated no runoff prior to urbanization may now generate runoff due to the decreased infiltration capacity of the soil. The amplification of peak flows and creation of new peak events can lead to channel overflow, causing the surrounding land area to flood, especially downstream (Booth 1991, 101-102, Paul and Meyer 2001, 335). Increased flooding can have a detrimental effect on riparian areas that are not accustomed to a high frequency of flooding.

Increased quantity of surface runoff also alters the stream channel and causes visible physical degradation. Paul and Meyer (2001) describe three phases of physical alteration that stream channels undergo in order to accommodate the changes in runoff spurred by urbanization. The first alteration occurs at the onset of development during the construction phase, in which stream channels experience increased sediment loads after erosion of exposed soils. The stream channel then enters a phase of aggradation in which channel depths, now filled in with sediment, can shallow.

Once construction is complete and impervious surfaces have been installed, channel incision will typically occur as increased overland flows begin eroding the channel and its banks. There are two implications of increased erosion, the first being decreased stability of large structures, such as trees or artificial structures that are located along steam riparian zones (Paul and Meyer 2001, 338-341). The second impact is increased sedimentation within the stream channel, which affects the ecological structure and therefore functioning of aquatic organisms. Species that can adapt to unstable habitats are generally more abundant in streams in which sedimentation processes and patterns are changing (Pedersen and Perkins 1986, Collier 1995, Paul and Meyer 2001, 349) and some non-adaptive invertebrate communities are degraded as a result of sediment accumulation (Hogg and Norris 1991, Paul and Meyer 2001, 350). Additionally, benthic sediments, which provide sustenance to some stream invertebrates, can bind to toxins, leading to invertebrate mortality (Benke and Wallace 1997, Paul and Meyer 2001, 350).

Not only is the increased quantity of water entering a stream channel a problem, but increased runoff also causes water quality to decline as the large quantity of incoming runoff carries urban pollutants to the stream (House et al. 1993, Paul and Meyer 2001, 334). First of all, water entering the stream as overland stormflow may not experience the intense filtration that occurs during percolation through the soil. Additionally, overland stormwater runoff travels across paved areas and can collect and transport nutrients, pesticides, and other pollutants into aquatic systems. These pollutants are more abundant in urban environments and the combination of increased pollutants and greater volume of overland flow produces a synergistic effect that acts to pollute steam channels. For example, nutrients, such as nitrogen (in the form of nitrates) and phosphorus, found in fertilizers used on urban gardens or lawns, can be collected by runoff. Because nitrogen and phosphorus are limiting factors in primary production in aquatic environments, elevated levels of nitrogen and phosphorus can lead to increased algal biomass, which can ultimately lead to eutrophication in the receiving water body. Despite high influxes of nitrogen and phosphorus, primary productivity, however, may not necessarily increase in the upstream environment. Algal accumulation can actually decrease if nutrient influxes are counteracted by bed disturbance, high turbidity and metal accumulation. Nutrient influxes, however, can still impact receiving waters as they are carried downstream. In the event of decreased primary productivity, decreased food availability can lead to decreased biodiversity within an aquatic system. Likewise, the addition of pesticides can also act to decrease biodiversity within an aquatic system, as these chemicals bioaccumulate in both aquatic organisms and sediment (Paul and Meyer 2001, 341-355).

Other water quality problems created by impervious surfaces, especially roads and parking lots, include the accumulation of heavy metals and road salts that get carried and delivered to streams by stormwater runoff. Because heavy metals can bioaccumulate in aquatic systems, metals can be directly ingested by organisms or indirectly ingested by organisms through contaminated sediment. Metal accumulation may have a negative impact on the abundance of algae, mollusks, arthropods and annelids in a stream by altering the community structure of these species. Similarly, the introduction of salts can negatively impact species diversity within aquatic communities. Many organisms are sensitive to salinity and can only survive within in a certain range of saline conditions. When road salt is carried by runoff into a stream, it can raise the salinity of the water enough to become lethal to certain species (Paul and Meyer 2001, 341-355).

Economic Background

Such ecological issues associated with the alteration of stormwater runoff mechanisms in a watershed suggest the necessity of urban stormwater runoff abatement measures in order to maintain natural resources and human well-being. To ensure optimal stormwater management, some type of regulation should exist within a watershed. This idea is supported by an economic analysis of optimal stream abatement strategies completed by Bhat et al. (1999). Bhat et al. (1999) model the process of river contamination via surface runoff at various influx locations along a river. Their environmental management problem is identified as maximizing the pollutant-generating economic activities (specifically agricultural activities) less the environmental damage cost of basin-wide water contamination of point source surface runoff

(Bhat et al. 1999, 176-177), which is essentially the same as minimizing the damage and abatement costs of stormwater runoff.

Using functional forms of two total revenue functions (or the functions for the total benefit of pollution emission), Bhat et al. (1999, 180-181) find the marginal revenue functions (or marginal benefit functions), introduce the environmental damage and optimize this model. The resulting mathematical analysis implies that the privately optimal level of pollutant loadings is higher than the socially optimal level, meaning that pollution generators will pollute at an unsustainable level and society will suffer external damage costs. This provides evidence for the need to regulate runoff contamination in a watershed, and Bhat et al. (1999) propose implementing an effluent tax or a marketable permit scheme in a watershed to ensure that the socially optimal pollution level is achieved. In the absence of pollution constraints, pollution generators face zero marginal costs for abatement and will only maximize the total benefit function. The introduction of a tax or permit program for stormwater runoff ensures that pollution generators are now subject to positive marginal costs, motivating them to reduce their level of pollution.

Given these results, there are a number of ways for a government, small or large, to regulate runoff within a given area. Thurston et al. (2003, 409-411) describe various approaches of stormwater runoff control and the effectiveness of each. Stormwater runoff can be controlled using centralized methods, decentralized methods or a combination of both. Centralized control methods include large-scale efforts that typically are built downstream, like the creation of wastewater treatment plants and city sewage or tunnel systems. This approach to mitigation is considered to be the "reactive approach", as it allows stormwater runoff to collect and travel downstream until it reaches a mitigation structure. In contrast, decentralized control methods, such as adoption of site-specific Best Management Practices (BMPs), focus on small-scale mitigation and are "proactive", upstream source reducers. BMPs help to decrease the volume of stormwater runoff that travels downstream by encouraging stormwater retention. Examples of BMPs include retention ponds, infiltration trenches, constructed wetlands, rain barrels, swales/rain gardens and filter strip/sand filters. Each abatement technology may have specific space, soil permeability and/or slope restrictions (Thurston et al. 2003).

Two ways in which decentralized control methods can be implemented include command and control mechanisms or market-based incentive programs. A command and control mechanism is a standard regulation system in which individuals are required to abate a certain amount of stormwater runoff by setting up BMPs on individual properties and penalties are given for non-compliance. Market-based incentives are tools that use economic incentives to produce a desired outcome.

Four market-based incentives are identified and evaluated in Parikh et al. (2005, 136-142), who provide examples of two price instruments and two quantity instruments. A stormwater user fee and a stormwater runoff charge are examples of price instruments. A stormwater user fee is charged to property owners based on the quantity of stormwater runoff that leaves a parcel of land, but the political mechanism for setting the fee often results in a price that is too low to generate the target results. The idea of a stormwater runoff charge is similar to the user fee, but the runoff charge should be a more accurate price signal, as it would reflect the marginal costs of measured stormwater abatement.

Two examples of quantity instruments include an allowance market and a voluntary offset program. An allowance market, or perfectly competitive cap and trade program, would put a cap on the total volume of runoff allowed in a community over a certain time period and acts to equalize marginal abatement costs across "polluters" (Montgomery 1972). A mandatory permit to release a certain volume of runoff would then be distributed at a cost to each property owner throughout the community, in which the volume allowed by each permit depends on the number of property owners in the community and the predetermined runoff cap. Faced with the cost of holding this mandatory permit, property owners would have the option to abate the runoff on their property, rather than pay the cost for the permit that allows them to release the runoff from their property. Property owners with abatement costs that are lower than the cost of purchasing permits will abate runoff, while property owners who have abatement costs higher than the price of the permits will not abate runoff and purchase permits instead. A cap and trade program, therefore, acts to equalize the marginal abatement. Marginal abatement costs are equal across properties, but each property owner is abating different amounts of stormwater runoff as a result of varying factors (like impervious surface or vegetation) across different properties. Likewise in a voluntary offset program, abatement types and magnitudes can vary for different properties, but in the voluntary offset program incentives to abate are offered on a voluntary, rather than required, basis. Because the program is voluntary, however, the incentive to abate may not be strong enough to achieve optimal level of abatement (Parikh et al. 2005, 136-142).

A third quantity instrument, a reverse auction, is described by Thurston et al. (2008) as a cost-effective way in which to implement small-scale abatement solutions in a community and an alternative to offering fixed payments to residents that participate in abatement on their properties. In a reserve auction, bids are closed and community members bid on how much they are willing to accept in compensation for the installation of a BMP on their residential properties. Thurston et al. (2008) conducted this auction in an urbanized residential community in Cincinnati, Ohio in 2007, asking residents how much monetary compensation they would require to install and maintain a BMP on their property. According to the bids received, Thurston et al. (2008) found that the total cost to implement this small-scale abatement measure was lower than the cost of the fixed payment plan. It should be noted that the bid forms were sent via mail and that they were sent to residents two weeks after receiving an informational packet on the benefits of stormwater abatement.

Although market-based incentives have not been widely applied to stormwater abatement, Thurston et al. (2003) conducted a study suggesting that a tradable allowance program, based on the use of a dispersed set of BMPs across a watershed, can be more cost-effective than implementing large infrastructural projects. Thurston et al. (2003, 414-417) applied estimated cost functions (Schueler 1987, Heaney et al. 2002) for various BMP solutions to parcels in the Shepherd Creek watershed in Cincinnati, Ohio, based on the land use and soil type of each parcel. The total cost of abatement using only BMPs under a tradable allowance program was determined for the watershed and then compared to the estimated cost of a deep tunnel system. Thurston et al. (2003) conclude that the tradable allowance program based on the use of BMPs has the potential to achieve significant stormwater runoff abatement in a more cost-effective manner than a centralized control method in this area (Thurston et al. 2003, 416-417). These results also agree with Booth and Jackson's (1997, 1088) suggestion that stormwater runoff management should move away from general and uniform solutions. Although Booth and Jackson (1997) made this suggestion from an ecological standpoint, recognizing that uniform abatement approaches often fail to mitigate stream degradation, this illustrates that economic and ecological efficiency of stormwater runoff abatement share common ground and can be considered in tandem to find an optimal solution to stormwater runoff abatement.

There seems, however, to be no model that simultaneously considers the specific hydrologic and economic factors present in a watershed of concern, which can be used to guide urban stormwater managers to an optimal abatement solution for their specific watershed. Therefore, in order to improve the efficiency of urban stormwater abatement in any given watershed, there should exist a general cost-minimizing model, strongly rooted in the hydrologic principles of stormwater runoff, that can be tailored to reflect local conditions. The purpose of this research is to develop an ecological-economic model that relies on basic economic principles and the hydrologic components of stormwater runoff to indicate to urban stormwater mangers the amount of excess runoff they should abate. Based on this ecological-economic model, urban stormwater managers should be able to more accurately devise the methods and policies needed to manage excess stormwater runoff in their watershed.

Case Study

In the case of this proposed theoretical model for stormwater runoff, the idea is quite similar to the Bhat et al. (1999) model, but with slight modifications. In the proposed stormwater runoff model, the pollution generating economic activity is not agricultural and households are being considered instead of firms. Households will minimize the distance between the damage and abatement cost curves, and the cost of damages will generally be perceived as zero without some type of regulatory intervention or public information campaign. Households will therefore choose to minimize their marginal abatement costs and not abate any runoff. The volume of excess stormwater in the watershed would be equal to the volume at which the abatement cost function is equal to zero, which is a larger volume than indicated by the point where the marginal damage cost is equal to the marginal abatement cost. The theoretical model determines the target abatement level for watershed managers, who then can make an informed decision on how to deal with residential abatement practices in the watershed.

To demonstrate a small-scale application of the theoretical model, a portion of the Allen Creek watershed that is located in Monroe County, NY, primarily in the Town of Brighton, is used as a case study. While the ecological-economic model can be used on a larger scale to help optimize the stormwater management plans on a regional level or watershed level, including different types of properties such as commercial, institutional and residential, the case study is used simply to demonstrate the application of the model and therefore is restricted the small region of the upper portion of the Allen Creek watershed and is focused only on residential abatement measures. Although small-scale residential abatement measures are often not as effective at mitigating stormwater quality as larger abatement measures (Schueler 1987), for the purposes of the case study, it is assumed that the abatement technologies used to mitigate the impacts of excess runoff not only impede flooding and maintain baseflow, but also act to reduce pollutant loading to some degree.

Figure 1a shows the location of the Allen Creek watershed in Monroe County, New York. Figure 1b shows a more detailed view of the entire Allen Creek watershed and identifies the area of interest for this case study. Figure 1b shows the 2006 land use/land cover (LULC) data provided by the National Land Cover Database (NLCD) and the Allen Creek watershed boundary depicted is defined by the Natural Resources Conservation Service (NRCS).

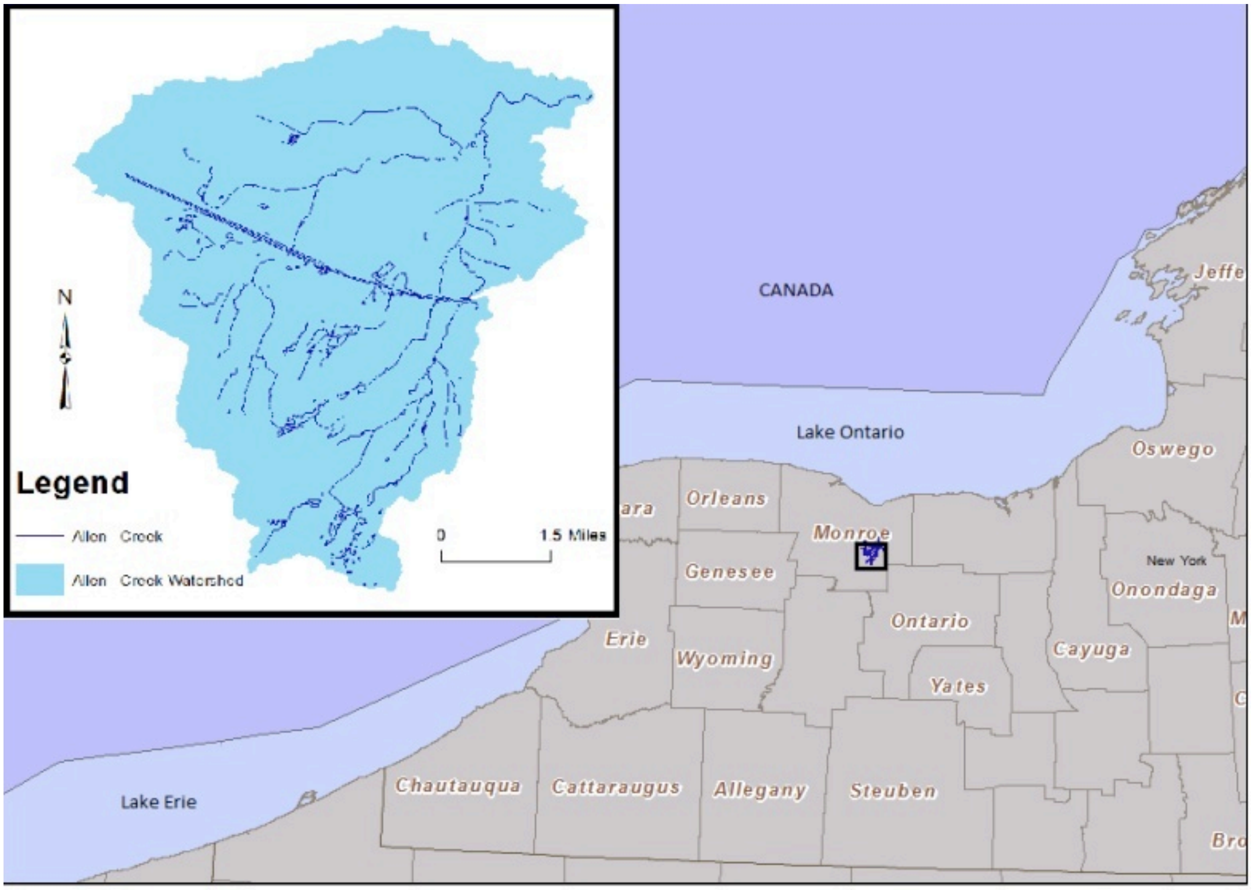

Figure 1a. Reference map showing the location of the Allen Creek watershed in Rochester, NY, located in Monroe County.

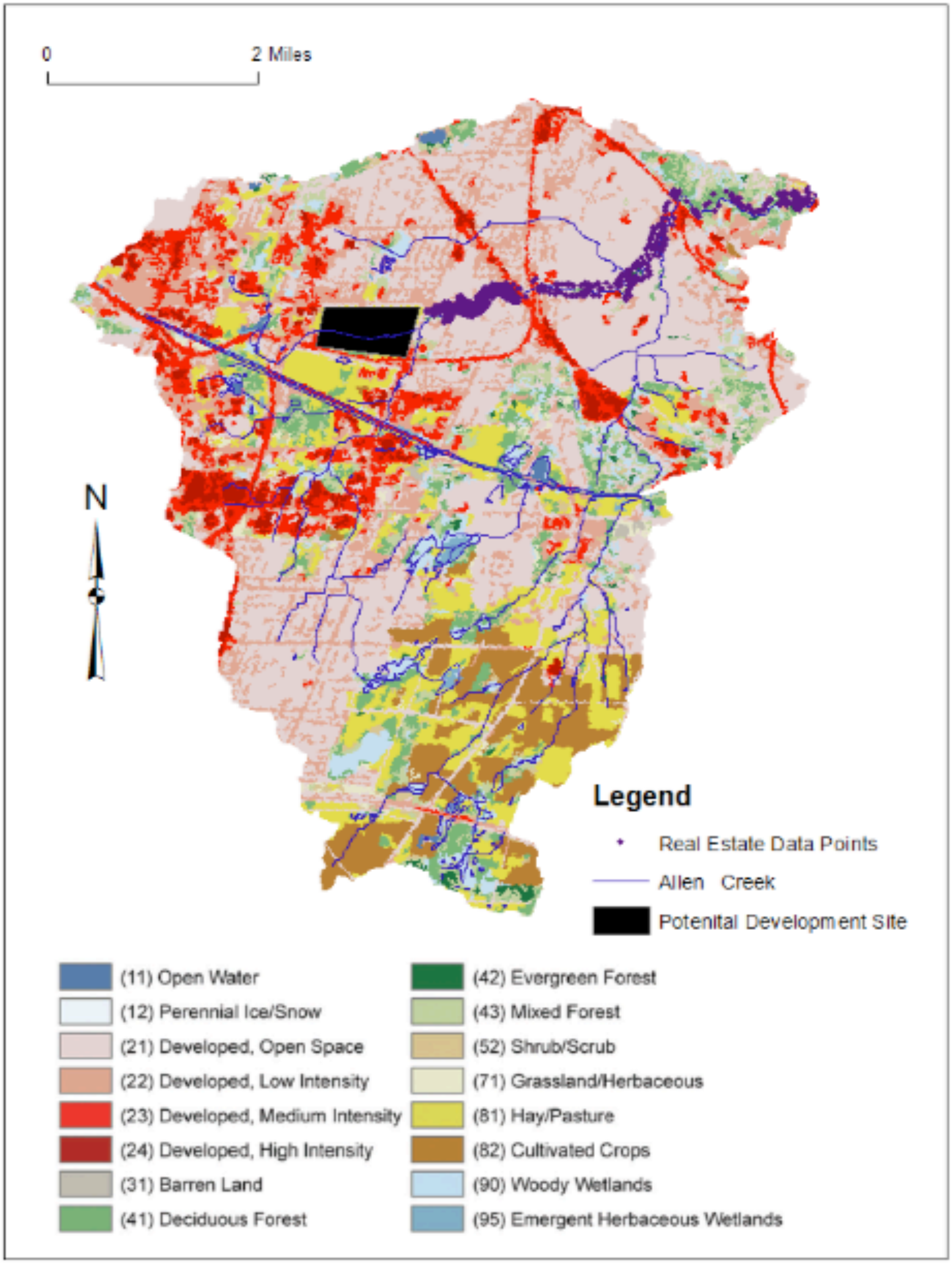

Figure 1b. 2006 LULC map of Allen Creek watershed, highlighting the potential development site and the homes of interest along a small stretch of Allen Creek.

In Figure 1b the black polygon in the upper watershed is a space in Brighton that currently exists as open, undeveloped land. This is an area that is being proposed for development and is one of the few undeveloped areas of this extent still remaining in Brighton. Any change in LULC at this site will have the greatest impact on properties located downstream from this area. These downstream residences within 100 meters of the creek are shown by the purple dots along Allen Creek. Given Brighton's high density of development, the decision to approve the increased development may not be ecologically or economically efficient if the cost of damage from unmitigated runoff to these downstream properties is sufficiently high enough to impose a cost burden on the community.

Determination of the optimal abatement volume and of urban stormwater runoff by estimating the marginal damage cost and marginal abatement cost for stormwater in the area of concern should provide a clearer picture of the environmental costs of excess runoff relative to the cost for the abatement of any excess runoff. This analysis should answer two main questions: (1) can a small-scale abatement program in the downstream community accommodate current runoff conditions; and (2) can a small-scale abatement program in the downstream community accommodate the volume of runoff that would occur under the developed condition? Ultimately these answers should help to identify whether the cost of the proposed new development in the community is likely to exceed the benefit of the development by creating an unreasonable abatement burden on individual residents.

The model can be used to answer these questions by comparing the marginal cost of runoff abatement to the marginal cost runoff damage under different development scenarios. At any volume of existing runoff where the marginal damage cost exceeds the marginal abatement cost, increased runoff should be abated. At any volume of existing runoff where the marginal abatement cost exceeds the marginal damage cost, the volume of runoff abated should be decreased. If increased development were to occur, the volume of runoff experienced by the community would also increase and, logically more runoff will need to be abated to minimize damages. The model will indicate how much runoff should be abated and determine if the community can realistically support this volume of abatement. If the community cannot support the suggested abatement volume for a reasonable cost, the development project should be reevaluated. In the case where the community can reasonably accommodate the increased abatement, the benefit of the development should exceed the cost of the abatement.

METHODOLOGY

Theoretical Economic Model

The theoretical economic model demonstrates the general behavior of the costs associated with increased urban stormwater runoff and is based on the general economic model for pollution emissions. In the model for pollution emissions, society faces an upward sloping marginal damage curve as a result of pollution emissions, and firms face a downward sloping marginal product of emissions curve, or abatement cost curve (Baumol and Oates 1988, 52-53). The marginal damage cost curve is upward sloping due to the increasing cost to society as pollution emissions increase. The marginal abatement cost curve is downward sloping due to the decreasing cost to society as pollution increases and therefore abatement decreases. The theoretical economic model for urban stormwater runoff is assumed to have cost curves that behave in general as the economic model of pollution emissions with excess stormwater runoff considered as the pollutant being "emitted," or in this case, discharged.

The model assumes that there are two general cost components of urban stormwater management: runoff abatement cost and runoff damage cost. While the abatement cost and damage cost associated with urban stormwater runoff is a function of both quantity and quality, and watershed managers must consider both of these aspects of stormwater management, the model is simplified to use only quantity as a function of the abatement cost and damage cost. In focusing on the quantity aspect only, the model assumes that abating stormwater quantity will indirectly mitigate stormwater quality effects (Laukkanen et al. 2009).

The intent of this model is to determine the volume of urban stormwater runoff that should be abated in an urbanized watershed. To accomplish this, the model for the cost of urban stormwater runoff is minimized with respect to volume of stormwater runoff (Kolstad 2000, 117-119).

The function to defining the cost of excess stormwater runoff borne by society is:

$Z(S) = A(S) + D(S)$ where S = the volume of stormwater runoff

$Z(S)$ = total societal cost of excess runoff

$A(S)$ = total societal abatement cost

$D(S)$ = total societal damage cost

The minimization function for Z(S) is:

$$\text{Min } Z(S) = A(S) + D(S)$$

$$dZ/dS = dA/dS + dD/dS = 0$$

$$dD/dS = -dA/dS$$

The first order necessary condition indicates that the total cost of urban stormwater runoff is minimized when the slope of the total societal damage cost curve is equal to the slope of the total societal abatement cost curve, which is where the value of the marginal damage curve is equal to the negated value of the marginal cost of stormwater runoff abatement. This result is supported by a theoretical model completed by Bhat et al. (1999, 179-180) which demonstrates that the optimal pollutant loading at each point source pollution location along a river is the level at which the marginal benefit of releasing the pollution is equal to the marginal cost of the pollutants emitted. In this model, however, the pollutant is “runoff”.

A graphical demonstration of the derivation of the general economic model for urban stormwater management is displayed in Figures 2-6 and discussed. Figures 2-6 are simplified curves that are intended to illustrate the basic economic theory.

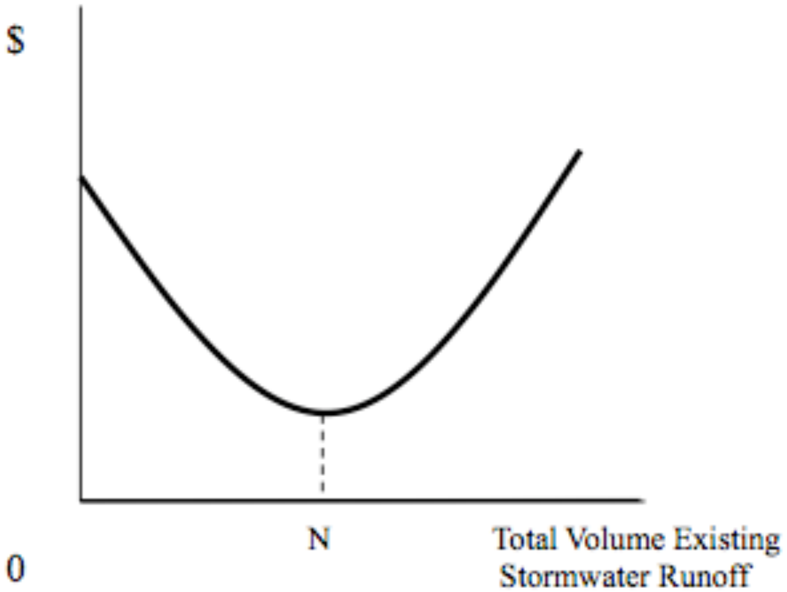

Figure 2. Theoretical total societal damage cost curve for urban stormwater runoff where N is the natural volume of runoff that exists in a watershed pre-development.

Figure 2 is representative of a developed watershed where runoff is assumed to have increased beyond the naturally occurring volume (N) as a result of increased impervious surfaces and altered vegetation. Damages are defined as both the economic and ecologic costs that result from the change in quantity and quality of stormwater runoff post-development in the watershed.

Volume N represents the natural amount of stormwater runoff that would exist in the watershed pre-development. If watershed managers were able to reduce runoff to N, the lowest damage costs can be achieved. The total damage cost at point N, however, is not necessarily zero, as some property damage may occur as a result of occasional small floods in particularly wet years; however, the damage cost at N will be close to zero. Additionally, because runoff in an urban environment is subject to more pollutants than runoff along land in its natural state, abating down to N does not guarantee pre-development water quality. Therefore, even if the natural volume of runoff can be maintained in a developed watershed, depending of the effectiveness of water quality treatment by the abatement technologies being used, the water quality may be diminished, resulting in damage to natural communities and habitats and economic costs to improve water quality for drinking, recreational use, etc.

Volumes of runoff greater than N represent either the total additional volume of runoff resulting from development or the total additional volume of runoff resulting from development less the volume of runoff abated. As the volume of runoff increases beyond N, total damage costs increase. Ecological damages include habitat destruction and species loss as a result of channel alteration, flooding, decreased base flow and increased pollutants. Economic damages include property damage from flooding, loss of economically useful species, and decreased quality of water used for drinking, recreation, etc. It is assumed that the damages increase without bound and become more costly as the runoff increases beyond N; however it is possible that the actual damage curve reaches a threshold level at some volume of runoff in which both properties and ecosystem services have been permanently damaged and the cost cannot increase any further (Booth and Jackson 1997).

Runoff volumes less than volume N represent only the case where urban watershed managers have reduced excess runoff to any volume below the natural volume. As urban stormwater abatement continues to reduce the volume of stormwater runoff below N, the damage costs increase. Ecological damages occur because water bodies are deprived of recharge water and economic damages are associated with the loss of economically relevant species resulting from the change in aquatic habitats.

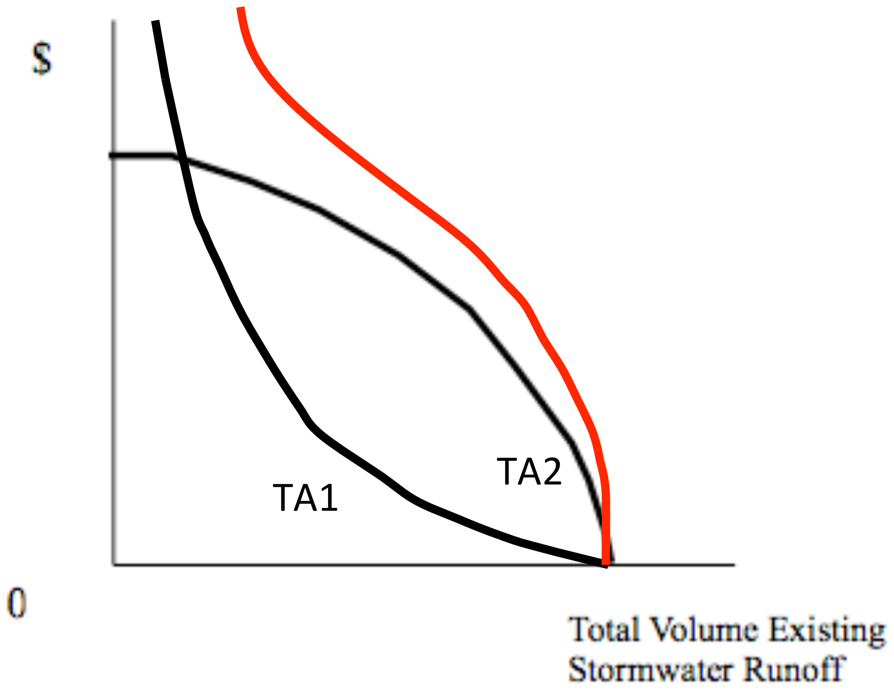

Figure 3. Theoretical total societal abatement cost curve for urban stormwater runoff shown in red, which reads from right to left. This curve is the addition of TA1 and TA2, which represent the opportunity cost effect and economies of scale effect, respectively.

In Figure 3 the total societal abatement cost curve in red is a combination of two competing cost effects shown by TA1 and TA2 in black, which demonstrate the opportunity cost effect and the economics of scale effect, respectively. The x-axis represents the volume of urban stormwater runoff that exists, meaning the total abatement cost curve and TAI and TA2 curves reads from right to left. Going from right to left the volume of existing stormwater runoff is decreasing, and thus, the volume of runoff abated is increasing. As the volume of runoff abated increases, the total societal abatement cost generally increases as well. At the maximum existing volume of stormwater runoff in the watershed, no abatement is occurring and therefore the total abatement cost is zero. The total societal abatement cost continues to increase until all runoff in the watershed is abated leaving zero units of existing stormwater runoff.

The specific behavior of the curve, which first increases at a decreasing rate and then begins to increase at an increasing rate, is a result of the shape of TA1 and TA2. TA1 shows the economies of scale effect, which occurs for most abatement technologies. The total cost is increasing but at a decreasing rate as more volume of runoff is abated. TA2 shows the opportunity cost effect, which is the cost of devoting increasing land area to an abatement technology. This total cost is also increasing but at an increasing rate due the diminishing marginal utility of increased yard space. At low levels of abatement, small amounts of yard space are taken out of commission relative to the amount of useable yard space. At higher levels of abatement, larger amounts of yard space must be devoted to a BMP. Therefore, the cost to give up a small amount of yard space when the property owner already has a relatively large usable yard area is smaller than to give up a small amount of yard space when the relative usable yard area is small. The two curves show that at smaller volumes of abatement the economies of scale effect dominates but the opportunity cost effect eventually dominates at large volumes of abatement.

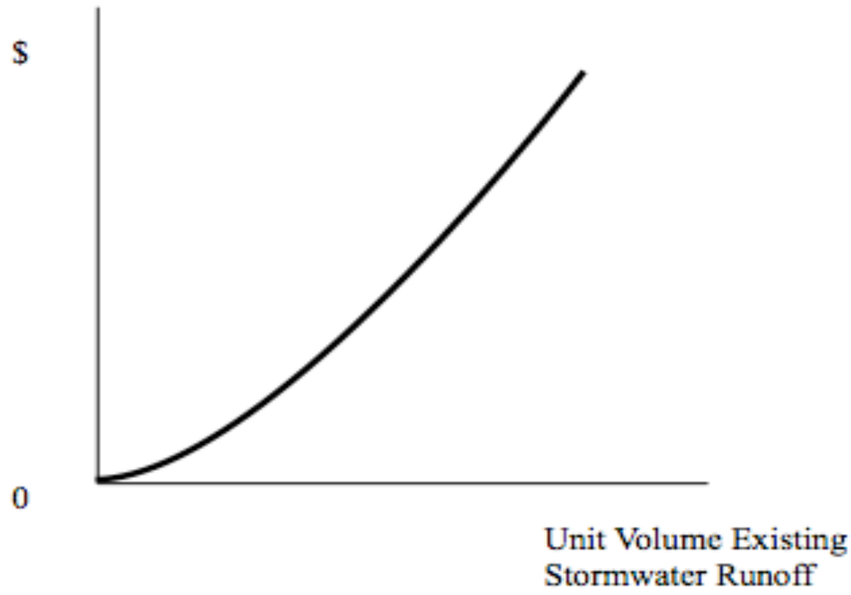

Figure 4. Theoretical marginal damage cost curve of additional volumetric units of stormwater runoff beyond the volume of runoff that exists in the pre-developed state of the watershed.

Figure 4 is derived from the total societal damage cost curve for urban stormwater runoff (Figure 2). Because the intent of the model is to determine the optimal volume of stormwater runoff in an urbanized watershed, it would not be economically or ecologically efficient to abate below the natural volume of runoff (N) (Figure 2). In Figure 4, therefore, the origin is equal to N. The marginal damage curve shows that the damage cost of each additional volumetric unit of stormwater runoff beyond N is increasing at an increasing rate. Each additional volumetric unit of stormwater runoff imposes both increased alterations to the natural environment and increased frequency and size of floods. This clearly imposes higher economic costs on society to deal with property damages and/or recover or do without lost natural resources.

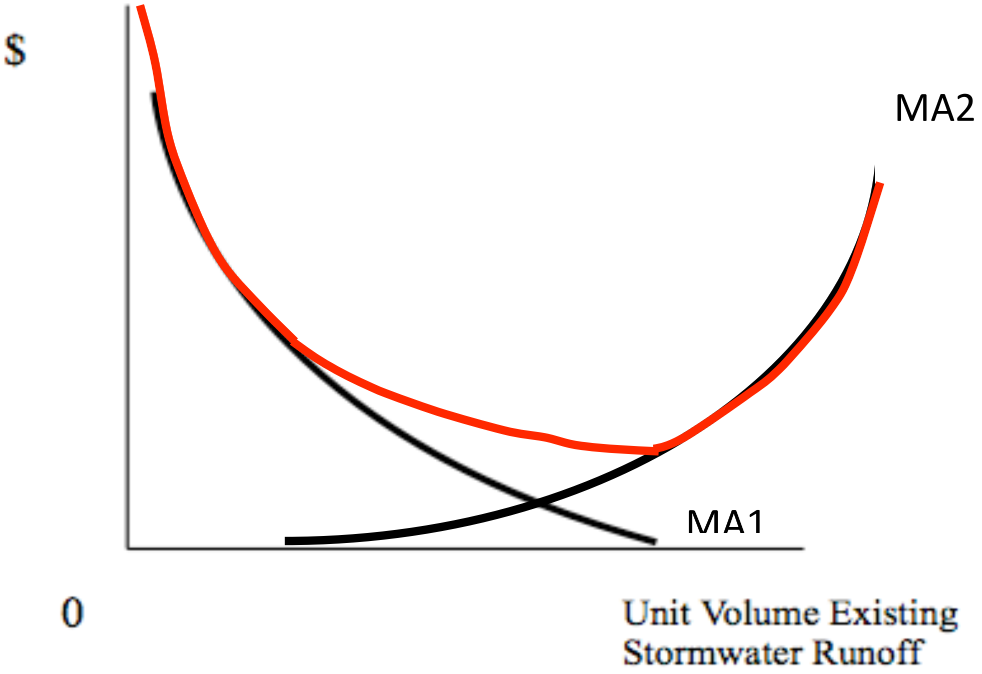

Figure 5. Theoretical marginal abatement cost curve per unit volume of stormwater runoff in red, which reads from right to left. This curve is the addition of MA1 and MA2, which are the negated derivatives of TA1 and TA2, respectively.

In Figure 5 curves MA1 and MA2 are the negated derivatives of the total abatement cost curves TA1 and TA2, respectively, as shown in Figure 3. Both curves are negated as indicated by the optimized model in which the minimum cost of runoff is achieved when the value of the marginal damage curve is equal to the negated value of the marginal abatement curve. MA2 shows the economics of scale effect that occurs as a result of economies of scale for most abatement technologies. Because an initial expenditure is typically required to abate a certain volume of runoff, the per unit cost to abate a smaller volume of runoff is larger than the per unit cost to abate a larger volume of runoff. The MA1 curve represents the opportunity cost of the land property-owners devote to a BMP. Each volumetric unit of stormwater abated has an increasing cost due to increasing yard space requirement (Thurston 2006).

It is reasonable to believe that the effect of economies of scale dominates at lower levels of abatement and at a sufficiently high level of abatement the opportunity cost effect dominates. Because these cost effects are additive, the marginal abatement curve is represented by the red curve in Figure 5.

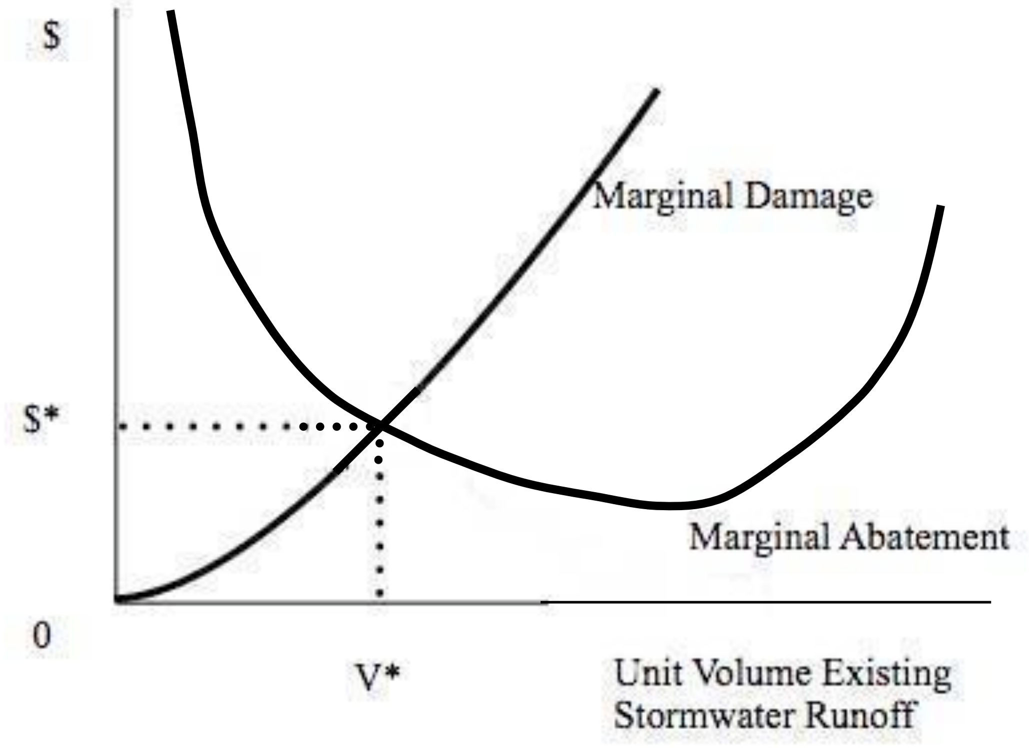

Figure 6. Theoretical cost minimizing model for urban stormwater runoff management showing the damage cost of each additional unit of existing runoff and the abatement cost of each additional unit of runoff abated. The intersection of the marginal damage curve with the negated marginal abatement curve at V*, indicates the optimal volume of runoff that should exist in the watershed.

Figure 6 is a model of both the marginal damage cost curve and the marginal abatement cost curve. The intersection of these curves indicates the economically efficient volume to abate in a watershed. The intersection of these curves at (V*, $*) is where the marginal damage cost is equal to the negated marginal abatement cost (or $-dA/dS= dD/dS$, the condition for cost minimization).

According to Figure 6, the optimal level of stormwater runoff in an urbanized watershed is V* volumetric units. Therefore, stormwater runoff in the watershed should be abated to volume V*. To allow volumes of runoff above V* (to the right of V*) is inefficient because the damage cost is higher than the cost to abate. In this case abating additional units of runoff can save money by reducing damage costs. If the community were to abate runoff below V* (to the left of V*), the damage cost is lower than the abatement cost and cost savings can be achieved by abating less units of runoff. At V* no cost savings can be gained by abating more or less units of runoff.

Empirical Economic Model

The Study Area and Data

After extensive literature review, no published studies have been found to present an empirical model of stormwater runoff management that can estimate the optimal volume of stormwater runoff abatement in a watershed. Due to the scarcity of current research in this area and time constraints, the development of the empirical model incorporates elements of a number of studies and includes modifications to the theoretical model. The goal of the model is to estimate the marginal damage and marginal abatement cost curves for a small area downstream from the potential site of development in Brighton, as this area should be the most impacted by flooding resulting from any development upstream. This downstream area is shown in Figure 1b and in an enlarged view in Figure 7.

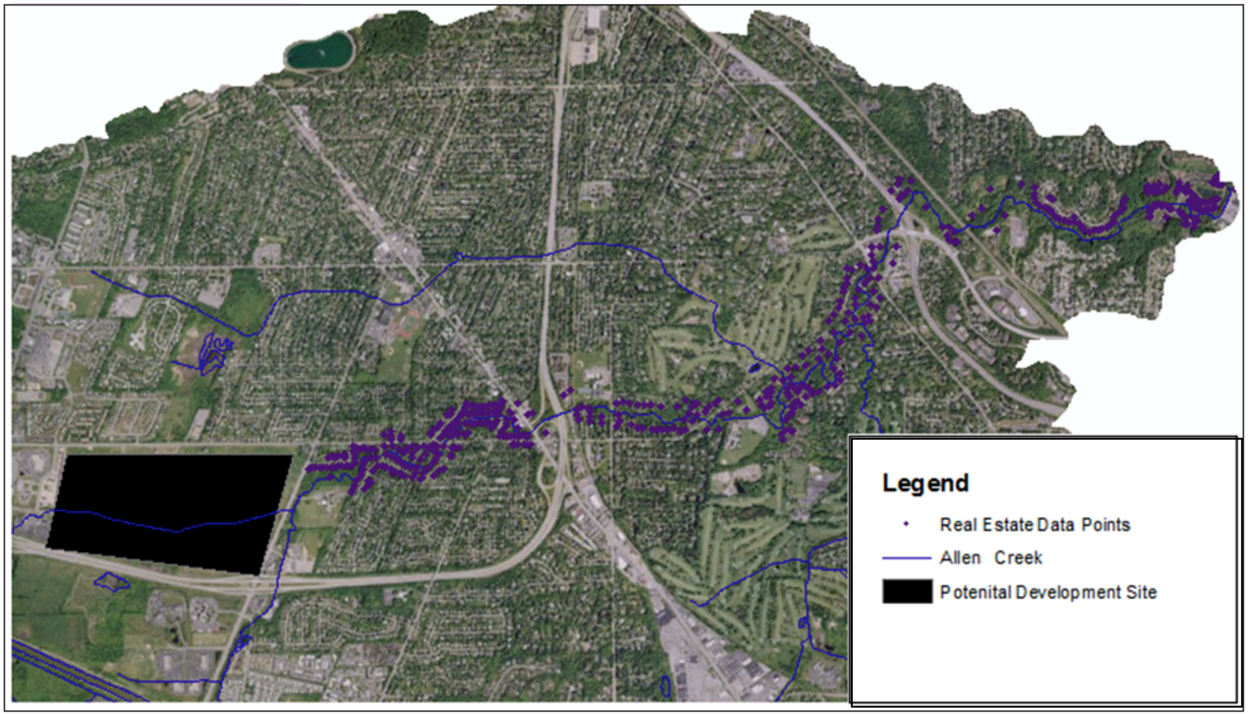

Figure 7. Enlarged aerial view of the area of interest depicted in Figure 1b.

Figure 7 shows the nearly 500 properties (in purple) that are located within 100 meters of Allen Creek and extend roughly 8,000 meters from the potential development site (the black polygon) to the ending portion of Allen Creek. These length and width buffers were chosen to include the properties that should be most impacted by any development at the selected upstream site. The properties are all located directly downstream from the potential development site and should be close enough to the stream to be impacted by any flooding as indicated by Federal Emergency Management Agency (FEMA) flood maps for the area of interest (FEMA 2011).

Figure 7 includes all properties that meet this criterion, however, about 240 properties were removed from the analysis. Most of the removed properties were commercial properties to restrict the analysis to residential properties. The remaining properties removed included townhouses and mansions. The townhouses were removed to restrict the analysis to single family residences, and homes classified by the town as “mansions” were removed because they have comparatively large assessment values relative to the average property assessment value of roughly $200,000 for the rest of the homes in the area. The final data set, therefore, consists of approximately 260 houses.

The majority of the homes in the data set are located in the zip code 14618 and therefore selected characteristics from this area are reported in Table 1 using information provided by the

United State Census Bureau 2000 Census. According to Table 1, in the 14618 zip code more than half of the population is comprised of women and over 90% of the population is white. Average median household income is almost 60% higher than reported national median household income and the percentage of adults with higher education is nearly 40 percentage points higher than the national percentage. Additionally the population in this area is older than the average age of the national population and household size is a bit smaller. Finally, most residents are homeowners and the median house value is reported as $137,500.

Table 1. US Census Bureau 2000 Census data for the zip code 14618 in Rochester, NY.

Characteristic	14618	USA
Population	22,387	------
Sex (% male)	45.2	49.1
Race (% white)	91.9	75.1
Median age (years)	41.7	35.3
% Population 25+ w/ bachelor's degree or higher	63.2	24.4
Median household income (1999$)	66,093	41,994
Number of households	8,649	-------
Household size	2.30	2.59
Percent owner occupied	76.5	66.2
Median house value ($)	137,500	119,600

The following sections detail separately the methods for estimation of the marginal damage curve and marginal abatement curve for the area of interest described above.

Marginal Damage Estimation

The development of the marginal damage cost curve is derived from an estimated total damage cost curve for urban stormwater runoff. The total damage cost curve is determined by generating two points on the curve and forcing the curve to be linear. Forcing the total damage curve to be linear is a simplification made to the theoretical model in Figure 2, which suggests that the slope of the total damage curve is increasing at an increasing rate, due to limited available data. One point on the curve is assumed to be (0,0) as the total damage cost of zero units of runoff above the natural predevelopment volume of average annual runoff should be near zero. A hedonic price model is then used to generate an additional point on the curve.

However, given the available real estate data, the hedonic model can only generate one additional point on the curve.

The hedonic model is constructed similar to the Poor et al. (2007) model, which is used to estimate the cost of water quality damage. The model in this study simply replaces Poor et al.'s (2007) water quality variable with a water quantity variable, average annual volume of runoff, to assess the cost of runoff to homeowners in terms of impact on the assessed values of their homes. Since the average annual runoff is a function of the volume of flooding conditions in a given year, the runoff variable is used as a proxy for flood damage. Based on the environmental science, it is assumed that increased volumes of average annual runoff in a watershed will results in increased frequency and/or volume of flooding in that watershed.

Because the area of concern has existed in its current state during the years for which the home assessment values in this area could be obtained (2005-2010), the results of the hedonic model are only representative of the cost of runoff under the current conditions of the area under consideration for development. The hedonic model gives the total cost to a homeowner if the current average annual volume of runoff were to increase by one additional unit. Calculating the one unit change in average annual runoff and multiplying the total cost to a homeowner by 260 homes downstream gives the total community damage cost at a specific volume of average annual runoff. Using this point and (0,0) and assuming that the slope is constant along the curve, total cost figures are extrapolated for various volumes of average annual runoff and therefore various development scenarios. Since the total damage curve in the empirical case is made linear, the marginal damage curve (the derivative of the total damage curve) is simply a constant cost per each additional average annual cubic foot of runoff.

The first step in the estimation of the total damage cost curve for urban stormwater runoff is finding the total average annual volume of runoff coming from the proposed developed area under the current conditions for the years 2004-2009. The runoff from 2004-2009 is needed because the runoff variable in the hedonic model is lagged one year corresponding to the assessment values. While it is possible that the assessment values may reflect runoff volumes, and therefore flooding occurrences, from more than one year in the past, it is certainly not reasonable to correlate the volume of runoff that occurred during the assessment year to that year's assessed value. To obtain the runoff volumes for these years the Long-Term Hydrologic Impact Analysis (L-THIA) model, which is based on the Soil Conservation Service's (SCS)

Curve Number (CN) method and daily precipitation records for the specified area (OEEF 1997, US Department of Agriculture 1986), is used.

The CN method assigns a value of 0 to 100 to each unique LULC and soil combination in the area of interest, with 0 indicating a perfectly porous surface that generates no runoff and 100 representing a completely impervious surface along which all water will runoff. The data required for this analysis were obtained from the Monroe County soils database the 2006 National Land Cover Database (NCLD) for the area of interest in its current state (as shown in Figure 1b). The soils database generally classifies soils as A, B, C or D, A indicating the most well-drained soil and D indicating the most poorly-drained soil. The daily precipitation data is from the National Oceanographic and Atmospheric Administration's National Climate Data Center Summary of the Day (NOAA NCDC SOD) database for the Rochester International Airport, which gives the daily precipitation in the Rochester area from 1965-2010.

Using ArcGIS 10, the area of the potential development site was calculated to be 3,410,748 square feet. The soil drainage class in the area of interest is uniformly C and there are roughly three LULC representations, wetlands, forest and grass/pasture. The CNs for each of these LULC/soil type combinations as estimated by the L-THIA model are shown in Table 2, along with the area of each LULC/soil type combination and the weighted average CN for each unique area. The sum of each weighted average CN for current conditions on the 3,410,748 square feet of the potential developed area is 52. This is a conservative estimate for this area, as it assumes that the wetlands in this area are acting completely as a sink for water. This conservative estimate, however, should have little impact on the analysis. If the wetlands are assumed to be mainly a source and not a sink for water, the wetlands are given higher CN of 100. This changes the weighted average CN to roughly 74. As the CN increases from 0 to 100 the volume of runoff indicated by the CN increases at an increasing rate. Because CNs 52-74 generate relatively small volumes of runoff (runoff depths of 0.09 to 0.94 inches, respectively, out of an annual precipitation average of 44 inches), the assumption that the potential development site is CN 52 should not cause drastically different results than if site were assumed to be a CN 74 in current conditions. Additionally, while the soil in the area of interest is classified as C, meaning it is relatively poorly-drained, the Purdue L-THIA model calculator (which was used in this analysis) identifies all wetlands with a CN of 100 (Purdue 2011).

Table 2. Calculation of the CN for the proposed area of development using the L-THIA model.

LULC	Soil Type	CN	Area (ft^2)	Weighted Average
Wetlands	C	0	980,100	0
Forest	C	70	531,432	10.91
Grass/pasture	C	74	1,899,216	41.21
		TOTAL	**3,410,748**	**52.11**

According to the L-THIA model for this area, a CN of 52 should generate an average annual runoff depth of 0.091 inches, which is the long-term average annual runoff depth for the Rochester area over the last 40 years. Additionally, Table 3 shows the estimated average annual runoff depths in Rochester that occurred in the years 2004-2009 as estimated by the L-THIA model using CN 52 and the annual precipitation data. The volume of runoff for each year and for the 5-year period average shown in Table 3 is calculated by converting depth from inches into feet and multiplying the depth in feet by 3,410,748 square feet, the area of the potential development site.

Additionally, Table 3 compares the 5-year period average of annual runoff volume to the 40-year period average of annual runoff volume in the Rochester area. A comparison of both period averages shows that average annual runoff during the five years used in the hedonic model is slightly lower than the average annual runoff indicated by the 40-year period average. This means that 2004-2009 generally experienced relatively lower volume of precipitation, causing less runoff in these years. However, because the hedonic model is only representative of assessed home values from 2005-2010, the lower period average of 19,043 ft^3 must be used.

Table 3. Volume of runoff in cubic feet occurring in the years 2004-2009 in Rochester, NY, as estimated by the L-THIA model.

Year	Runoff Depth (in)	Runoff Volume (ft^3)
2004	0.02	5,685
2005	0.17	48,319
2006	0.21	59,688
2007	0.00	0.00
2008	0.00	0.00
2009	0.00	0.00
5 -Yr Period Average	**0.067**	**19,043**
40-Yr period Average	**0.091**	**25,865**

The hedonic price model attempts to capture any relationship that may exist between the average value of a residential property and volume of average annual flooding experienced in the area. Because the volume of flooding is directly related to the average annual volume of runoff, the lagged yearly values of runoff from Table 3 are related to the yearly-assessed values of the 260 properties used in the hedonic price model. The annual average runoff volumes in cubic feet are used in the hedonic price model to estimate the total cost of a one unit change in the period average of 19,043 ft^3 to a single homeowner located downstream from the potential development site. In other words, if that average annual volume of runoff were to increase by one unit, how much would the average assessed value of a home change? The hedonic price model follows the typical form used by economists and closely resembles the regression completed by Poor el al. (2007), who use hedonic price valuation to estimate the costs of water pollution to homeowners in an urbanized watershed in the Chesapeake Bay area. The Poor et al. (2007) hedonic price model uses various structural and neighborhood characteristics of 1,377 residential properties and an environmental variable of water quality to predict the natural logarithm of the real sale price for each property. The regression model is defined as (Poor et al. 2007, 803):

$$LNREALPR_i = \alpha + \beta_1 S_i + \beta_2 N_i + \beta_3 E_i + e_i$$

where $LNREALPR_i$ = log of real price (January 2003 constant dollars)
α, β_1, β_2, and β_3 are estimated coefficients
S = structural characteristics
N = neighborhood characteristics
E = environmental water quality characteristics, using total suspended solids (TSS) and dissolved inorganic nitrogen (DIN) as water quality indicators
e_i = random error term

Additionally, although many hedonic price models, including the Poor et al. (2007) model, use the price paid for a house after a sale as the dependent variable, due to limited availability of sales data, the dependent variable used in this regression is the real county assessed value of each residential property in 2010 constant dollars. Because the sale prices of residential properties are typically a function of the assessed value of the residential property, it is assumed that if there exists a relationship between real estate value and runoff, it should be present in the assessed value of the properties. Also, assessed values would presumably be less directly affected than sale prices by the housing crisis that occurred nationally during the 2005-

2010 period. Therefore the hedonic model used to estimate the damage cost of runoff is defined as:

$$\mathrm{LNREALAV}_{\mathbf{it}} = \alpha + \beta_i S_{\mathbf{it}} + \beta_2 N_{\mathbf{it}} + \beta_3 E_{\mathbf{it}} + e_{\mathbf{it}}$$

where $\mathrm{LNREALAV}_{\mathbf{it}\ i}$ = log of real assessed value (2010 constant dollars) for home i at time t
α, β_1, β_2, and β_3 are estimated coefficients
$S_{\mathbf{it}}$ = structural characteristics for home i at time t
$N_{\mathbf{it}}$ = neighborhood characteristic for home i at time t
$E_{\mathbf{it}}$ = annual volume of runoff for home i at time t-1, used as an indicator of flooding
$e_{\mathbf{it}}$ = random error term

The real estate data used in the model is publicly accessible and was collected for the years 2005-2010 from the NYS Department of Taxation and Finance's Office of Real Property Tax Services and the Monroe County Real Property database. These resources provide real estate data for over 20,000 properties in Monroe County. It should also be noted that the assessed values for each property taken from the NYS Department of Taxation and Finance's Office of Real Property Tax Services and the Monroe County Real Property database were all adjusted to reflect 2010 constant dollars. Monthly housing price indices for the years 2005 and 2010 (Freddie Mac 2011) were averaged to reflect the average yearly index for each year. The assessment values for the years 2005-2009 were converted to 2010 constant dollars using the following formula: $\mathrm{Price}_{\mathrm{baseyear}} = (\mathrm{Price}_{\mathrm{currentyear}} * \mathrm{Index}_{\mathrm{baseyear}})/(\mathrm{Price}_{\mathrm{currentyear}})$. The log of this variable is called "LADJTOTAL" and shown in Table 4.

Putting the dependent variable in natural log form is typical for hedonic models (Epp and Al-Ani 1979, Thurston 2006, Poor et al. 2007, Williamson et al. 2008, Ma and Swinton 2011) and is therefore used in the hedonic model to estimate the damage cost of runoff. While the Woolridge test, which is an indication of whether the independent variable should be in natural log form or linear form, technically supports the level model by a small margin (the correlation coefficients for both models are both greater than 91% and differ by less than 2%), semi-logarithmic models are often used in hedonic models due to the ease of coefficient interpretation as a percentage change in price given a one unit change in the independent variable. Additionally, the semi-log model can help minimize the presence of heteroskedasticity, which is common in time series cross-sectional data sets (Amacher and Hellerstein 1999, Malpezzi 2003).

Because the data contain houses that are located in a small area, the only characteristics that need to be controlled for are a number of structural characteristics for each residential property and one neighborhood characteristic, which defines the town in which the property is located. Additionally, unlike Poor et al. (2007), the hedonic model for runoff also adds a time trend to capture the influence of time upon assessed values and to ensure the environmental variable is not incidentally picking up any time trend. The environmental variable, as previously mentioned, is the average annual runoff volume in cubic feet lagged one year and shown in Table 3 and 4. Because the range of average annual runoff volumes is relatively large, the lagged runoff variable is also in natural log form.

Table 4. Variables used in regression analysis.

Variable	Description	Mean	S.D.	Min.	Max.
LADJTOTAL	Log of real assessed value (2010 constant dollars)	12.21	0.49	11.23	13.97
PITTS	Town dummy (=1 if home is located in Pittsford, else=0)	0.10	0.30	0.00	1.00
YRBUILT	Year home was built	1,945.68	19.44	1,826.00	2,003.00
BDROOMS	Number of bedrooms	3.53	0.81	1.00	7.00
GARAGE	Garage dummy (=1 if present, else=0)	0.86	0.35	0.00	1.00
BATH	Number of full bathrooms	1.90	0.92	1.00	5.00
FIRE	Number of fireplaces	1.24	0.65	0.00	4.00
HALF	Number of half bathrooms	0.72	0.46	0.00	2.00
LIVING	Living area in square feet	2,262.59	949.43	1,050.00	7,361.00
LIVING2	Living area squared				
LRO52FT3	Annual volume of runoff in cubic feet for CN 52 lagged one year from the assessed value year	5.09	5.13	0.00	11.00
TIME	Time dummy (=1 if assessed value from 2005, =2 if assessed value from 2006, …, =6 if assessed value from 2010	3.50	1.71	1.00	6.00
NETLOT	Yard size in square feet (parcel size minus footprint of house)	23,334.86	26,097.48	5,174.00	261,194.20
NETLOT2	Netlot squared				
NETLOT3	Netlot cubed				

The structural characteristics that were included in the regression for the selected properties are the area of the entire property in acres, the year in which the house was built, the number of bedrooms, full bathrooms, half bathrooms and fireplaces, the presence of a garage, and the living area in square feet. These variables are listed in Table 4, along with a squared variable of the living area called "LIVING2". This variable captures the non-linear relationship that typically exists between the value of the home and the size of the home's living area due to the diminishing marginal utility of an increase in living area (Thurston 2006, Poor et al. 2007). The neighborhood characteristic defining the town in which the property is located is represented by the dummy variable "PITTS" (Table 4). Although most observations are for homes located in the Town of Brighton (1,402 observations out of 1,557), the "PITTS" variable is included to control for the fact that homes in the Town of Pittsford generally cost more than those located in Penfield and Brighton.

The “NETLOT” variables shown in Table 4 are a function of structural characteristic, “LIVING”, as “NETLOT” is equal to the parcel size minus the footprint of the house, which gives the yard space in square feet. The “NETLOT” variable along with the squared and cubed “NETLOT” variables are included in the regression to estimate the opportunity cost of the land reserved for a BMP. “NETLOT” is squared like “LIVING”, as the value of yard space also displays diminishing marginal utility. “NETLOT” is cubed in an attempt to get a marginal abatement function that behaves similar to the theoretical curve (Figure 5). This is discussed further in the section detailing the steps in the estimation of the marginal abatement curve.

Given all of the variables discussed and summarized in Table 4, the explicit functional form of the hedonic model used to estimate the cost of runoff is:

$$\begin{aligned}\mathbf{LADJTOTAL}_{it} = {} & \beta_0 + \beta_1(\mathbf{PITTS})_{it} + \beta_2(\mathbf{YRBUILT})_{it} + \beta_3(\mathbf{BDROOMS})_{it} + \beta_4(\mathbf{GARAGE})_{it} + \\ & \beta_5(\mathbf{BATH})_{it} + \beta_6(\mathbf{FIRE})_{it} + \beta_7(\mathbf{HALF})_{it} + \beta_8(\mathbf{LIVING})_{it} + \beta_9(\mathbf{LIVING2})_{it} + \\ & \beta_{10}(\mathbf{LRO52FT3})_{it} + \beta_{11}(\mathbf{TIME})_{it} + \beta_{12}(\mathbf{NETLOT})_{it} + \beta_{12}(\mathbf{NETLOT2})_{it} + \\ & \beta_{14}(\mathbf{NETLOT3})_{it} + e_{it}\end{aligned}$$

The dependent variable “LADJTITAL $_{it}$” is the natural log of the inflation adjusted assessment value of home i at time t. Because both White’s test and the Breusch-Pagan test indicate the presence of heteroskedasticity, this model was run as a heteroskedasticity-robust model using SAS 9.2.

Using this model, the interpretation of the coefficient on runoff variable is such that, all other variables held constant and on average, a one percent change in the average annual runoff volume (in cubic feet) is related to a percentage change in the average annual assessment value of a home by the magnitude of the coefficient. Since it is assumed that the average annual runoff volume is equal to the period average of about 19,043 ft^3 (Table 3), a one percent change in this volume is equal to roughly 19,234 ft^3 of average annual runoff (see Appendix B). Therefore, the percentage change given by the runoff coefficient multiplied by the average home value, which is roughly $200,000, is equal to the total cost of runoff to a homeowner downstream from the potential development site at an average annual volume of 19,234 ft^3 of runoff. The total cost to a single homeowner multiplied by the 260 homes gives the total cost of runoff to this downstream community at a volume of 19,234 ft^3 of runoff. Assuming that the total cost of runoff to the Brighton community at a volume of 0 ft^3 of runoff is equal to $0, and assuming that the total community damage curve is linear for the purposes of this model, a total community damage curve can be constructed for any volume of runoff using a constant slope. The slope of the total community damage curve is equal to the marginal damage cost, or cost per ft^3 of average annual runoff.

Additionally, from this total damage curve, the total damage cost to the downstream community under the developed condition can be estimated after determining the total volume of runoff the community would experience if the potential development site were to be developed. The volume of runoff experienced by community in this case is determined in the same manner as the volume of runoff occurring under current conditions (Figure 2). In this case, however, the curve numbers for wetlands, forest, grass/pasture are replaced with a CN that is representative of commercial development, which according to the L-THIA model is CN 94. It is assumed that the entire 3,410,748 square feet of land will be replaced entirely with commercial development. Since the land use is defined as universally commercial, there is no need to calculate weighted average CNs; the CN for commercial development in this area is simply 94. According to the L-THIA model, the 40-year period average of average annual runoff depth estimated for CN 94 in the Rochester area is 12.28 inches. Therefore, the volume of runoff that can be expected downstream of the potential development site if developed is about 3,491,185 cubic feet of average annual runoff.

Marginal Abatement Estimation

Because stormwater runoff in the Town of Brighton is not treated by a wastewater treatment plant but is directly discharged into local streams (Keef 2010), the only community cost for residential runoff abatement is the cost to homeowners to set up and maintain an abatement structure on their property. The set up and maintenance costs of two small-scale, household level stormwater runoff abatement strategies, filter strip/sand filter and grassed swales/rain gardens, are estimated by Thurston et al. (2003) using information from two different studies completed by Schueler (1987) and Heaney et al. (2002). Thurston et al. use cost estimates given in Schueler (1987) and applies them to the functional forms for grassed swales/rain gardens and filter strips/sand filters identified in Heaney et al. (2002, 29-31). Thurston et al.'s (2003, 414) equations are defined as:

Filter strip/Sand filter: $C = 26.6Q^{0.64}$
Grassed swales/rain gardens: $C=4.94Q$,

in which Q= the volume of runoff abated in cubic feet. According to Thurston et al. (2003,414) both abatement technologies can be used on various soil types. Schueler (1987) describes two ways in which grassed swales/rain gardens act to control peak discharges. First of all, the grass is able to reduce the velocity of runoff flow, lengthening the time it takes for the runoff to travel to the receiving body, and secondly, the swale ensures that some of the runoff is infiltrated into the soil. Additionally, grassed swales/ rain gardens can be designed to filter out particulate pollutants; however, grassed swales/rain gardens have relatively low pollutant removal capabilities compared to other runoff abatement strategies. Filter strips/sand filters also have relatively low to moderate pollutant removal capabilities and are mechanistically similar to grassed swales/rain gardens but are not as effective at reducing peak discharges (Schueler 1987).

These cost equations can be used to roughly calculate the total cost of the set up and maintenance of these abatement technologies but not the opportunity of the land devoted to these abatement technologies. Therefore, Thurston (2006) modified these equations to add an estimate of the opportunity cost of the land. To estimate the opportunity of the land, Thurston (2006) runs a hedonic price model that includes the "NETLOT" variable in square feet that is used in the hedonic model for runoff (Table 4). According to Thurston (2006, 92), for a small-scale residential BMP, it is reasonable to assume that there is a 1:1 ratio between the square footage of BMP and volume of runoff abated by a BMP in cubic feet. Therefore the coefficient on Thurston's (2006) "NETLOT" estimate multiplied by the volume of runoff being abated is equal to the opportunity cost of runoff abatement. Thurston's (2006, 93) modified cost functions are defined as:

Filter strip/Sand filter: $C = 26.6Q^{0.64} + 0.126Q$
Grassed swales/rain gardens: $C=4.94Q + 0.126Q$,

in which Q= the volume of runoff abated in cubic feet and the loss of an additional square footage of yard space costs about $0.13 as indicated by the "NETLOT" variable in Thurston's

(2006, 92) regression equation. Thurston also has a "NETLOT" squared variable to capture the decreasing marginal utility of yard space; however, Thurston does not include the quadratic term in the cost equation because the coefficient is too small to be relevant for the small-scale BMPs for which he is concerned (2006, 91-93).

The total abatement cost curves (for the two different abatement technologies) for urban stormwater runoff downstream of the potential development site under current conditions are developed using the same method as Thurston (2006). However, in order to get a total or marginal abatement cost curve that resembles the theoretical curves (Figures 3 and 5), there must be a cubic relationship on "NETLOT". Therefore, the hope is for the hedonic model for runoff to have a significantly large "NETLOT" term, "NETLOT" squared term, and "NETLOT" cubed term. Assuming the 1:1 ratio between the square footage of the BMP employed and the volume of stormwater abated in cubic feet and adjusting Thurston et al.'s (2003, 414) equations to 2010 constant dollars using the historical CPI indices for 1987 and 2010 (US Bureau of Labor Statistics 2011), Thurston et al.'s (2003, 414) small-scale residential functions for the total community abatement cost are modified for the stormwater management model to:

Filter strip/Sand filter: $C = 51.06Q^{0.64} + \beta_{12}Q + \beta_{13}Q^2 + \beta_{14}Q^3$
Grassed swales/rain gardens: $C=9.48Q + \beta_{12}Q + \beta_{13}Q^2 + \beta_{14}Q^3$,

in which Q= the volume of runoff abated in cubic feet. Because Thurston (2006) defines Q as the volume of runoff abated in cubic feet, to set up the empirical models like the theoretical models with Q being the volume of existing runoff, Q must be modified. In the empirical total and marginal abatement cost curves Q is therefore equal to the volume of runoff a watershed should be experiencing based on the developed state as determined by L-THIA less the volume of the runoff that actually exists in the watershed (or the value of the x-axis). For example the total abatement cost equations for the downstream community when the area of interest is in its current conditions (CN 52) are:

Filter strip/Sand filter: $C = 51.06(19{,}043-x)^{0.64} + \beta_{12}(19{,}043-x) + \beta_{13}(19{,}043-x)^2 + \beta_{14}(19{,}043-x)^3$
Grassed swales/rain garden: $C=9.48(19{,}043-x) + \beta_{12}(19{,}043-x) + \beta_{13}(19{,}043-x)^2 + \beta_{14}(19{,}043-x)^3$

Taking the negated derivatives of these functions gives the marginal abatement cost curve for urban stormwater runoff. These functions can be used to estimate the abatement cost for any volume of runoff and therefore for all development levels and a total and marginal abatement costs curve is generated for the case in which the potential development site is a CN 52 and the case where the potential development site is a CN 94. It should be noted that while a single grassed swale/rain garden or filter strip/sand filter is probably not capable of abating the entire community runoff burden under any level of development, especially higher levels, it is assumed that multiple homeowners have established a single grassed swales/rain gardens or filter strip/sand filter on their property. Therefore, in calculating the total community abatement cost for any level of development, it is assumed that the total volumetric abatement burden of the community is being shared by multiple grassed swales/rain gardens and/or filter strips/and filters.

Model for Urban Stormwater Runoff Cost Minimization

To determine the optimal abatement volume under current conditions, the marginal damage curve runoff is graphed on the same axes as the negated marginal abatement curve that is relevant when the potential development site is CN 52. The intersection of the two marginal curves indicates the optimal volume of runoff that should exist in the community. Therefore, the total volume of runoff that should be abated is the volume of existing stormwater runoff less the optimal volume. For example, at CN 52 the potential development site currently generates 19,034 cubic feet of runoff. If the indicated optimal volume of runoff in the community is 10,000 cubic feet, the volume of runoff for the community to abate is 9,034 cubic feet.

This procedure is repeated to generate the optimal volume of abatement if the potential development site is actually developed and now exists in a state of CN 94. The marginal damage curve remains the same; however, the marginal abatement cost curve is adjusted to reflect abatement of the larger volume of runoff associated with a CN 94. The amount of runoff that should be abated in this case, once again, is the optimal volume indicated by the intersection of the marginal abatement and damage curve subtracted from the total volume of runoff generated by a CN 94 (or 3,491,185 cubic feet of runoff).

Once the abatement requirements are determined for each CN 52 and CN 94, whether the town can accommodate the current condition and the developed condition volume of runoff on a residential abatement level is determined. Assuming that each homeowner downstream from the development will abate equal volumes of runoff, the amount of yard space required to abate to the efficient volume of runoff as indicated by the intersection of the marginal damage and marginal abatement cost curves is calculated. Based on these calculations, the required abatement volume for development scenario CN 94 is assessed in terms of reasonability assuming that the average homeowner has about 23,000 ft^2 of yard space (Table 4). If the developers are not required to install any abatement measures on the commercial property, the potential development site should only be developed to a point where strictly residential abatement can accommodate the increased runoff. If the developers are required to share in the abatement responsibility, the potential development site can support additional impervious surface to the point where the developers and downstream households both have a reasonable abatement burden.

RESULTS

Hedonic Model

Table 5 shows the results from the heteroskedasticity-robust regression using assessed residential property values from 2005-2010 assuming the potential development site's development condition for those years is CN 52.

Table 5. Regression results.

Variable	Coefficient	S.E.[a]	t-value	P-value
Intercept	7.475659*	0.418	17.88	<.0001
PITTS	0.228854*	0.0225	10.18	<.0001
YRBUILT	0.001712*	0.000213	8.04	<.0001
BDROOMS	0.004795	0.00755	0.64	0.5252
GARAGE	0.115017*	0.0112	10.30	<.0001
BATH	0.015697	0.012	1.31	0.1911
FIRE	0.028274*	0.00857	3.30	0.0010
HALF	0.026509**	0.0118	2.25	0.0248
LIVING	0.000621*	0.000026	23.66	<.0001
LIVING2	-4.06E-08*	2.895E-09	-14.02	<.0001
LRO52FT3	-0.01461*	0.00141	-10.34	<.0001
TIME	0.003046	0.00414	0.74	0.4618
NETLOT	0.000004315*	7.736E-07	5.58	<.0001
NETLOT2	-1.82E-11**	8.91E-12	-2.04	0.0416
NETLOT3	1.46E-17	2.59E-17	0.56	0.5730
n	1557			
F-statistics	969.93			<.0001
Adj R^2	0.90			

a Heteroskedasticity-consistent standard errors
* P<0.001
**P<0.05

The interpretations of each coefficient are detailed below (see Appendix B):

1. While the intercept is statistically significant, it has no intuitive meaning and is ignored.
2. “PITTS” indicates that if all other variables are held constant, residences located in the Town of Pittsford have higher assessed values than those in Brighton or Penfield by an average of $51,923.52.
3. “YRBUILT” indicates that if all other variables are held constant, a home built one additional year later raises the assessed value by $401.98 on average.
4. “BROOMS” is statistically insignificant mostly like due to multicolinearity between “BDROOMS”, “BATH”, and “HALF” as indicated by an F-test of linear restrictions.
5. “GARAGE” indicates that if all other variables are held constant, homes with a garage have higher assessed values than those without a garage by an average of $25,599.71.
6. “BATH” is statistically insignificant.
7. “FIRE” indicates that if all other variables are held constant, an additional fireplace raises the assessed value of a home by $6,114.87 on average.

8. “HALF” indicates that if all other variables are held constant, an additional half bathroom raises the assessed value of a home by $6,114.87 on average.
9. “LIVING” and “LIVING2” together indicate that the slope with respect to living area = [$120.51-($0.01*2*LIVING)], so the effect of living area is mostly positive but becomes negative for sufficiently large living areas. The turning point occurs at the level of “LIVING” at which the slope is zero or at 6025.5 square feet. However, homes with living areas of greater than 6025.5 square feet comprise less than 1 percent of the data set and therefore the slope of “LIVING” will decrease at a decreasing rate but will not be relevantly negative.
10. “LRO52FT3” indicates that if all other variables are held constant, a one percent increase in the average annual volume of runoff would result in an average decrease in assessed value of a home 1 percent. Therefore if average annual volume of runoff were to increase by 1 percent, the average home value would be decreased by about $2000.
11. “TIME” is statistically insignificant, most likely due to the correction for inflation.
12. Because “NETLOT3” is not statistically significant, and the coefficient on “NETLOT2” is essential 0, the slope with respect to yard space is defined solely by “NETLOT” = 0.8.

This model generates economically logical results that are relatively comparable to the regression results of Poor et al. who have a similar average home value in their study area (2007, 803-804). However, the only parameters of interest are the “NETLOT” parameter and the runoff parameter (“LRO52FT3”).

The coefficient on “LRO52FT3” is negative, as predicted, suggesting that increasing average annual volumes of runoff are related to lower housing values as a result of increased flooding. The coefficient says specifically that if all other variables are held constant, a one percent increase in the average annual volume of runoff would result in an average decrease in the assessed value of a home by about $2000.00. Since the regression is run using assessed values related to runoff occurring from the potential development site in its current conditions (CN 52) (Table 2), a one percent increase in the average annual volume at CN 52 (19,043 ft^3) is equal to 19,234 cubic feet. Therefore, the regression results indicate that the total cost of 19,234 cubic feet of runoff to a homeowner is about $2000. The total cost to the community of 19,234 cubic feet of runoff is $2000*260 downstream properties, which equals $520,000. Assuming that the total cost of zero cubic feet of runoff to the community is $0 and that the slope of the total community damage curve is linear, the slope of the total community damage curve is calculated using these two points and plotted in Figure 8 (See Appendix B).

Optimal Model for Current Conditions

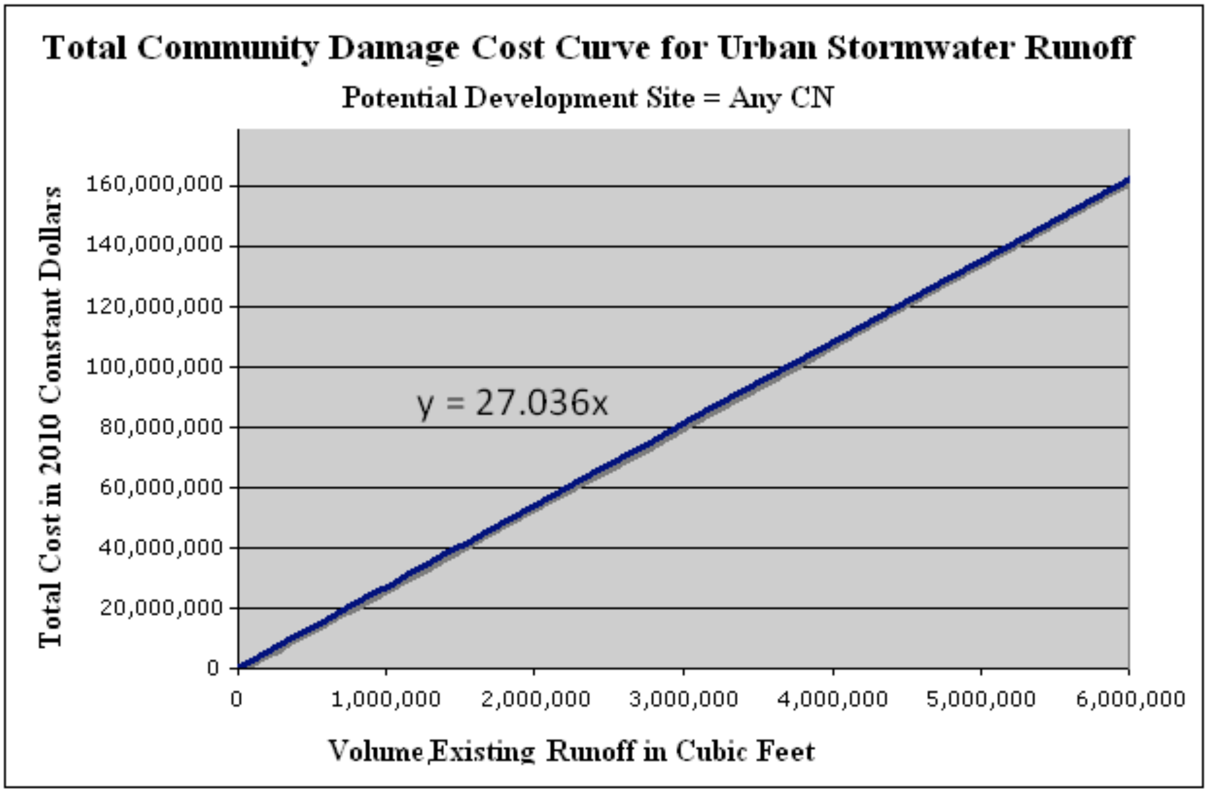

Figure 8. Empirical total community damage cost curve extrapolated to estimate the cost of any existing stormwater runoff being discharged from the potential development site, and therefore the curve is assumed to increase linearly without bound.

Because the total community damage curve is modified to be linear and extrapolated for average annual runoff volumes for CNs greater and less than that associated with CN 52, the total cost of average annual runoff volumes greater than CN 52 are mostly likely understated in such a way that the greater the runoff volume from CN 52, the total damage cost becomes increasingly understated due to the assumed relationship between increased runoff and cost in the theoretical model (Figure 2). Additionally, the total cost of runoff for volumes less than CN 52 may be overstated in such a way that the lower the runoff from CN 52, the total damage cost becomes increasingly overstated also due to the assumed relationship shown in Figure 2. It is possible that with the collection of more data the empirical curve would behave similar to the theoretical total damage curve (Figure 2), which shows the total damage cost increasing at an increasing rate. The equation for the total community damage curve for urban stormwater runoff is y=27.036x, where is x is runoff volume in cubic feet and y is 2010 constant dollars.

To continue building the model from there, the total abatement cost curves must be constructed, and the parameters of interest for the abatement cost curves are the "NETLOT" variables as they are used to generate the opportunity cost estimate. The "NETLOT" parameters indicate that only a quadratic trend is present in the data; however, the coefficient on "NETLOT2" is essentially zero and therefore the slope with regard to "NETLOT" is considered to be simply linear (See Appendix B). Without the cubic trend, this unfortunately will not cause the empirical abatement cost curves to take shape as the theoretical model in Figure 3. The opportunity cost will add a cost of 0.8Q (as indicated by the coefficient on "NETLOT") to the equations defining the set up and maintenance cost of the abatement technologies (See Appendix B). Since the opportunity cost is so small, the abatement cost curves only depict the economies of scale effect as shown in Figure 9.

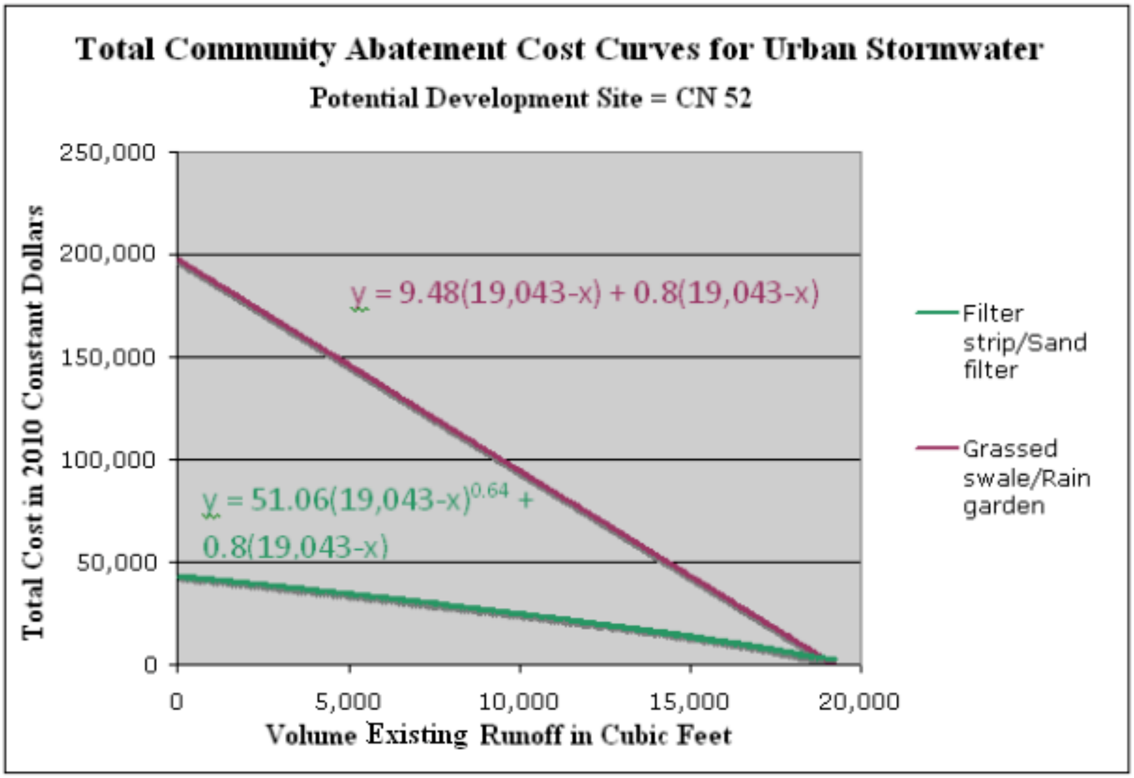

Figure 9. Empirical total community abatement cost curves for urban stormwater runoff when the potential development site is in current conditions (CN 52).

Figure 9 shows the total community abatement cost curves for two different abatement technologies assuming that the potential development site exists in its current condition with an average annual runoff volume of 19,042 ft^3. Therefore, if the community is experiencing an average annual volume of runoff of 19,043 cubic feet (or more), no abatement is occurring and the total community abatement cost is $0. This curve also assumes that if the community is experiencing zero average annual runoff, all of the runoff is being abated and the total community abatement cost is at its peak.

To get the equations to read right to left, Q, the volume of runoff abated, must be defined as19,043-x, which is the total average annual runoff expected for the community less the volume of existing runoff . The two abatement technologies shown in Figure 9 are for filter strips/sand filters and grassed swales/rain gardens. The equation for filter strips/sand filters is $y= 51.06(19{,}043-x)^{0.64} + 0.8(19{,}043-x)$ and the equation for grassed swales/rain gardens is $y=9.48(19{,}043-x) + 0.8(19{,}043-x)$. The cost curve for the grassed swales/rain gardens shows that this technology does not actually have an economies of scale effect present (like the filter strip/sand filter technology) but displays constant per unit cost. Additionally with only a linear trend, the opportunity cost adds no visible impact to the shape of these abatement curves, which do not behave as the theoretical total abatement cost curve (Figure 3).

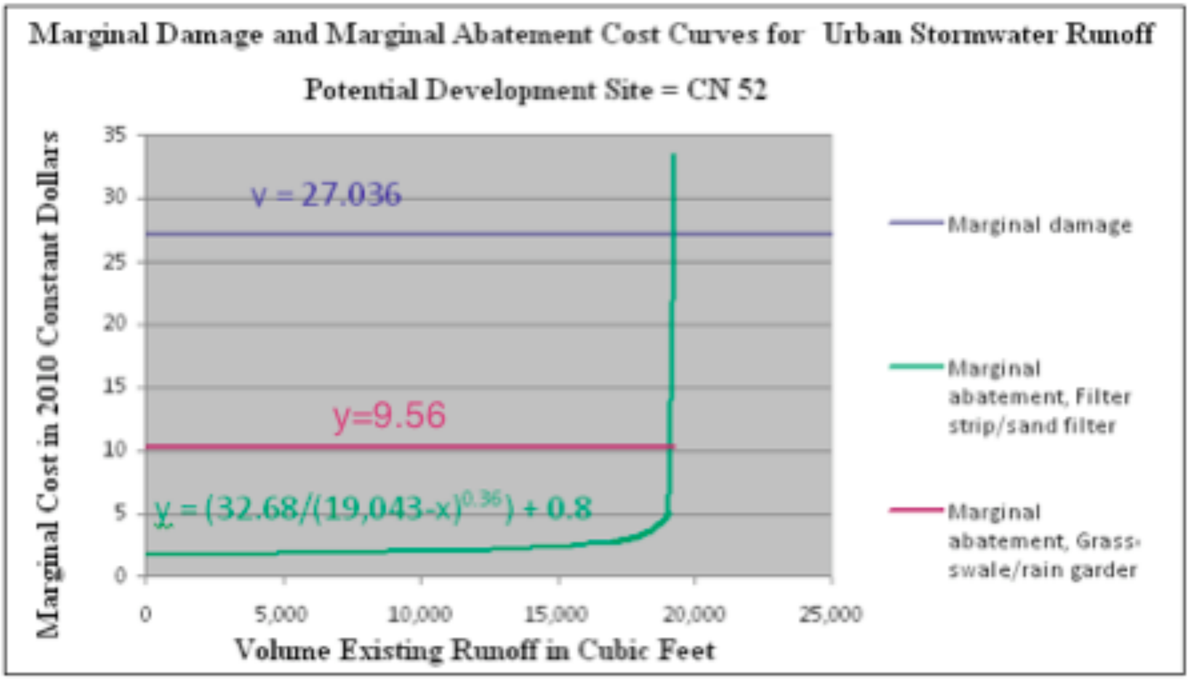

Figure 10. Empirical marginal damage cost curve and negated marginal abatement cost curves for urban stormwater runoff when the potential development site is in current conditions (CN 52).

Figure 10 shows the marginal damage cost curve and marginal abatement cost curves for urban stormwater runoff in the study area when the proposed development site is in current conditions (CN 52). The marginal curves are derived from the total cost curves shown in Figures 8 and 9. The equation for the marginal damage curves is a constant y=27.036 (See Appendix B). The marginal abatement curve for the filter strip/sand filter is $y = (32.68/(19{,}043-x)^{0.36}) + 0.8$ and the negated marginal abatement curve for the grassed swales/rain garden is y= 9.56 (See Appendix B). The marginal abatement cost curves are still read from right to left. Note that the marginal damage curve increases without bound but both marginal abatement cost curves have a cost of zero beyond an average annual runoff volume of 19,043 ft^3 as a volume of 19,043 ft^3 or greater indicates that no abatement is occurring.

In Figure 10 the marginal damage cost curve never intersects the marginal abatement cost curve for grassed swale/rain garden and the marginal damage cost for each additional unit of runoff is always larger than the marginal abatement cost using a grassed swale/rain garden to abate each additional unit of runoff. Additionally, this curve shows constant per unit cost but is not impacted by an opportunity cost effect. In this case the optimal volume of abatement is 19,043 ft^3, all runoff.

In the case of using filter strip/sand filter abatement technology, however, the marginal abatement cost curve intersects the marginal damage cost curve around the first unit of runoff that is being abated. Thereafter the abatement cost for filter strips/sand filters falls due to economies of scale and never increases as a result of increasing opportunity cost. Due to the absence of the opportunity cost effect in the abatement cost curve for filter strips/sand filters and the linearization of the marginal damage cost curve, the intersection of the marginal damage cost curve and marginal abatement cost curve for filter strips/sand filters is not indicative of the optimal runoff volume in the community as it is in the theoretical model (Figure 6). To abate less than one unit of runoff (moving to the right of the intersection point) is not efficient because it would cost the community more to abate than accept the damage cost. However, to abate more than one unit of runoff (moving to the left of the intersection point), cost savings can be achieved as the marginal cost of abatement continues to decline while the marginal damage cost remains the same. The most cost efficient situation, therefore, is to abate until there are zero units of excess runoff, where the distance between the marginal damage cost curve and the marginal abatement cost curve for the filter strip/sand filter is the greatest.

Optimal Model for Developed Condition

Therefore with the potential development site under the current conditions (CN 52), the marginal damage and abatement costs indicate that all runoff in the community should be abated. If the proposed development site is in fact developed to the point of reaching CN 94 as estimated, the total average annual volume of runoff will increase from 19,043 ft^3 to 3,491,185 ft^3. Since this is such a large increase in runoff volume, the theoretical model suggests that the marginal abatement cost curve might increase due to increasing opportunity cost of yard space at sufficiently large levels of abatement under this development scenario (Figure 5). However, the opportunity cost estimate from the hedonic model (Table 5) is insufficient to cause this expected behavior as shown in Figures 11 and 12 below. Figures 11 and 12 are simply Figures 9 and 10, respectively, adjusted to reflect an average annual runoff of 3,491,185 ft^3.

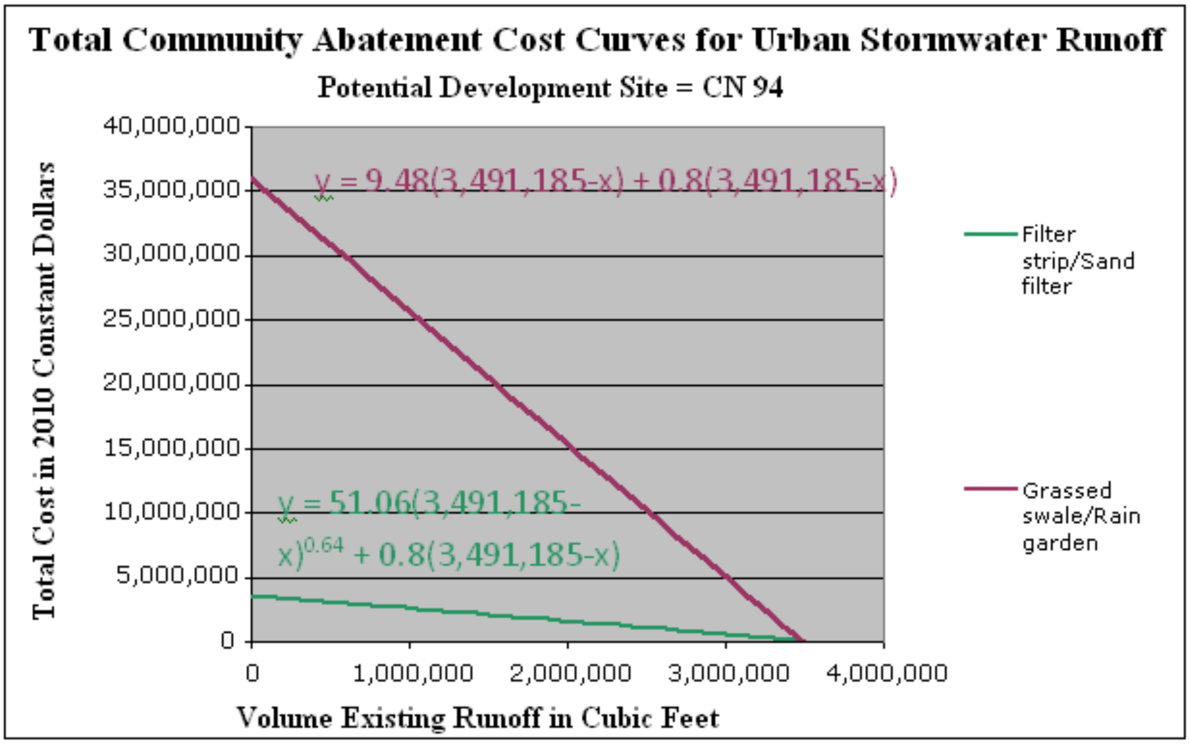

Figure 11. Empirical total community abatement cost curves for urban stormwater runoff when the potential development site is in the developed conditioned (CN 94).

Figure 11 shows the total community abatement cost curves for the filter strip/sand filter and grassed swales/rain garden technologies, assuming that the average annual runoff volume is 3,491,185 cubic feet, meaning that the potential development site has been developed to CN 94. Therefore, if the community is experiencing an average annual volume of runoff of 3,491,185 cubic feet (or greater), no abatement is occurring and the total community abatement cost is $0. If the community is experiencing zero average annual runoff, all of the runoff is being abated and the total community abatement cost is at its peak.

To get the equations to read right to left Q, the volume of runoff abated, must be defined as 3,491,185 -x, which is the total average annual runoff expected for the community less the volume of existing runoff . The equation for filter strips/sand filters is $y= 51.06(3,491,185 -x)^{0.64} + 0.8(3,491,185 -x)$ and the equation for grassed swales/rain gardens is $y=9.48(3,491,185 -x) + 0.8(3,491,185 -x)$. As with the total abatement cost curves for CN 52, with only a linear trend present, the opportunity cost adds no visible impact to the shape of these abatement curves, which do not behave as the theoretical total abatement cost curve (Figure 3). This lack of a sufficiently large opportunity cost at such large volumes of abatement, however, is not likely to be realistic and should have a greater effect on the accuracy of these curves than the CN 52 curves.

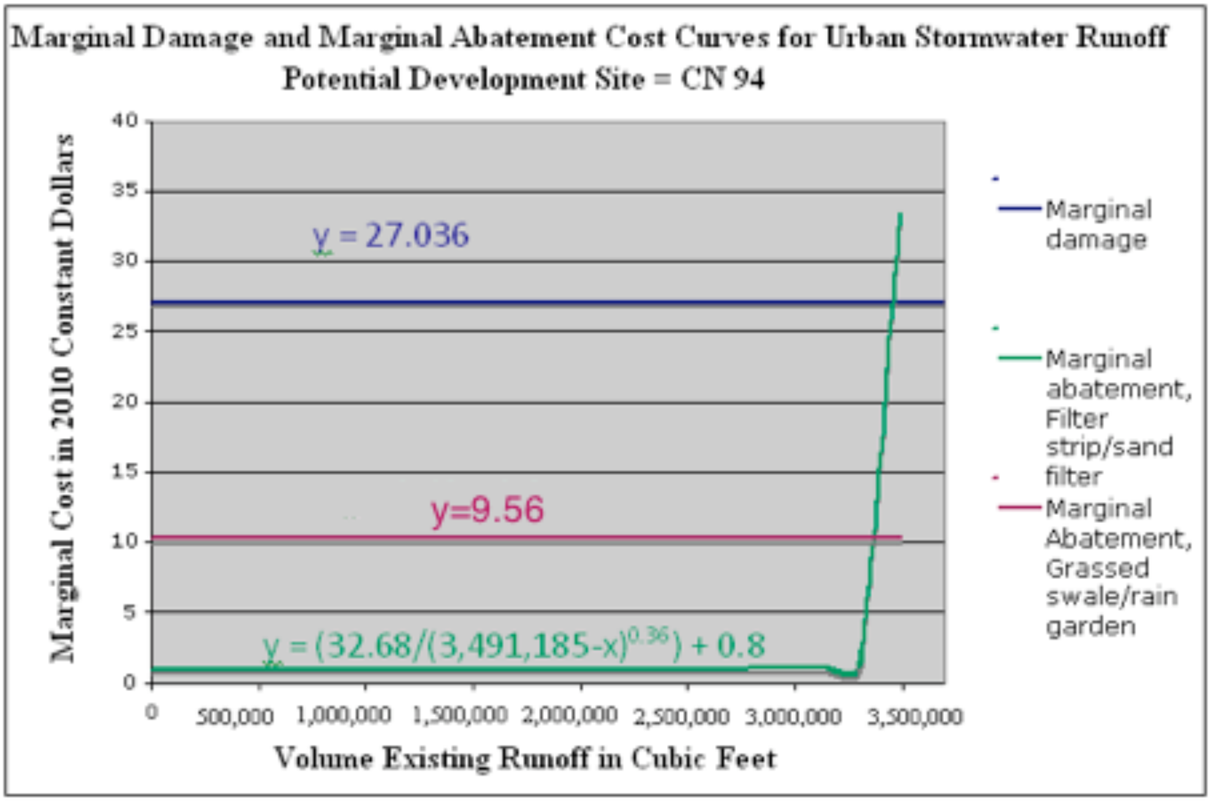

Figure 12. Empirical marginal damage cost curve and negated marginal abatement cost curves for urban stormwater runoff when the potential development site in the development condition (CN 94).

Figure 12 shows the marginal damage cost curve and marginal abatement cost curves for urban stormwater runoff in the study area when the potential development site is developed (CN 94). The marginal curves are derived from the total cost curves shown in Figures 8 and 11. The equation for the marginal damage curves is y=27.036 (See Appendix B). The negated marginal abatement curve for the filter strip/sand filter is $y= (32.68/(3{,}491{,}185-x)^{0.36}) + 0.8$ and the negated marginal abatement curve for the grassed swales/rain garden is y= 9.56 (See Appendix B). The marginal abatement cost curves are still read from right to left. Note that the marginal damage curve increases without bound, but both marginal abatement cost curves have a cost of zero beyond an average annual runoff volume of 3,491,185 ft^3 as a volume of 3,491,185 ft^3 or greater indicates that no abatement is occurring.

In Figure 12 (as in Figure 10) the marginal damage cost curve never intersects the marginal abatement cost curve for grassed swale/rain garden and the marginal damage cost for each additional unit of runoff is always larger than the marginal abatement cost using a grassed swale/rain garden to abate each additional unit of runoff. In this case the optimal volume of abatement is 3,491,185 ft^3 or all runoff.

Also, as in Figure 10, the marginal damage cost curve intersects the marginal abatement cost curve for filter strips/sand filters around the first unit of runoff that is being abated. Thereafter the abatement cost for filter strips/sand filters falls due to economies of scale and never increases as a result of opportunity cost. As with Figure 10, the point of intersection is not indicative of the optimal runoff volume in the community as it is in the theoretical model (Figure 6). To abate less than one unit of runoff (moving to the right of the intersection point) is not efficient because it would cost the community more to abate than accept the damage cost. However, to abate more than one unit of runoff (moving to the left of the intersection point), cost savings can be achieved as the marginal cost of abatement continues to decline while the marginal damage cost remains the same. The most cost efficient situation, therefore, is to abate until there are zero units of excess runoff, where the distance between the marginal damage cost curve and the marginal abatement cost curve for the filter strip/sand filter is the greatest.

Community Abatement Burden

Under these conclusions drawn from Figure 12, if potential development site were to be developed to the suggested level (CN 94), all runoff in the community should be abated. As previously stated, 3,491,185 ft^3 is an extremely large volume of runoff, especially compared to the 19,043 ft^3 of average annual runoff experienced by the community with the potential development site in its current conditions. To determine if this volume of runoff can be realistically and practically abated by only residential abatement technologies, the amount of yard space required for abatement use for each household is calculated in Table 6. Note that the calculations in Table 6 assume that the households participating in abatement are located downstream from the potential development site, that all households are abating equal volumes of runoff, and that the average homeowner has roughly 23,000 ft^3 of yard space (Table 4).

Table 6. Volumes of runoff that can be realistically and/or practically abated by strictly residential abatement downstream from the potential development site in the area of interest.

Yard Space Used per Household (%)	Abatement Area Required per Household (sqft)	Total Community Abatement Area (sqft)	Total Community Abatement Volume (cubic feet)	Maximum Development Scenario (CN)	Reasonable per Household Abatement Volume?
0.1	23	5,980	5,980	41	YES
0.5	115	29,900	29,900	53	YES
1	230	59,800	59,800	58	YES
5	1,150	299,000	299,000	73	MAYBE
10	2,300	598,000	598,000	79	MAYBE
60	13,800	3,588,000	3,588,000	94	NO
100	23,000	5,980,000	5,980,000	97	NO

The first column in Table 6 defines arbitrary percentages of yard space to be given up by each homeowner, which is multiplied by 23,000 ft^2 of yard space to obtain the abatement area required by each household in the second column. Multiplying the second column by 260 homes downstream from the potential development site gives the total area available to the community for abatement (Column 3). Since it is assumed that there is a 1:1 ratio between the size of a BMP in square feet and the volume of runoff abated by the BMP in cubic feet (Thurston 2006, 92), Column 4, which is the total volume of runoff that the community is able to abate for each specific household burden, is equal to Column 3. (See Appendix B for calculation of Columns 2-4). Using the estimated volumes of average annual runoff predicted for the area by the L-THIA model, the maximum level of runoff (indicted by the CN) that can realistically be handled by residential abatement, assuming all runoff is abated, is shown in Column 5. The last column in Table 6 indicates whether such volumes of runoff can be practically abated by strictly household abatement. The determination of the reasonableness of a particular abatement burden is a partially subjective judgment made using a scale picture of the size of each household's abatement burden compared with the size of the average homeowners yard space (Figure 13).

Figure 13. Scale model of an average sized residential property (indicated by the black outline) in the area of interest compared to various abatement burdens (indicated by the red and purple outlines and solid boxes) required by corresponding development scenarios.

Figure 13 is a scale model of an average sized residential property in the area of interest (Table 4) that was completed using ArcGIS 10 and information from the Monroe County Real Property database. The lot size is 24,200 ft^2 (shown by the black outline) with the living area defined as 2,313 ft^2, making the total yard area 21,887 ft^2. The red outline corresponds to the area each household downstream must devote to abatement if the potential development site were to be developed to CN 97. This is higher than the predicted CN 94 for the development project; however, if the development were to be more extensive than predicted, this level of abatement is obviously not reasonable, as each homeowner would need to give up nearly 100% of their property. Therefore, this is simply a case for illustration that if the development project ended up generating an average annual volume of runoff that corresponds to CN 97, strictly residential abatement of all runoff is certainly not reasonable.

The next case assumes that the potential development site is developed and now generates a volume of runoff corresponding to CN 94 as estimated. This average annual volume of runoff would require homeowners to devote a very large portion of their yard space for abatement as indicated by the purple outline. Since this abatement burden requires homeowners to devote most of their yard space to abatement, it is not reasonable to assume that homeowners would be willing to accept this burden, even for reasonable monetary compensation and therefore strictly residential abatement at this volume of runoff is not reasonable either.

The pink and blue solid boxes, which correspond to residential abatement if the potential development site were a 79 and 73, respectively, may also take up too much yard space to assume that a sufficient number of homeowners would participate in abatement even given reasonable monetary compensation. Although at these abatement burdens some environmentally concerned homeowners are likely to accept either or both of these size burdens, the size of these abatement burdens may still be too large for *most* homeowners to accept. Figure 13 shows that both of these boxes are larger than twice the size of the visible vehicle parked in the homeowner's driveway. However, because the opportunity cost of land is not known for this community, Table 6 indicates that these two abatement sizes (for CN 73 and 79) might be accepted by homeowners, especially in an environmentally conscious community like Brighton (Keef 2011).

Because the abatement burdens for development scenarios CN 58, 53 and 41 (the teal, green and yellow boxes, respectively) are relatively small compared to the average homeowner's yard size, it is reasonable to assume that abatement for average annual runoff volumes at these levels could be taken care of by strictly residential abatement measures. Therefore, the potential development site can exist at a development level of CN 58 if the community is to optimally abate urban stormwater runoff on a strictly residential level. This threshold could, however, increase if some of the abatement burden is extended to the developers of the potential development site.

DISCUSSION AND RECOMMENDATIONS

According to the results and conclusions drawn from Figures 10 and 12, the Brighton community should be abating all runoff, no matter the CN of the potential development site, as the marginal damage cost is almost always larger than the marginal abatement cost. Therefore, the community should currently be abating all runoff with the potential development site existing in its current conditions (CN 52). Development of this area would put an additional abatement burden on the community with the size of burden depending on the magnitude of the development. Table 6 shows that the abatement burden for current conditions (CN 52) can be both realistically and practically taken care of by strictly residential abatement downstream from the potential development site. This burden, however, can only be realistically and practically placed on the downstream residents to the point where the potential development site exists as CN 58. A CN 58 is still a very low CN and the potential development site would still have to exist basically entirely in its current state, This implies that development of the potential development site cannot be mitigated by strictly residential downstream abatement. As shown in Figure 13, the per household abatement burden when the potential development site exists as a CN 94 or 96 is certainly not reasonable.

In conclusion, the results of this study indicate that in order to optimally manage stormwater runoff in the Town of Brighton, watershed planners have three options: 1) preserve the potential development in its current state and ensure current abatement measures are sufficient, 2) allow development of the potential development site and require the developers to share a large portion of the abatement burden, or 3) allow the development of the potential development site and reduce the abatement burden by creating more green space downstream from the area. In the case where development is desired by the Town and could provide significant benefits to the town, the second two options must be considered. Since larger, more expensive abatement technologies such as porous pavement, infiltration basins, infiltration trenches, and detention and retention ponds have the capacity for greater pollutant removal than grassed swales/rain gardens and filter strips/sand filters, it may actually be beneficial to place a large portion of the abatement burden on the developers, which is the current practice in Brighton (Keef 2011). Additionally, in Brighton it may be difficult and costly to create a sufficiently large enough green space downstream from the development. Further studies revealing the benefits of the development and the cost to create additional green space downstream would help to clarify these issues.

Further studies would also help to confirm the validity of these results by accounting for a number of limitations of the empirical model. First of all, the model is limited by the assumption of linearity of the total community damage cost curve. It is expected that the total community damage cost curve should behave as the theoretical curve (Figure 3), in which the total community damage cost increases at an increasing rate as the volume of average annual runoff increases. Therefore, in the empirical model (Figure 8), the total community damage costs of runoff below 19,043 ft^3 is most likely overstated while the total community damage costs of runoff above 19,043 ft^3 is most likely understated. It is possible to generate a more accurate total community damage cost curve for urban stormwater runoff by running another hedonic price analysis using the assessed values of homes in the Allen Creek watershed that are located downstream from an area with a CN larger than 52, ideally an area with a CN of or close to 94. Additionally, the accuracy of both the marginal damage cost curves and marginal abatement cost curves would benefit from further consideration of water quality since the Town is required to mitigate both quantity and quality (Keef 2011).

A second issue with the empirical model is the limitation of the method used to estimate the opportunity cost of yard space devoted to a BMP. Although the "NETLOT" estimates are comparable to Thurston's (2006, 92) results, this method seemingly did not generate an accurate enough opportunity cost in this case or Thurston's (2006). In both cases the addition of the opportunity cost measure from the hedonic model to the abatement equations indicated that residents have an extremely low opportunity cost of yard space even when required to abate extremely large volumes of runoff. Figure 13 and Table 6 suggest that there would be a high opportunity cost for the residential abatement burden of at least 1,150 ft^3 of runoff. This cost, however, is not reflected in the total community abatement costs curves (Figures 9 and 11) and therefore the marginal abatement cost curves.

Using Table 6 and Figure 13, it can be assumed that the empirical abatement cost curves should behave similar to the theoretical abatement cost curves (Figures 3 and 5), in which sufficiently large abatement volumes have large costs to the community due to the opportunity cost of the land. Since the hedonic model appears to be unable to capture an accurate measure of the opportunity cost of yard space, a willingness to accept or contingent valuation study may be able generate more accurate results. Since these methods require input from community members, they certainly help watershed managers get a better idea of the capacity for residential abatement in the community.

The magnitude by which the limitations of the marginal damage cost and marginal abatement cost curve estimates affect the results of this study depends on the true opportunity cost of the yard space in the community. If the opportunity cost of yard space is correctly implied in Figure 13 and Table 6, the marginal abatement cost curve might begin to increase around at least the 300,000 ft^3 unit of runoff abated due to the opportunity cost effect, and the opportunity cost effect should come to dominate by at least 3,588,000 ft^3 unit of runoff abated.

While this is very uninformative because the opportunity cost can come to dominate anywhere between the 200,000 unit and 3,588,000 unit, a willingness to accept survey should help to reveal how quickly the opportunity cost increases and determine a more accurate intersection point of the marginal abatement cost curve and marginal damage cost curve. If the opportunity cost increases at a fast rate, the marginal abatement cost curve will intersect the marginal damage curve sooner than if the opportunity cost increases at a slower rate. In the developed case (CN 94), a more accurate marginal abatement cost curve is likely to intersect the marginal damage cost at a lower volume of runoff than the empirical curve (Figure 12), and abatement of all runoff in the community is likely an overestimate of the optimal volume of runoff abatement.

Despite any limitations of the study, however, the preliminary research and results can be useful in a number of ways to both the Town of Brighton and other communities that are looking to improve or implement a small-scale abatement program in their watershed. In a community like Brighton, where mostly larger scale abatement measures exist, this analysis could serve as a government tool for justifying the value of small, site-specific stormwater mitigation programs. Additionally, in a community like Brighton, where residents are relatively willing to participate in actions that support the greater good of the community and/or the environment, a reverse auction might be cost-effective manner for town officials to go about designing and implementing a small-scale residential abatement program.

Implementing a residential abatement program in the Town of Brighton would benefit the community by encouraging individual abatement efforts. First of all, this would help to educate community members on the issues of urban stormwater runoff and allow them to help take action. Secondly, the installation of BMPs like rain gardens around the town can provide aesthetic benefits to the community as a result of increased landscaping efforts. Finally, in implementing a small-scale residential abatement program in the Town of Brighton, there is potential to more equitably deliver the benefits of stormwater abatement efforts across the community in the long term. With dispersed BMPs throughout the watershed, stormwater runoff should be more evenly distributed throughout the community, as opposed to mostly downstream which occurs when abatement programs are mainly large-scale, centralized efforts. These benefits should also be considered by other communities looking to enhance stormwater mitigation efforts and use the results of this study as a guide for future management plans.

LITERATURE CITED

Amacher, Gregory S., and Hellerstein, Daniel. 1999. "The Error of Time Series Cross Section Hedonic Models with Sporadic Event Timing and Serial Correlation." *J App Econometr* 14(3):233-52.

Baumol, William J., and Oates, Wallace E. 1988. *The Theory of Environmental Policy*. Edition 2. Cambridge University Press.

Benke, Arthur C, and Wallace J. Bruce. 1997. "Trophic Basis of Production Among Riverine Caddisflies: Implications for Food Web Analysis." *Ecology* 78:1132–45.

Bhat, Mahadev, Fister, Renee K., and Lenhart, Suzanne. 1999. "An Optimal Control Model for the Surface Runoff Contamination of a Large River Basin. *Nat Resour Model* 12(2):175-95.

Booth, Derek B. 1991. "Urbanization and the Natural Drainage System-Impacts, Solutions, and Prognoses.' *Northwest Environ.* . 7:93-118.

Booth, Derek B, and Jackson C. Rhett. 1997. "Urbanization of Aquatic Systems--Degradation Thresholds, Stormwater Detection, and the Limits of Mitigation. *J Am Water Resour. Assoc* 33: 1077-90.

Collier, Kevin J. 1995. "Environmental Factors Affecting the Taxonomic Composition of Aquatic Macro-invertebrate Communities in Lowland Waterways of Northland, New Zealand. *N. Z. J Mar Freshw Res* 29:453–65.

Coon William F. 2008. "Hydrologic Evidence of Climate Change in Monroe County, New York." U.S. Geological Survey Scientific Investigations Report 2008-1199.

Dunne , Thomas, and Leopold, Luna B. 1978. *Water in Environmental Planning*. W. H. Freeman and Company: San Francisco.

Epp, Donald J., and Al-Ani K. S. 1979. "The Effect of Water Quality on Rural Nonfarm Residential Property Values." *Amer J Ag Econ.* 61: 529-34.

Federal Emergency Management Agency (FEMA). 2011. "Map Service Center." Accessed Oct. 17. http://msc.fema.gov/webapp/wcs/stores/servlet/FemaWelcomeView?storeId=10001&catalogId=10001&langId=-1.

Freddie Mac. 2011. "House Price Index (FMHPI) Data - Freddie Mac." Accessed April 22. http://www.freddiemac.com/finance/cmhpi/.

Heaney James P., Sample David, and Wright, Leonard. 2002. “Costs of Stormwater Control Systems.” EPA 600-R-02-021, U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Washington, DC.

Hogg, Ian D, and Norris, Richard H. 1991. “Effects of Runoff From Land Clearing and Urban Development on the Distribution and Abundance of Macroinvertebrates in Pool Areas of a River.” *Aust. J Mar Freshw. Res* 42: 507–18.

Kolstad, Charles D. 2000. *Environmental Economics*. Edition 2. Oxford University Press.

Keef, Tim, pers. comm., September 2010.

Keef, Tim, pers, comm, October 2011.

Laukkanen, M., Ekholm, P., Huhtala, A., Pitkänen, H., Kiirikki M., Rantanen, P., and Inkala, A. 2009. “Integrating Ecological and Economic Modeling of Eutrophication: Toward Optimal Solutions for Coastal Area Suffering from Sediment Release of Phosphorus.” *Ambio* 38(4):225-35.

Ma, Shan, and Swinton, Scott M. 2011. “Valuation of Ecosystem Services from Rural Landscapes Using Agricultural Land Prices.” *Ecol Econ* (In press)

Malpezzi, Stephen. 2002. “Hedonic Pricing Models: A Selective and Applied Review,” in Gibb, K. and O’Sullivan, A. (eds.), Housing Economics: Essays in Honor of Duncan Maclennan, Oxford: Blackwell.

Montgomery, W. David. 1972. “Markets in Licenses and Efficient Pollution Control Programs.” *J. Econ Theory* 5:395-418.

Ohio Environmental Education Fund (OEEF). 1997. Assessing the Impact of Land Use Change on Runoff, Recharge and Wetland Hydrology: A Practical Approach. Manual supported by the Ohio Environmental Educational Protection Agency.

Paul, Michael J., and Meyer, Judy L. 2001. “Streams in the Urban Landscape.” *Annu Rev Ecol Syst* 32: 333-65.

Parikh, Punam, Taylor, Michael A., Hoagland, Theresa, Thurston, Hale W., and Shuster, William. 2005. “Application of Market Mechanisms and Incentives to Reduce Stormwater Runoff: An Integrated Hydrologic, Economic and Legal Approach.” *Environ Sci Policy* 8:133-144.

Pedersen, E.R., and Perkins, M.A., 1986. “The Use of Benthic Macroinvertebrate Data for Evaluating Impacts of Urban Runoff.” *Hydrobiologia* 139:13–22.

Poor, P.Joan, Pessagno, Keri L., and Paul, Robert W. 2007. “Exploring the Hedonic Value of Ambient Water Quality: A Local Watershed-based Study. *Ecol Econ* 60(4):797-806.

Purdue. 2011. “L-THIA Detailed Input.” Accessed Oct. 17. https://engineering.purdue.edu/ mapserve/LTHIA7/lthia/detailed_input.htm.

Schueler Thomas R. 1987. Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs. Washington Metropolitan Water Resources Planning Board, Washington, DC

Thurston, Hale W., Goddard, Haynes C., Szlag, David, and Lemberg, Beth. 2003. “Controlling Stormwater Runoff with Tradable Allowances for Impervious Surfaces.” *J Water Resour Plan Manage.* 129(5): 409-18.

Thurston, Hale W., 2006. “Opportunity Costs of Residential Best Management Practices for Stormwater Runoff Control.” *J Water Resou. Plan and Manage* 132(2): 89-96.

Thruston, Hale W., Taylor, Michael A., Roy, Allison, Morrison, Matthew, and Shuster, William. 2008. “Applying a Reverse Auction to Reduce Stormwater Runoff.” *Ambio* 37(4): 326-7.

US Department of Agriculture. 1986. “Technical Release 55:Urban Hydrology for Small Watersheds.” Engineering Division, Soil and Conservation Service, Washington, DC.

U.S. Department of Labor: Bureau of Labor Statistics. 2011. “Consumer Price Index (CPI).” Accessed July 2. ftp://ftp.bls.gov/pub/special.requests/cpi/cpiai.txt.

Williamson, James M., Thurston, Hale W., and Heberling, Matthew T. 2008. “Valuing Acid Mine Drainage Remediation in West Virginia: A Hedonic Modeling Approach. *Ann Reg Sci* 42: 987-99.

APPENDIX A: GLOSSARY

Marginal cost (pg.5)-
The marginal cost is the additional cost in dollars for each additional unit of a good. In this study the marginal cost is the additional cost of each additional unit of average annual stormwater runoff abated. The dollar figure is determined using the modified total abatement cost functions from Thurston (2006).

Marginal damage (pg. 8)-
The marginal damage is the additional damage in dollars caused by each additional unit of a good. In this study the marginal damage is the additional cost of each additional unit of average annual stormwater runoff. The proxy for that dollar figure is the change in assessed property value corresponding to a change in average annual volume of stormwater runoff.

Privately optimal (pg, 5)-
The privately optimal condition occurs where the private marginal benefit is equal to the private marginal cost. Private benefit and cost applies only to those directly involved in a transaction. In this study those that engage in activities that produce excess runoff (ie-developers) derive benefits and costs of those activities. Without runoff regulations, developers may perceive the private marginal cost as zero.

Socially optimal (pg, 5)-
The socially optimal condition occurs where the social marginal benefit is equal to the social marginal cost, where the social marginal benefit is equal to the private marginal benefit plus the external marginal benefit and the social marginal cost is equal to the private marginal cost plus the external marginal cost. In this study those experiencing external costs and benefits are those not directly engaging in activities that produce excess runoff (ie-town residents). An example of an external cost is the impact in dollars of downstream flooding (on residential properties) that occurs as a result of upstream commercial development.

Price instruments (pg.6)-
A price instrument is a policy lever that relies upon altering the price of a good to achieve a policy objective. For example, a tax levied on volume of runoff discharged from a parcel of land may act to discourage runoff emission and encourage runoff abatement if the tax is high enough.

Quantity instruments (pg.6)-
A quantity instrument is a policy lever that relies upon altering the quantity of a good to achieve a policy objective. For example, a quota established for runoff volume controls the volume of runoff discharged from a parcel of land and acts to reduce runoff in the community.

Opportunity cost effect (pg.16-17)-
The opportunity cost is the cost of an activity measured by the next best alternative activity foregone. The opportunity cost effect in this study is reflected in the tendency of the marginal abatement cost curve to increase as residential runoff abatement increases. As homeowners devote more of their yard space to BMPs, they typically sense that they are paying an increasing

“cost” in terms of not being able to use that parcel of land for other purposes (ie-sandboxes, playgrounds, sheds, gardens, fish ponds, etc).

Economies of scale effect (pg.16)-
Economies of scale refers to a technological advantage that causes the per unit cost to fall as output increases. The economies of scale effect in this study is the tendency of the marginal abatement cost to decrease [over some range of abatement effort] as residential abatement of runoff increases. The filter strip/sand filter abatement technology displays an economies of scale effect in such a way that the per-unit cost of utilizing a filter strip/sand filter is highest if treating only one unit of stormwater runoff and falls uniformly as additional units are treated.

Diminishing marginal utility (pg.17)-
The total utility that people glean from most goods and services increases with units of consumption, but tends to increase at a diminishing rate. Economists refer to this phenomenon of gleaning additional utility at a diminishing rate as "diminishing marginal utility". In this study, we expect that while homeowner utility increases with square feet of living and outdoor area, that rate increases at a decreasing rate. Therefore, if we think about this concept in the reverse direction, we expect that if outdoor space is removed from general use for the purpose of managing stormwater runoff, homeowners will become increasingly concerned about losing the general purpose utility they glean from each additional square foot of land converted for that purpose.

Hedonic price analysis (pg.22)-
The hedonic method of analysis is based on the idea that all goods are bundles of characteristics. Some of the characteristics are easy to measure and some are not. A house is a classic unit of analysis in hedonic studies, as they have straightforward characteristics (e.g., number of bedrooms) but also difficult-to-measure characteristics (ambient air quality, water quality, and school district quality). A hedonic price analysis is a statistical method one can use to hold the value of straightforward characteristics constant in order to estimate the value of less-easy-to-measure characteristics. In this study the cost of urban runoff is measured by correlating average annual runoff volume to changes in assessed property values of homes located along Allen Creek.

Real sale price (pg.26)-
The real sale price is the sale price of a good adjusted for the change in prices as a result of time. For example, in this study the 2005-2010 assessed property values of the downstream homes are adjusted to remove the effect of movement in prices over the course of the five years.

APPENDIX B: CALCULATIONS

Pg. 29- One Percent Change in 19,043 ft^3 Runoff

19,043 ft^3 *1.01= 19,233.43 ft^3 ≈ 19,234 ft^3

Pg. 35-36-Interpation of Coefficients (Table 5)

“PITTS” e(12.21)*[(e(0.23)-1] = $51,923.52

“YRBUILT” e(12.21)* [e(0.002)-1] = $401.98

“GARAGE” e(12.21)*[(e(0.12)-1)] = $25,599.71

“FIRE” e(12.21)*[e(0.03)-1] = $6,114.87

“HALF” e(12.21)*[e(0.03)-1] = $6,114.87

“LIVING” e(12.21)*[e(-0.000004)-1] = $120.51

“LIVING2” e(12.21)*[e(-0.00000004)-1] = -0.008 ≈ -0.01

“LIVING” slope = $120.51 – 2(0.01*LIVING)

0 = $120.51 – 2(0.01*LIVING)

“LIVING” turning point = 6025.5 square feet

“LRO52FT3” e(12.21)*[e(-0.01)-1] = -$1997.86 ≈ -$2000.00

“NETLOT” e(12.21)*[e(0.000004)-1]= 0.80

“NETLOT2” e(12.21)*[e(-0.00000000002)-1] = 0

Pg. 36- Slope of Total Community Damage Cost Curve (Figure 8)

Point (0,0)
Point (19,234, 520,000)
Slope = Δy/Δx
Slope = (520,000-0)/(19,234-0)
Slope ≈ 27.036

Pg. 38 ‘NETLOT2” & “NETLOT” Coefficient Interpretation

“NETLOT2” e(12.21)*[(e-0.00000000002-1)] = 0

“NETLOT” e(12.21)*[(e0.000004-1)]= 0.80

Pg. 40- Marginal Damage & Marginal Abatement Cost Equations for CN 52 (Figure 10)

Total damage cost curve: $y = 27.036x$
Marginal damage cost curve: $dy/dx = 27.036$

Total abatement cost curve (filter strip/sand filter):
$y= 51.06(19{,}043 -x)^{0.64} + 0.8(19{,}043 -x)$
Negated marginal abatement cost curve (filter strip/sand filter):
$dy/dx= (32.68/(19{,}043-x)^{0.36})*(-1) + 0.8*(-1)$
$-dy/dx= (32.68/(19{,}043-x)^{0.36}) + 0.8$

Total abatement cost curve (grassed swales/rain garden):
$y=9.48(19{,}043 -x) + 0.8(19{,}043 -x)$
Negated marginal abatement cost curve (grassed swales/rain garden):
$dy/dx= 9.48*(-1)+ 0.8*(-1)$
$-dy/dx= 9.56$

Pg. 43- Marginal Damage & Marginal Abatement Cost Equations for CN 94 (Figure 12)

Total damage cost curve: $y = 27.036x$
Marginal damage cost curve: $dy/dx = 27.036$

Total abatement cost curve (filter strip/sand filter):
$y= 51.06(3{,}491{,}185 -x)^{0.64} + 0.8(3{,}491{,}185 -x)$
Negated marginal abatement cost curve (filter strip/sand filter):
$dy/dx= (32.68/(3{,}491{,}185 -x)^{0.36})*(-1) + 0.8*(-1)$
$-dy/dx= (32.68/(3{,}491{,}185-x)^{0.36}) + 0.8$

Total abatement cost curve (grassed swales/rain garden):
$y=9.48(3{,}491{,}185 -x) + 0.8(3{,}491{,}185 -x)$
Negated marginal abatement cost curve (grassed swales/rain garden):
$dy/dx= 9.48*(-1)+ 0.8*(-1)$
$-dy/dx= 9.56$

Pg. 43- Abatement Burden Calculations (Table 6)

<u>Column 2-Abatement area required per household</u>
$0.001*23{,}000\ ft^2 = 23\ ft^2$
$0.005*23{,}000\ ft^2 = 115\ ft^2$
$.01*23{,}000\ ft^2 = 230\ ft^2$
$.05*23{,}000\ ft^2 = 1{,}150\ ft^2$
$.10*23{,}000\ ft^2 = 2{,}300\ ft^2$
$.60*23{,}000\ ft^2 = 13{,}800\ ft^2$
$1*23{,}000\ ft^2 = 23{,}000\ ft^2$

Column 3-Total community abatement area

23 ft^2*260 homes = 5,980 ft^2
115 ft^2*260 homes = 29,900 ft^2
230 ft^2*260 homes = 59,800 ft^2
1,150 ft^2*260 homes = 299,000 ft^2
2,300 ft^2*260 homes = 598,000 ft^2
13,800 ft^2*260 homes = 3,588,000 ft^2
23,000 ft^2*260 homes = 5,980,000 ft^2

Column 4-Total community abatement volume

5,980 ft^2*(1 ft^3/1 ft^2) = 5,980 ft^3
29,900 ft^2*(1 ft^3/1 ft^2) = 29,900 ft^3
59,800 ft^2*(1 ft^3/1 ft^2) = 59,800 ft^3
299,000 ft^2*(1 ft^3/1 ft^2) = 299,000 ft^3
598,000 ft^2*(1 ft^3/1 ft^2) = 598,000 ft^3
3,588,000 ft^2*(1 ft^3/1 ft^2) = 3,588,000 ft^3
5,980,000 ft^2*(1 ft^3/1 ft^2) = 5,980,000 ft^3