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Modeling Effectiveness of Low Impact Development on Runoff Volume in the Tan Brook Watershed

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MODELING EFFECTIVENESS OF LOW IMPACT DEVELOPMENT ON RUNOFF VOLUME IN THE TAN BROOK WATERSHED

An Honors Thesis

Presented by

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ABSTRACT

Title: **Modeling effectiveness of low impact development on runoff volume in the Tan Brook watershed**

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The Tan Brook is a heavily channelized stream that runs through an urbanized watershed in Amherst, MA. It poses a stormwater management problem for the University of Massachusetts Amherst due to flooding of soccer fields and erosion of a drainage ditch. The purpose of this study was to estimate reductions in runoff volume to the Tan Brook based on the hypothetical implementation of permeable pavements in various combinations of parking lots, driveways, roadways, and sidewalks, which cover 26% of the watershed area. A spreadsheet model-based approach utilized the Watershed Treatment Model to estimate runoff volume. The percent imperviousness of various land uses was altered to model permeable pavements. Total replacement of parking lots, roadways, sidewalks, and driveways were found to reduce runoff by 18%, 15%, 12%, and 3%, respectively. Recommendations were made to begin replacing parking lots on the UMass Amherst campus and Town of Amherst property.

1. Introduction

1.1 Low Impact Development

Land use development in urban areas has negative impacts on stream hydrology with potentially severe consequences for stream biota and humans living in the watershed. For humans, altered hydrology can decrease water quality in streams and increase the risk of damaging floods (Paul and Meyer 2001). Decreased water quality and habitat destruction resulting from altered hydrology have negative impacts on natural stream biota, like plants, fish, microbes, and invertebrates (Paul and Meyer 2001). As a result of the potential impacts to humans and the environment, stormwater management practices are often employed to facilitate the removal of water from a "site" and concentrate it somewhere downstream with the specific intent of minimizing the impact to human populations and the environment. The focus of most stormwater management practices, however, is often on controlling peak discharge in receiving waters without addressing the problems of runoff volume due to impervious surfaces (Gilroy and McCuen 2009).

While stormwater systems are designed to deal with water once it enters the stormwater system, the root cause of altered hydrology from urbanization is generally from the impacts of impervious surfaces like roads, parking lots, sidewalks, driveways, roofs, and compacted soils. Impervious surfaces prevent water from infiltrating into the ground, causing it to run off the land and concentrate downstream. Water running over impervious surfaces collects quicker in drainage channels and streams than it would if it had moved through the ground, which results in high runoff volumes and pollutant loads in receiving waters (Williams and Wise 2006). High runoff volumes lead to higher and quicker peak stream flows, which cause channel incision, bank erosion, increased sediment transport, and reduced groundwater recharge, which lowers baseflow in streams (Paul and Meyer 2001, Brattebo and Booth 2003).

Low Impact Development (LID) is a land management and development method to manage stormwater with decentralized systems and technology that functions onsite rather than systems that transport and concentrate runoff at a downstream location (Ahiablame et al. 2012). The main goals of LID are reducing runoff peak and volume, recharging groundwater, protecting streams from erosion and pollution, and enhancing water quality (Ahiablame et al. 2012). LID accomplishes this by lengthening flow paths of water to increase runoff time in order to increase the natural infiltration of water. Longer residence time of water before entering streams promotes pollutant removal, which improves water quality (Chang 2010). Land development strategies that incorporate systems to promote infiltration across urban areas can promote a natural hydrologic response to precipitation events that is similar to pre-development conditions (Williams and Wise 2006). LID systems that promote infiltration should decrease the "flashiness" typical of urban streams that are characterized by shorter response times and higher peak flows in receiving waters than in undeveloped watersheds (Hood et al. 2007).

There are number of different technologies that can be called "LID". Bioretention ponds or rain gardens are depressional areas that are meant to collect, hold, and treat stormwater runoff (Ahiablame et al. 2012). Water captured in depressional areas can infiltrate into the soil and recharge groundwater while evapotranspiration can decrease the amount of water entering the stormwater system (Ahiablame et al. 2012). Bioretention ponds are also effective at reducing concentrations of metals and other harmful chemicals such as nitrogen, phosphorus, and petroleum hydrocarbons (Dietz 2007). Green roofs or vegetated roofs consist of thick soil with plants, grass, and trees on top of buildings, which absorb and hold onto precipitation that traditionally runs straight off of rooftops. Water is stored in the soil, and it is released back into the atmosphere through evapotranspiration by plants (Ahiablame et al. 2012). Green roofs can retain a range of 60%-70% of the water that falls on them; some studies, however, found that nitrogen and phosphorus were actually concentrated on greed roofs but possibly resulted from excessive fertilizer applications used on some plant systems (Dietz 2007). Cisterns or rain barrels are similar to green roofs and collect and hold precipitation running off rooftops. However, cistern water sits in a tank (of varying size), and infiltration happens slowly as residents us the water gradually for gardening, greenhouse watering, or other purposes. Cisterns can reduce up to 100% of rooftop runoff, but become less effective for large storms because of capacity limitations (Gilroy and McCuen 2009).

1.2 Permeable Pavements

The LID strategy I focused on in this study was permeable pavements. Permeable pavements have a surface with void spaces in order to allow infiltration of stormwater into the underlying soil (Brattebo and Booth 2003). Permeable surfaces overlay a series of supporting layers, most importantly a basecourse of porous media (e.g., gravel), through which stormwater flows and slowly enters the soil below. An underdrain may be installed when the subgrade soil is poor (Fassman and Blackbourn 2010). Permeable pavement systems have the potential to substantially reduce runoff volume compared to conventional asphalt and concrete, including systems installed over clayey subgrade soils (Fassman and Blackbourn 2010). Permeable pavements are designed to decrease peak runoff rates, reduce runoff quantity, and delay peak flows by promoting surface infiltration rates (Collins et al. 2008).

Permeable pavements have a number of different design options from two major categories. First, porous pavements are similar to traditional asphalt or concrete but are made without the very fine particles that plug up pore spaces through which water travels and allow for increased water infiltration (Dietz 2007). Second, block pavers (made from plastic or concrete) are installed in a grid or matrix of separated blocks with soil, sand, or gravel filling the spaces between blocks (Dietz 2007). The spaces between blocks provide a pathway for water to infiltrate into the soil (Dietz 2007). Individual plastic grid pavers are typically a plastic framework filled with crushed stone or soil, which makes the blocks pervious. Concrete pavers, however, are mostly impervious but provide spaces between different-shaped concrete blocks to allow infiltration to the soil (Dietz 2007). Block pavers can result in 72%-93% reduction in runoff compared to similar sized areas covered in asphalt (Dietz 2007).

The efficiency of permeable pavements for decreasing runoff depends on the type of pavement installed, the region of the world they operate in, rainfall in the study year, extent of surface usage, presence of an underdrain, and other factors. Depending on these factors, percent runoff reduction compared to conventional asphalt has been reported as 50%-93% (Ahiablame et al. 2012) and 98.2%-99.9% (Collins et al. 2008). A runoff coefficient (i.e., the fraction of total rainfall that appears as runoff) is another indicator for infiltration efficiency, with a value of 1.0 for surfaces that infiltrate no water. Permeable pavements have a runoff coefficient ranging from 0.005 to 0.2 or 0.4 (Dietz 2007, Fassman and Blackbourn 2010).

The effectiveness of permeable pavements also varies among storm conditions. They can be effective for every day storm events up to 10-year average recurrence interval storms and can even work on steep slopes over impermeable soils with frequent rainfall (Fassman and Blackbourn 2010). 100% infiltration can be achieved through an effective limit of less than 2 cm rainfall (Ahiablame et al. 2012). However, surface runoff is less than 2% for most permeable pavement types for storms of less than 5 cm (Collins et al. 2008). Commercially available

Grasspave, Gravelpave, Turfstone, and UNI Eco-Stone virtually infiltrate all precipitation, including moderate to intense storms (Brattebo and Booth 2003).

Some common concerns about installation of permeable pavements include clogging and winter performance. Clogging of permeable pavement void spaces can occur due to fine particle accumulation, which then traps larger particles and reduces infiltration (Bean et al. 2007). Clogging can be limited by regular maintenance, including vacuum sweeper or pressure washing (Dietz 2007). A proper base and installation will allow infiltration to occur through the winter, but reduced sanding and salting is needed to avoid clogging pores and introducing potential groundwater contamination (Dietz 2007).

1.3 Modeling of Low Impact Development

Choosing a method for modeling LID is difficult because of the variations in how different technologies impact hydrology. Many models range in complexity based on the ways in which they account for various technologies and planning efforts, but they are similar in the way that runoff from impervious areas is generated (Elliott and Trowsdale 2007). Other studies have tried to take a simpler approach by looking at the SCS Curve Number method, an empirical approach for calculating stormwater volumes with a single representative value based on the impacts of land use, soil type, vegetative cover, and moisture conditions (Damodaram et al. 2010). This modeling technique simply lowers the curve number of impervious surfaces by certain amounts, depending on effectiveness (Damodaram et al. 2010).

1.4 Purpose of the Study

The purpose of this study is to estimate reductions in runoff volume to the Tan Brook based on the hypothetical implementation of permeable pavements in various combinations of parking lots, driveways, roadways, and sidewalks. I hypothesized that introducing permeable pavements will substantially decrease runoff volume due to the considerable coverage of impervious surfaces in the watershed.

Permeable pavements were selected as focus type of LID in this study for a number of reasons. They are easily modeled in a spreadsheet-based watershed model by simply changing the percent imperviousness of current land uses. There is no need to account for volumes of storage such as with swales, bioretention ponds, or cisterns. They generally work well for numerous types of storm events and there is a lot of literature available on effectiveness. The available data on current roads, sidewalks, parking lots, and driveways simplifies the process for developing suggestions for locations of new pavements.

2. Methods

For this study, I took a model-based approach to estimate runoff reductions based on impervious surfaces. To do this, I used the Watershed Treatment Model, which is a spreadsheet tool used for modeling runoff volume in an urbanized watershed. I estimated changes in runoff volume by altering the percent imperviousness of various land uses input into the spreadsheet to model impervious pavements.

2.1 Study Area

The Tan Brook is a stream that runs through an urbanized watershed in Amherst, MA. It is heavily culverted and channelized underground, largely due to development of schools, businesses, and the University of Massachusetts (Lynch 2009). The Tan Brook watershed starts with its headwaters in eastern Amherst. This upper reach is mostly residential but it also flows through Wildwood elementary school, Amherst middle school, and Amherst Regional High school, each with large percentages of impervious surfaces and alterations to the brook through culverts or channelization (Figure 2). The middle reach runs from the end of the high school up to a drainage pipe at a southern UMass parking lot (Figure 2). The area surrounding this reach has numerous parking lots and roofs and minimal tree cover because it is composed of a business district and urbanized downtown. The lower reach is mostly piped underneath the UMass campus where it briefly “daylights” in the campus pond before being piped off to a steep, sloped channel that leads to the Mill River just off the western side of the UMass campus. During storm events, some of the water is diverted through an overflow pipe before it reaches the campus pond. Water from the overflow pipe then floods onto a drainage swale along the practice fields near the Mullins Center (Figure 2). The area surrounding this lower reach also has high levels of impervious surface, a lack of trees, and high vehicle, bus, and pedestrian traffic.

The Tan Brook poses a stormwater management problem for the University. Normally, the stream daylights in the campus pond before being piped off to a steep-sloped channel that leads to the Mill River just off the western side of the UMass campus (Figure 2). However, the inflow culvert south of the Visitor Center parking lot diverts surplus water during large storm flows into a separate overflow pipe, which leads to a drainage ditch at the south end of the practice fields along Massachusetts Avenue (Figure 2). This ditch drains into a stream and is causing considerable amounts of erosion, which likely results in high sediment loads being transferred to the Mill River. Water from the overflow pipe also tends to flood onto the practice fields, which causes problems for UMass students.

2.2 Watershed Treatment Model

The Watershed Treatment Model is a simple spreadsheet developed by the Center for Watershed Protection to provide planners a method for estimating annual pollutant loads and runoff volumes (Caraco 2010). The model provides options for accounting for future management practices, stream restoration, and future land use/development (Caraco 2010). This study focused on calculating annual runoff volume. This spreadsheet model works by inputting various data (Table 1) on land use, annual rainfall, soils, depth to groundwater, percent impervious and turf surfaces, drainage area for existing management practices, and riparian buffer widths into defined cells (Table 2) within the spreadsheet. The model sums total annual runoff and subtracts out the runoff reduction due to existing management practices (See appendix for model details).

Table 1. Summary of data sources including the type of data, where it came from, and a short description.

Dataset Type	Organization	Description
Land Use 2005	MassGIS	0.5m resolution land cover/land use for the state of Massachusetts
Soil Hydrologic Grouping	Soil Survey Geographic Database (SSURGO)	Spatial extent of soils connected to tabular data for hydrologic grouping (A, B, C, or D)
Roads, parking lots, sidewalks, driveways	UMass Campus Planning	Polygon shapefile used for mapping impervious surfaces
Drainage network – Town of Amherst	Town of Amherst	Outfalls, culverts, and drainage pipes
Drainage network – Umass Amherst campus	Tighe and Bond – UMass Campus Planning	Outfalls, culverts, and drainage pipes
Annual Rainfall	National Oceanic and Atmospheric Administration	Daily data was averaged over 2008-2012 for yearly precipitation in Amherst, MA
Hydrography	UMass Campus Planning	Stream lines and water body polygons
Digital Elevation Model	United States Geological Survey	1/3 arc second (~10m) resolution Digital Elevation dataset
Orthophotos used for reference	United States Geological Survey	Color Ortho Imagery taken in 2009

Table 2. Inputs to the model and a description of how that data is used in the model.

Data Type	Use in Model
Land Use within the watershed (acres)	Used to breakdown land areas by different percentages of impervious surface and turf coverage
Annual Rainfall (inches)	Used to calculated runoff volume
Soils (Fraction of total area)	Used to determine infiltration rates and volume of runoff
Depth to Groundwater	Used to determine infiltration rates and volume of runoff
Percent impervious area for each land use type	Used to determine volume of runoff
Percent turf area for each land use type	Used to determine volume of runoff
Drainage area for dry swales and bioretention ponds	Used to determine reductions in runoff volume
Riparian buffer length and width	Used to determine reductions in runoff volume

2.3 Watershed Delineation

Watershed boundaries were delineated using ArcMAP version 10.1 (ESRI, Redlands, CA) from a 10m resolution digital elevation model. The Tan Brook watershed is a rather complicated system because so much of it is piped underground. There is a series of drainage pipes that convey water from one catchment over a drainage divide into another watershed. For this study, the two catchments identified from digital elevation models were combined to reflect the real boundaries of the Tan Brook watershed. As a result, the Tan Brook seems to split into two stream paths which both end up in the Mill River which eventually feeds the Connecticut River (Figure 2). The DEM-based watershed edge was modified based on the drainage map of the Town of Amherst and UMass Amherst campus so as to reflect the true catchment area and transport of water underneath the urbanized areas. Figure 1 shows the initial DEM-delineated watersheds with underlying drainage systems, while Figure 2 shows the final Tan Brook watershed and its above- and below-ground pathways.

2.4 Spreadsheet Model Inputs

Land use acreage is the primary input variable for the Watershed Treatment Model. A land use layer from the state of Massachusetts (mass.gov) including 22 classes of land use was used for the analysis. The Watershed Treatment Model only allows the input of 11 land use types. Thus, all 22 original land uses were combined into the various categories used by the model according to Table 3. The model does allow for sub-categories of land use for more specific analyses. Since the focus of this study was on permeable pavements, the general "Roadway" land use category in the spreadsheet was expanded to include roadways, parking lots, sidewalks, and driveways.

The percent imperviousness for each land use type was calculated by combining all of the available impervious layers (building footprints, sidewalks, roadways, driveways, parking lots) and then intersecting them with the land use layer using ArcGIS. The intersection of these two layers was used to determine how much impervious surface existed within the total acreage of that land use type. The acreage of impervious cover divided by the total acreage of the land use type was the value used for the percent imperviousness for each land use type. The percent turf cover for each land use type was determined by subtracting the impervious layer from the land use area and dividing the remaining area by the total acreage for that land use type.

Table 3. List of land use types and how they were aggregated for use in the model.

Land Use Type	Spreadsheet Model Category
Low Density Residential	Low Density Residential
Medium Density Residential	Medium Density Residential
High Density Residential	High Density Residential
Multi-Family Residential	Multi-Family Residential
Forest	Forest
Transitional	
Forested Wetland	
Brushland/Successional	
Industrial	Industrial
Waste Disposal	
Powerline/Utility	
Participation Recreation	Commercial
Spectator Recreation	
Commercial	
Driveway	Driveway
Sidewalk	Sidewalk
Parking Lot	Parking Lot
Transportation	Roadway
Pasture	Rural
Open Land	
Cemetery	
Very Low Density Residential	
Urban Public/Institutional	Urban Public
Non-Forested Wetland	Open Water
Water	

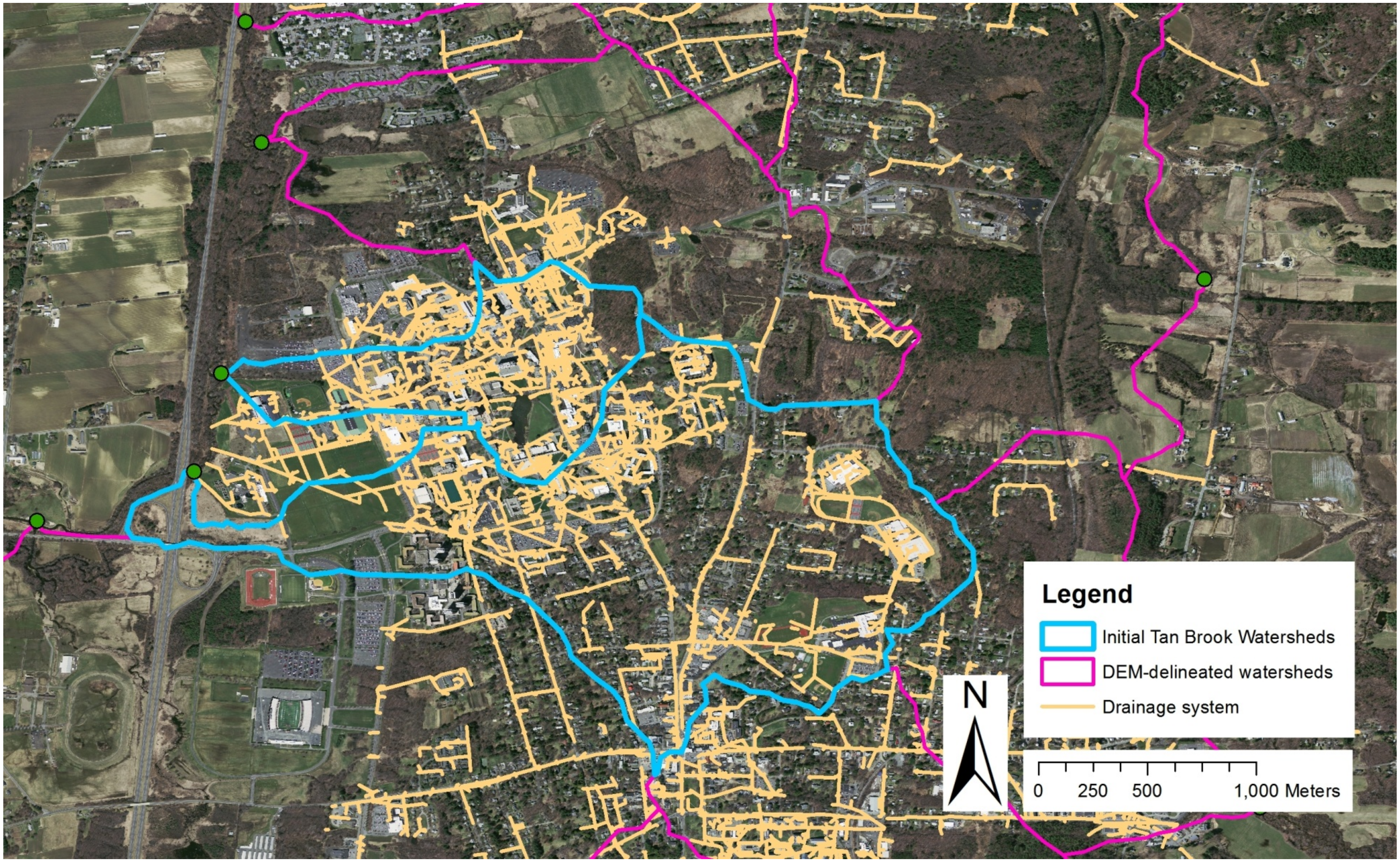

Figure 1. Watersheds were delineated using a Digital Elevation Model. The two connected Tan Brook watersheds are outlined in blue, with a drainage map underneath to show that the DEM-based watersheds do not represent an accurate watershed boundary.

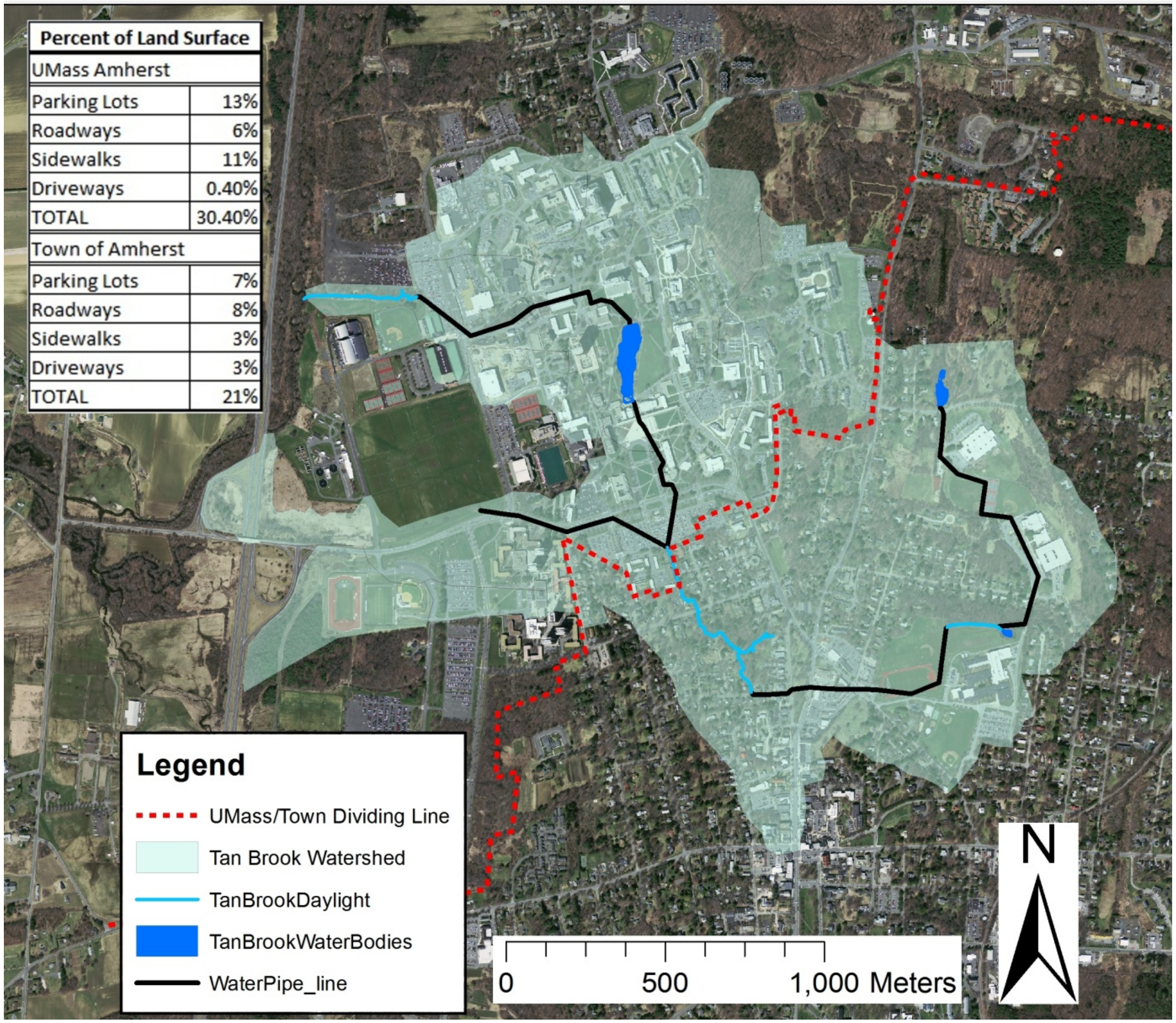

Figure 2. The final Tan Brook watershed takes into account subsurface drainage systems (not pictured, but can be viewed in Figure 1). The Tan Brook is largely piped underground and only daylights in a few streams and ponds. The table in the top-left corner summarizes the percentage of land covered by various impervious surfaces for UMass property and Town of Amherst property in the watershed.

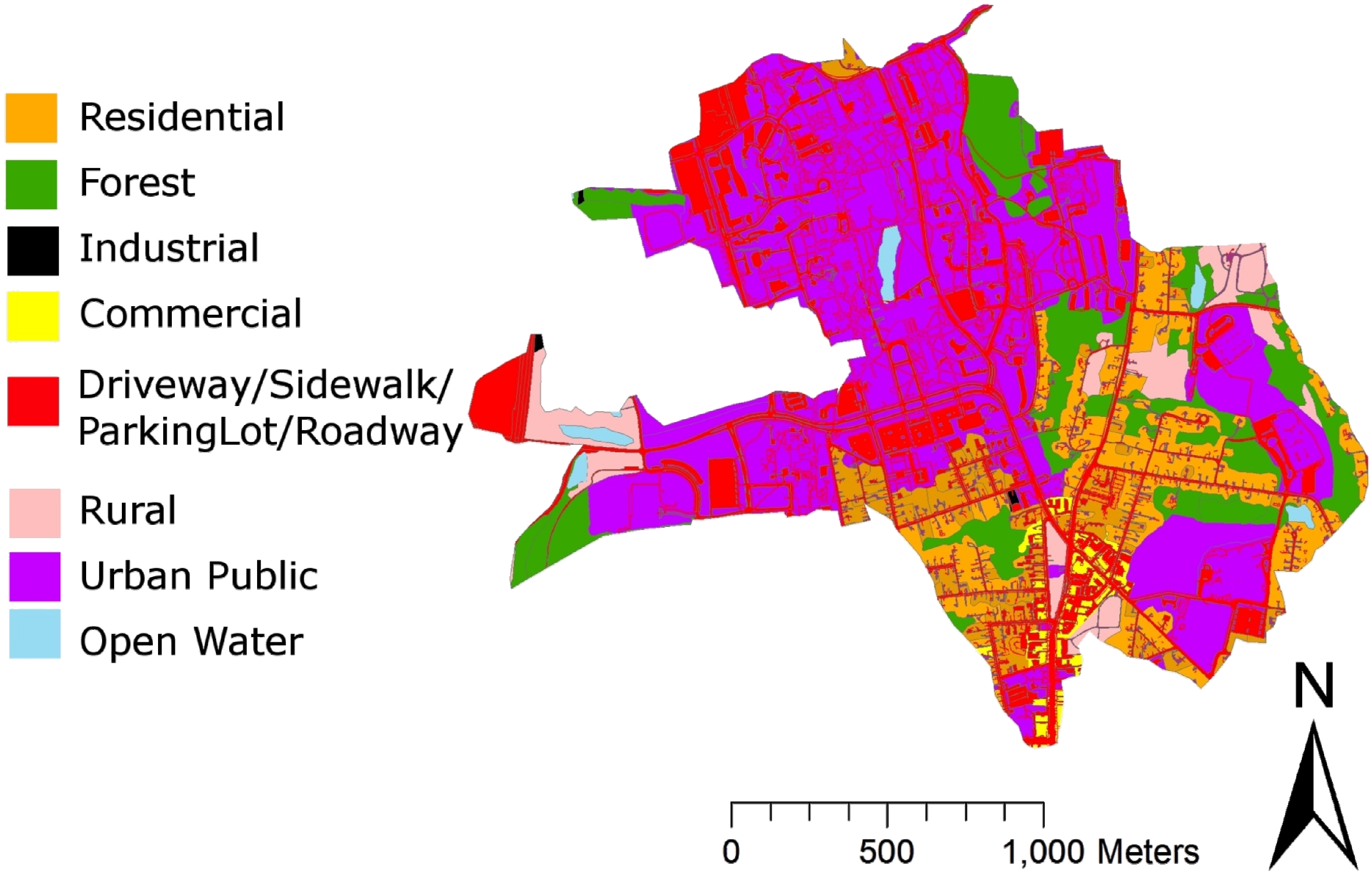

Figure 3. These land use categories were input into the Watershed Treatment Model. Note that the four residential land use types and transportation land use types (Table 3) were combined into single respective colors for easier viewing in this figure.

Very few existing management practices were in place in the Tan Brook watershed which have an impact on runoff reduction. However, a bioretention pond and various dry swales were included with a small catchment area which had the effect of reducing runoff volume by about 0.06%. Additionally, small stretches of riparian buffers (ranging from 45-125 feet) along daylighted portion of the stream were added to the Riparian Buffers section of the Existing Management Practices worksheet in the model. These had the effect of 0.33% reduction in total runoff volume. Additional known management practices like wet ponds, wet swales, and wetlands were not included because the spreadsheet model assigns them a value of 0% for runoff reduction efficiency (i.e., they are only useful for water quality modeling).

Annual rainfall was calculated by taking annual sums of daily precipitation data collected in Amherst, MA for 2008-2012 (NOAA.gov) and then taking an average of the five years. This value was used as an estimation of the annual precipitation distributed over the watershed.

2.5 Spreadsheet Manipulation

The focus of this study was to determine the magnitude of runoff volume reduction based on implementing permeable pavements in parking lots, sidewalks, driveways, and roadways. A value of 98% imperviousness was assigned to all impermeable study surfaces, with a value of 3% imperviousness for the introduction of one of the various permeable pavement technologies (USDOA 1986, USEPA 2010, and Dietz 2007). The relationship between percent imperviousness and runoff volume is linear in this model (see Appendix), so only the endpoints needed to be tested.

Runoff volume was monitored based on two types of changes. First, individual types of surfaces (parking lots, roadways, sidewalks, and driveways) were compared by increasing the percent permeability of each surface type originally described as impervious pavements. Second, the cumulative effect of all surfaces together was modeled by increasing the cumulative area of installed permeable pavements. Theoretically, roadways would be replaced with porous asphalt, sidewalks with porous concrete, and parking lots and driveways with concrete or plastic grid pavers. However, for both modeling situations, there was no distinction between the different permeable pavement technologies because their values are all contained within the same range of effectiveness (i.e., all surfaces could theoretically reach the same maximum level of permeability with different technologies).

3. Results

Figure 4 shows reduction in annual runoff volume (given in percent of total) against a gradient of imperviousness of permeable pavements installed in various locations. The data points on the graph represent different particle sizes commonly used in permeable asphalt (Table 6) but does not apply to interlocking concrete pavers. The connecting line for each surface is based on the equations from the Appendix and applies to the change in the percent imperviousness of all types of permeable pavements, not just permeable asphalt. The slopes of the lines correspond to the acreage of each pavement type (i.e., a larger area of pavement type means a steeper reduction in runoff). Parking lots, with the most acreage, show the greatest decrease in runoff. Assuming a complete changeover of 98% imperviousness to 3% imperviousness, parking lots, roadways, sidewalks, and driveways were found to reduce runoff by 18%, 15%, 12%, and 3%, respectively. The equations used to model runoff for each surface depend only on acreage of each pavement type since each permeable pavement technology was assumed to fall in the same range of maximum effectiveness.

Table 6. Grain sizes of asphalt and their percent imperviousness (US EPA 2010)

Particle Size	% Imperviousness
3/8 in	5
#4	65
#8	85
#16	90
#30	98

Figure 5 shows a reduction in annual runoff volume (given in percent of total) against the total cumulative acres of all installed permeable pavements within the Tan Brook. Despite different theoretical installed permeable pavement technologies, each pavement type was modeled with the same assumed 3% imperviousness. Therefore, this graph shows how permeable pavements installed on different combinations of pavement locations can have cumulative effects on annual runoff volume reduction. At 100% total runoff, no permeable pavements have been installed. With replacement of all 220 acres of parking lots, roadways, sidewalks, and driveways, runoff has been reduced to 52% of its original value.

Figure 5 also shows two separate cost scenarios which differ only between the types of pavement technologies used for parking lots. In cost scenario 1, interlocking concrete pavers are used, while in cost scenario 2, porous asphalt is used. Interlocking concrete pavers cost an average of $326,700/acre while porous asphalt costs an average $32,670/acre (University of Maryland Extension). Porous concrete, used for sidewalks, cost an average $185,130/acre (University of Maryland Extension).

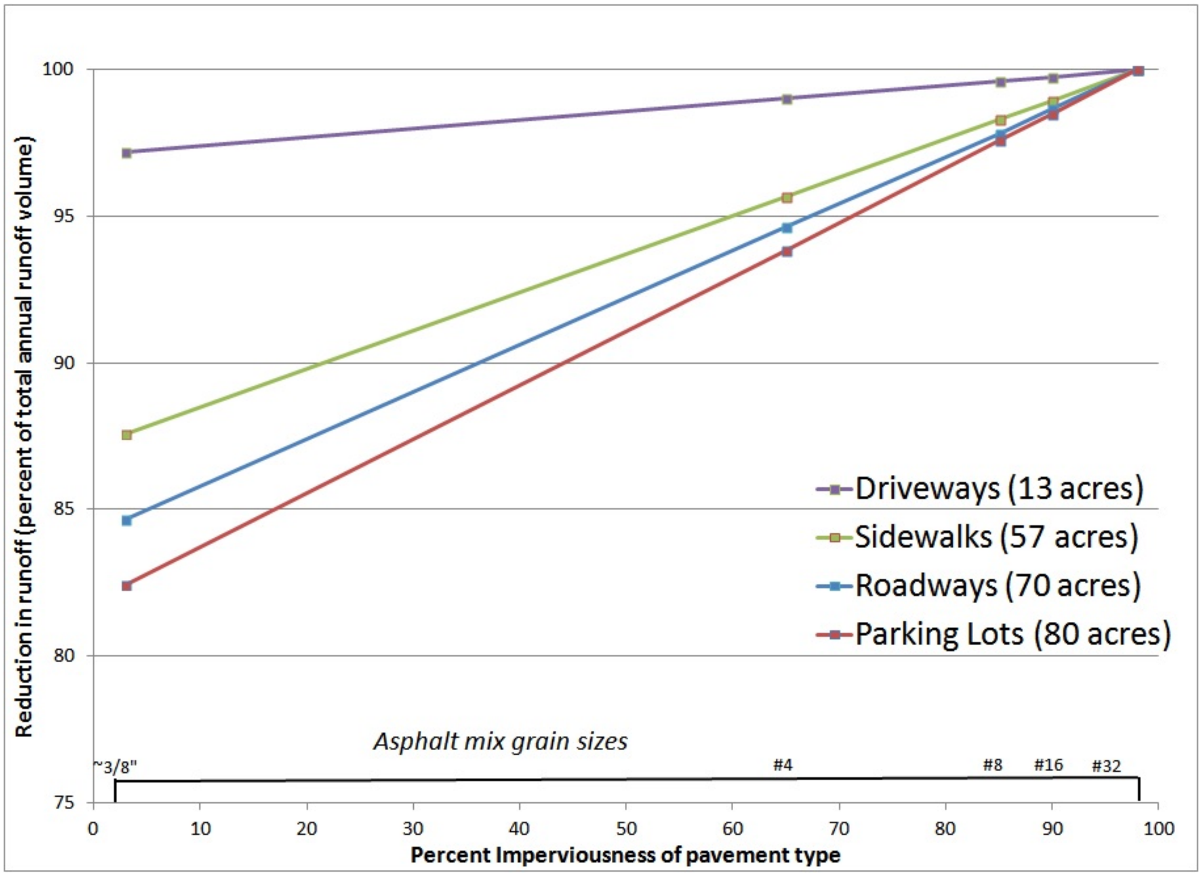

Figure 4. Total runoff (given in percent of total) decreases as the percent imperviousness of each permeable pavement type decreases. Note that the points along the lines represent different particle sizes commonly used in permeable asphalt (Table 6). The connecting lines are based on the equations from the Appendix and the slopes vary only based acreage of each pavement type

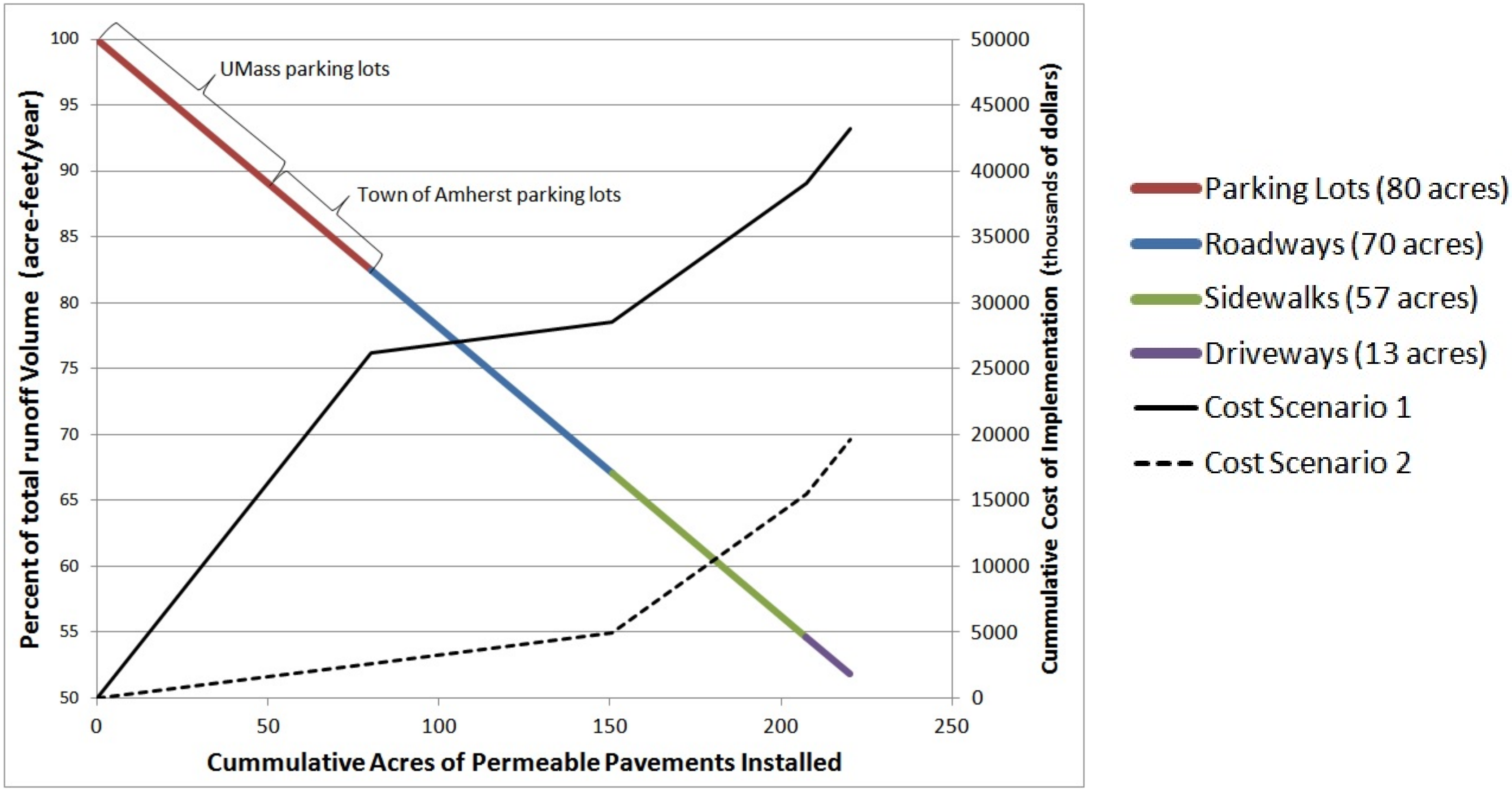

Figure 5. Total runoff (given as percent of total) decreases as the cumulative area of installed permeable pavements increases. At 100% total runoff, no permeable pavements have been installed. With replacement of all 220 acres of parking lots, roadways, sidewalks, and driveways, runoff has been reduced to 52% of its original value. UMass and TOA parking lots are marked.

Cost Scenario 1: Concrete pavers for parking lots and driveways, porous asphalt for roadways, and porous concrete for sidewalks.

Cost Scenario 2: Porous Asphalt for parking lots and roadways, concrete pavers for driveways, and porous concrete for sidewalks.

4. Discussion

The results of this study show that installation of permeable pavements could substantially decrease annual runoff volume within the Tan Brook watershed. The Watershed Treatment Model shows that changing the percentage of impervious surfaces or the area of impervious land can decrease annual runoff volume. Parking lots, roadways, sidewalks, and driveways were found to reduce runoff by 18%, 15%, 12%, and 3%, respectively. In total, these land uses cover 26% of the land surface in the watershed, yet account for a total of 52% of the annual runoff volume.

Parking lots are the most widespread impervious surface in the watershed at 80 acres, or 9.45% of the watershed area. They account for 13% of the UMass-owned land and 7% of the Town of Amherst land in the watershed. The model suggests that replacement of all parking lots could reduce runoff by 18%, with UMass parking lots accounting for 12% of watershed runoff and Town of Amherst parking lots accounting for the remaining 6%. Parking lots are usually built with conventional asphalt, but they experience less constant traffic than roads. Thus, parking lots are less prone to wear and require less frequent resurfacing than roads. Parking lot plots cover large surface areas in one place and are likely easier to replace section by section than roads.

Replacement of all UMass parking lots with interlocking pavers would cost roughly $17,000,000 and porous asphalt would cost roughly $1,700,000. While porous asphalt usually lasts 15-20 years, interlocking pavers can last 20-30 years (University of Maryland Extension). UMass Amherst's operations and maintenance budget for fiscal year 2012 was $89 million (University of Massachusetts), with $31.9 million spent by the Physical Plant (University of Massachusetts Amherst) which is responsible for maintenance, repairs, and upgrades to pavements. This implementation seems feasible, but does not take into account logistical costs, such as planning, engineering, traffic control, etc.

Replacement of all Town of Amherst parking lots with interlocking pavers would cost roughly $1,700,000 while porous asphalt would cost roughly $900,000. On Town property, however, roadways cover a slightly larger area of 8.4% compared to parking lots at 7.2%. Replacement of all Town of Amherst roads with porous asphalt would cost roughly $1 million. Amherst's projected fiscal year 2014 spending includes $674,000 for general road maintenance, repair, and improvements (Town of Amherst 2013). Between fiscal years 2016 and 2017, there is $508,000 budgeted for repaving and resurfacing of parking lots at four particular municipal buildings (Town of Amherst 2013). Replacement of half of Town of Amherst roads or parking lots is feasible, but again does not include logistical costs.

Figure 6 shows the spatial distribution of all parking lots in the watershed. There are especially dense concentrations of parking lots located on the east and south edges of the Tan Brook pipe pathway as well as the region around the overflow pipe connection where the pipe splits into two. These parking lots are located at Amherst Middle School, the shops around Kendrick Park, and the UMass Robsham Visitor's Center. A first step towards reducing runoff volume to the Tan Brook would be to replace the parking lots at these sites which are closest to and most dense around the Tan Brook and its stormwater system inputs.

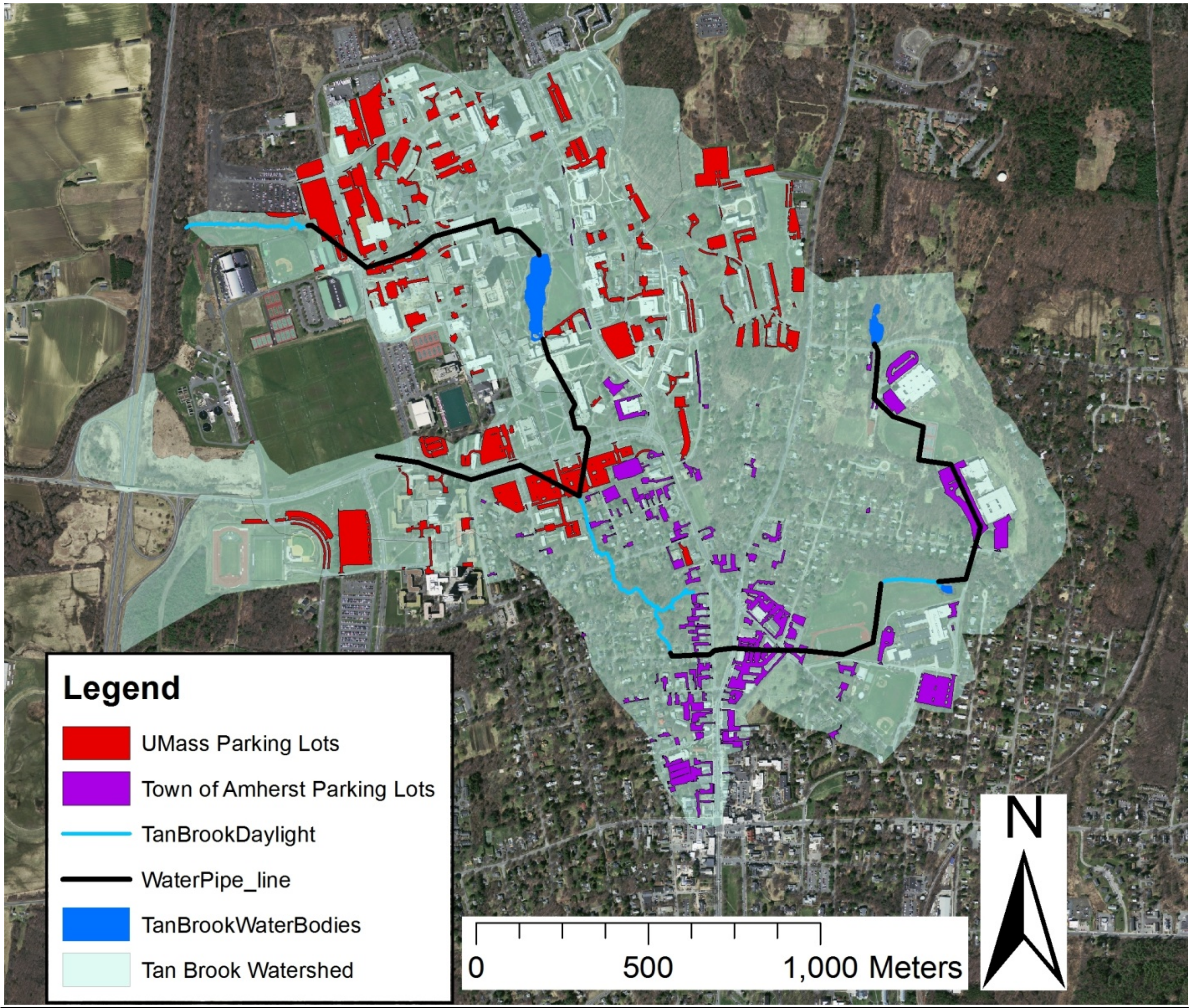

Figure 6. Parking lots on UMass and Town of Amherst property are highlighted within the Tan Brook watershed. Note that there are many parking lots concentrated around several sections of the Tan Brook underground piping.

While roadways provide a watershed-wide 15% reduction in runoff, they are more difficult to replace and experience higher daily use. Ongoing maintenance such as pressure washing, vacuuming, and eventually replacement would happen more frequently and could be costly. Sidewalk replacement could reduce runoff by 12%, but sidewalks are more distributed in thin strips over a large area, rather than larger area parking lots. This makes maintenance and installation more difficult. Driveway replacement could reduce runoff by 3%, but offers more challenges when dealing with homeowners on private property. Additionally, determining if driveways drain to stormwater systems and the Tan Brook or simply infiltrate on their own in residential lawns is difficult to discern with GIS data.

The spreadsheet approach has a number of limitations. The spreadsheet method does not take into account the spatial location of different land use types and impervious surfaces. Thus, the output cannot take into account the proximity of particular influencing land use types to the stream location. The Tan Brook is also heavily culverted, and much of the stream is piped underground. The spreadsheet modeling approach is based on a simpler above ground stream network which does not take into account the conveyance of water through storm management systems. It may overestimate runoff volumes if there are small storm system catchments that divert water either outside of the watershed or to locations far from the stream channel where it can infiltrate. Third, the spreadsheet incorporates numerous assumptions that must be kept in mind when interpreting results. The assumptions include: 1) scaled discounts (based on legal infrastructure, regulations, design, and capture area), 2) estimations of impervious and turf cover based on land use type if not input specifically by the user, and 3) estimated runoff coefficients based on land use and soil type combinations.

Future extensions of this work exist in a number of different directions. This study did not make use of the water quality options in the spreadsheet model. The user can input additional information about secondary sources of pollution and other management practices to output estimations of nitrogen, phosphorus, and other pollutant loads. This would provide a more in-depth look at the effects of different management practices. Future efforts could also model different types of LID technologies, such as rain barrels, green roofs, bioretention ponds, or swales in addition to pervious surfaces. Other modeling techniques are available for the response of runoff to low impact development (e.g., WinSLAMM, SWMM, HEC-HMS, Basins, AGWA) and the use of these models may help to answer different questions about the effectiveness of pervious surfaces for reducing runoff. These modeling infrastructures allow for spatial and temporal processes, and some account for stormwater infrastructure, which could provide a more accurate measure of water quality and quantity.

Appendix

Equations used by the model:

(1) Runoff for Urban Land Usages (inches per year) = (Annual rainfall, inches) * 0.9 * [*Impervious Surface Runoff Coefficient* * (% Impervious cover) + (*Turf surface runoff coefficient*) * (% Turf cover) + (*Forest surface runoff coefficient*) * (1 - %Turf - %Impervious)]

…where the impervious, turf, and forest runoff coefficients are calculated as a SUMPRODUCT function of the percentage of each soil type in the watershed and some pre-determined variables.

(2) Runoff for Forest Land Usages (inches per year) = (Annual rainfall, inches) * 0.9 * [(% A-type Soil) * HLOOKUP value + (% B-type Soil) * HLOOKUP value + (% C-type Soil) * HLOOKUP value + (% D-type Soil) * HLOOKUP value]

…where HLOOKUP values provide the total expected natural runoff area from a particular forested soil surface.

(3) Load reduction from Existing Management Practices (Structural Stormwater Practices) = Weighted Runoff Reduction % * (Annual runoff volume in acre-feet) * (Fraction of watershed area treated by the practices) * (Maintenance discount) * (Capture discount) * (Design discount)

…where "Weighted Runoff Reduction %" is calculated as a function of soil type and the various discounts reduce the effectiveness of existing management practices based on age, maintenance, legal regulations, etc.

(4) Load reduction from Existing Management Practices (Riparian Buffers) = Weighted Runoff Reduction % * (Annual runoff volume in acre-feet) *(Treatability) * (Maintenance discount) * (Capture discount) * (Design discount)

…where "Weighted Runoff Reduction %" is calculated as a function of soil type, Treatability is the fraction of runoff-producing area captured by riparian buffers, and the various discounts reduce the effectiveness the buffer based on maintenance, legal regulations, etc.

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