Stormwater Non-potable Beneficial Uses: Modeling Groundwater Recharge at a Stormwater Drywell Installation

Leila Talebi[1] and Robert Pitt[2]

[1]Graduate student, Dept. of Civil, Construction, and Environmental Engineering, Univ. of Alabama, P.O. Box 870205, Tuscaloosa, AL 35487; e-mail: ltalebi@crimson.ua.edu.
[2]Cudworth Professor, Urban Water Systems, Dept. of Civil, Construction, and Environmental Engineering, Univ. of Alabama, P.O. Box 870205, Tuscaloosa, AL 35487; e-mail: rpitt@eng.ua.edu

ABATRACT

The harvesting of urban stormwater to supply non-potable water demands is emerging as a viable option, amongst others, as a means to augment increasingly stressed urban water supply systems. A main objective of this Water Environment Research Foundation (WERF)/EPA funded project is to show how currently available models and other tools can be interactively used to calculate the benefits of stormwater beneficial uses. For the past several years, the city of Millburn has required cisterns to accommodate the flow from newly developed areas. Currently, these are infiltration cisterns for groundwater recharge, but water storage cisterns for irrigation is becoming increasingly of interest. In this stage of the project, this paper presents land use characteristics and soil parameters to fit an appropriate model to the infiltration data which are important inputs for the WinSLAMM model. The Horton and Green-Ampt infiltration equations are two widely used methods to describe infiltration capacities at small stormwater infiltration controls. In this paper, the Horton and the Green-Ampt parameters were determined for actual events at dry well recharge sites in Millburn, NJ. The results indicated that the Horton equation better fits the actual data, however, the fitted equation parameters did not always compare well to prior published parameters from the literature. Other elements of this WERF/EPA supported project include a broad review of US and international regulations pertaining to stormwater beneficial uses, many case study summaries, and descriptions of likely stormwater sources having acceptable quality that would minimize any adverse effects. Later project activities will involve extensive modeling of stormwater beneficial use opportunities at many US locations, including the development of production functions that can enable local water managers to make top-level evaluations of this water source.

INTRODUCTION

Water availability is a matter of widespread international concern. The harvesting of urban stormwater to supply non-potable water demands is emerging as a viable option, amongst others, as a means to augment increasingly stressed urban water supply systems. Stormwater harvesting is an ancient technique for collecting and storing rainwater from rooftops, land surfaces, road surfaces or rock catchments enjoying a revival in popularity in many areas of the world, due to the inherent quality of rainwater and interest in reducing consumption of treated water. We are currently conducting a research project examining the non-potable beneficial uses of stormwater that is being supported by WERF and EPA. This project is a combination of literature reviews, case studies, and modeling to investigate the feasibility of these non-potable beneficial uses of stormwater under various conditions in the US. Infiltration information is one of the important inputs for the WinSLAMM model when considering groundwater recharge options. In this paper the infiltration measurements were used to test the validity of two commonly used infiltration models; Horton and Green-Ampt. Also as a part of literature review of this project many case studies around the U.S. and abroad have been reviewed.

Several important trends were seen from these case studies. The heavily urbanized developing countries in water stressed areas (such as China and India) are most concerned with harvesting as much runoff as possible, with less concern related to water quality. Not only is roof runoff harvested, but also runoff from all urban areas. Usually, all paved areas are used to harvest runoff water, as maximum volumes are needed to augment the poor quality and poorly available local sources. The water is stored in large ponds, and usually injected to shallow aquifers. These improve the water quality to some extent, greatly depending on these storage conditions. In developing countries with large rural populations in water stressed areas (such as in Africa), most of the runoff harvesting schemes focus on collecting roof runoff for storage in tanks near the homes. The water is used for all domestic purposes and for irrigation of food subsistence crops during dry weather. The storage tanks are therefore relatively large to provide seasonal storage. In developed countries with large urban population centers in water scarce regions (such as Australia), runoff harvesting has long been used to augment the water supplies. In most cases, the runoff is collected from roofs and stored in large tanks adjacent to homes where the water is used for non-potable uses. In some rural cases, the water is used for all domestic water uses. Large development water harvesting projects (such as for urban city centers for large apartment buildings), runoff is collected from all areas and undergoes some pretreatment before storage in large (usually underground) storage tanks. The water then undergoes very sophisticated water treatment before use. In many cases, this highly treated harvested runoff is still restricted to non-potable uses. Examples of runoff harvesting in developed countries that currently are not under-going water shortages (such as Germany) are similar to the processes used in Australia. The purposes are to develop “sustainable” urban environments, where water conservation is a key factor.

METHODS and MATERIALS

Besides the obvious benefit of reduced stormwater discharges (and attendant receiving water benefits), many stormwater use options also benefit other components of the urban water infrastructure. If stormwater is stored and used to irrigate landscaped areas and flush toilets, as is common in many water-stressed locations today, less highly treated domestic water needs to be delivered. Groundwater recharge to augment local groundwater resources, possibly for later local use as demonstrated in many developing countries, is also a suitable beneficial use of stormwater. This paper presents a review of infiltration equations that can be used to calculate groundwater recharge potential at a case study location currently collecting data in Millburn, NJ (a current EPA funded project).

One of the case studies being examined is a project located in Millburn, NJ. This project, supported by the Wet Weather Flow Research Program of the US EPA, is gathering data to evaluate other alternatives of stormwater disposal in this area. For the past several years, the city of Millburn has required dry wells/cisterns to infiltrate the increased flows from newly developed areas. There are some water storage tanks now being installed to use the increased stormwater for irrigation. The current project is investigating whether increased beneficial uses of the runoff would be a more efficient use of the water instead of infiltrating into the shallow groundwaters. There are substantial data available for this community, and we are supplementing these data with more detailed site information to allow a comprehensive review of beneficial stormwater uses.

This EPA project in Millburn includes monitoring the water levels in several dry wells and concurrent rainfall conditions. This information is also being used to calibrate WinSLAMM for detailed evaluations of alternative stormwater management options, including beneficial water use (irrigation and groundwater recharge). Some locations are being monitored in detail, representing a range of conditions throughout the township. Design details for the cisterns are also being collected, along with site landscaping information. This information, along with the rainfall and evapotranspiration data, will be used to calculate the amount of stormwater that can be beneficially used for local groundwater recharge and site irrigation and to show how landscaping irrigation needs integrates with the available rainfall.

The major development characteristics for an area needed for modeling relate to the type and amount of the source areas, such as roofs, paved parking, landscape (grass and tree), street, sidewalk, etc. Figure 1 shows three of the Millburn neighborhoods surrounding the monitoring sites and related land use characteristics manually measured from aerial images from Google Earth Pro.

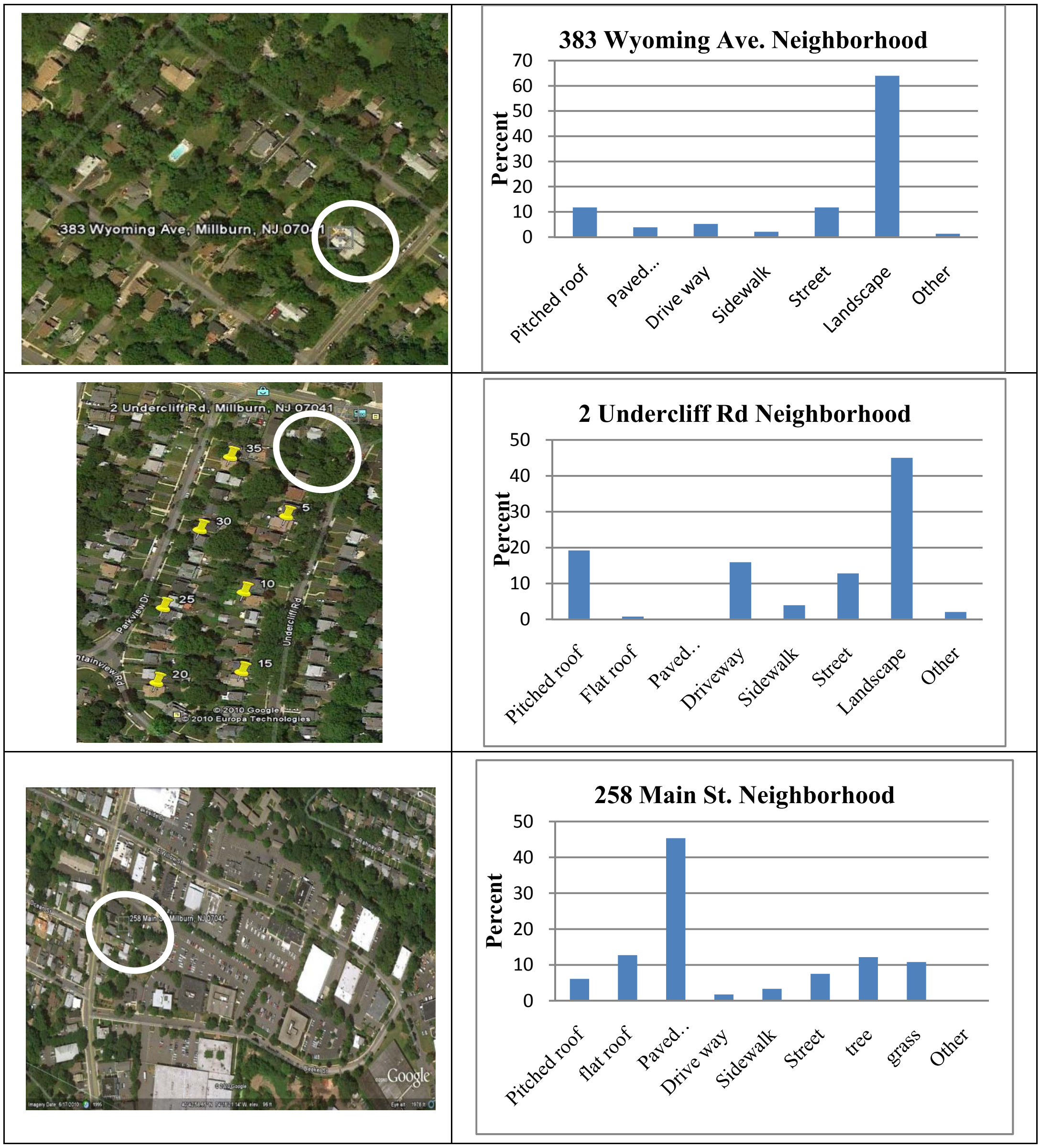

Figure 1 Land development characteristics for three of the study locations in Millburn, NJ

Soil characteristics are also needed when evaluating stormwater infiltration and recharge potential. Table 1 describes the soil characteristics for some of the Millburn's sites from the NRCS on-line soil survey. Except one site, all the sites have soils with the hydrologic soil class of "C". Group "C" Soils have slow infiltration rates when thoroughly wet. These consist chiefly of soils having a layer that impedes the downward movement of water or soils of moderately fine to fine texture. These soils have a slow rate of water transmission. Also, all of the sites' soil are well drained in terms of drainage class. The dry wells are usually 6 ft deep, with another 2 ft of gravel, so the main infiltration layer is about 8 ft below the ground surface. The soil profiles indicate likely increased infiltration potentials at these deeper soil depths.

Table 1 Soil Characteristics for some sites in Millburn, NJ.

Address	Soil Name	Soil Group	Slope (%)	K_{sat}[1]	Drainage class	Typical profile
383 Wyoming Ave.	Boonton-Urban land, Boonton substratum complex, red sandstone	C	3-8	Moderately low to moderately high (0.06 to 0.20 in/hr)	Well drained	0 to1 in: Slightly decomposed plant 1-3 in: Silt loam 3-10 in: Loam 10-27 in: Gravelly loam 27-67 in: Gravelly fine sandy loam 67-83 in: Gravelly sandy loam
258 Main St.	Dunellen sandy loam	A	3-8	High (1.98 to 5.95 in/hr)	Well drained	0-42 in: Sandy loam 42-70 in: Stratified gravelly sand to sand to loamy sand
11 Fox Hill Ln 8 South Beechcroft 2 Undercliff Rd Linda's Flower	Boonton - Urban land, Boonton substratum complex, terminal moraine	C	3-8	Moderately low to moderately high (0.06 to 0.20 in/hr)	Well drained	0-1 in: Highly decomposed plant 1-24 in: Sandy loam 24-42 in: Gravelly sandy loam 42-60 in: Fine sandy loam
9 Lancer	Boonton - Urban land, Boonton substratum complex	C	8-15	Moderately low to moderately high (0.06 to 0.20 in/hr)	Well drained	0-5 in: Loam 5-30 in: Silt loam 30-40 in: Gravelly fine sandy loam 40-47 in: Fine sandy loam 47-72 in: Loamy sand

[1]*Capacity of the most limiting layer to transmit water*

Source: http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm

INFILTRATION

Site soil evaluations include infiltration measurements, along with soil density, texture, and moisture determinations. The water infiltration data could be fitted to some commonly used soil water infiltration models such as the Green–Ampt (1911), the Kostiakov (1932), the Horton (1940) and the Philip's (1957) equations. Although various infiltration equations have different mathematical structures and calibration parameters, their estimates are all premised on observed water infiltration data.

One of the most commonly used infiltration equations was developed by Horton (1940). The equation is as follows:

$$f = f_c + (f_o - f_c)e^{-kt} \qquad (1)$$

Where f is the infiltration rate at time t (in/hr), f_o is the initial infiltration rate (in/hr), f_c is the final infiltration rate (in/hr), and k is first-order rate constant (hr^{-1}). This equation assumes that the rainfall intensity is greater than the infiltration capacity at all times and that the infiltration rate decreases with time (Bedient and Huber 1992).

The capacity of the soil to hold additional water decreases as the time of the storm increases because the pores in the soil become saturated with water. The Horton equation's major drawback is that it does not consider the soil storage availability after varying amounts of infiltration have occurred, but only considers infiltration as a function of time (Akan 1993). However, integrated forms of the equation can be used that do consider the amount of water added to the soil. It is recommended that f_c, f_o, and k all be obtained through field data, but they are rarely measured locally. Table 2 shows commonly used Horton infiltration parameter values, as summarized by Akan (1993).

Table 2 Horton parameters (Akan, 1993)

Soil Type	f_o (in/hr)Dry
Sandy soils with little to no vegetation	5
Dry loam soils with little to no vegetation	3
Dry clay soils with little to no vegetation	1
Dry sandy soils with dense vegetation	10
Dry loam soils with dense vegetation	6
Dry clay soils with dense vegetation	2
Moist sandy soils with little to no vegetation	1.7
Moist loam soils with little to no vegetation	1
Moist clay soils with little to no vegetation	0.3
Moist sandy soils with dense vegetation	3.3
Moist loam soils with dense vegetation	2
Moist clay soils with dense vegetation	0.7

Table 3 summarizes the Horton equation coefficients as measured by Pitt, et al. 1999 for different urban soils, showing the dramatic effect soil density has on the infiltration characteristics.

Table 3 Horton Coefficients (Pitt et al., 1999)

Infiltration Parameter	Soil Group	90%	75%	50%	25%	10%
fo (in/hr)	Clay – Dry Noncompact	42	24	11	7	5
	Clay-Other	7	3.75	2	1	0
	Sand-Compact	42	12	5	1.5	0
	Sand-Noncompact	52	46	34	24	0.25
fc (in/hr)	Clay – Dry Noncompact	20	12	3	0.75	0.25
	Clay-Other	0.75	0.5	0.25	0	0
	Sand-Compact	5	1.25	0.5	0.25	0
	Sand-Noncompact	24	19	15	9	0
k (1/hr)	Clay – Dry Noncompact	0.3	0.22	0.16	0.07	0.05
	Clay-Other	0.18	0.1	0.06	0.03	0
	Sand-Compact	0.28	0.2	0.1	0.05	0.016
	Sand-Noncompact	0.32	0.2	0.08	0.03	0

Another common equation for infiltration calculations is by Green-Ampt. The Green-Ampt equation calculates cumulative infiltration with assuming water flow into a vertical soil profile (Green and Amp, 1911).

$$f_t = K(\frac{\psi\Delta\theta}{F_t} + 1) \quad (2)$$

Where f_t is infiltration rate, cm/hr; ψ is the initial Matric potential of the soil, in; $\Delta\theta$ is the difference of soil water content after infiltration with initial water content, in^3/

in^3; K is hydraulic conductivity, in/hr; F_t is the cumulative infiltration at time t, in . This equation requires a linear relationship between f_t and $(1/F_t)$. Table 4 shows some typical values suggested by Rawls et al. (1983) for the Green-Ampt parameters.

Table 4 Green-Ampt parameters (Rawls et al., 1983)

Soil type	Porosity	Effective porosity	Suction head	Hydraulic conductivity
			mm	mm/h
Sand	0.437	0.417	49.5	117.8
loamy sand	0.437	0.401	61.3	29.9
sandy loam	0.453	0.412	110.1	10.9
loam	0.463	0.434	88.9	3.4
silt loam	0.501	0.486	166.8	6.5
sandy clay loam	0.398	0.330	218.5	1.5
clay loam	0.464	0.309	208.8	1.0
silty clay loam	0.471	0.432	273.0	1.0
sandy clay	0.430	0.321	239.0	0.6
silty clay	0.479	0.423	292.2	0.5
clay	0.475	0.385	316.3	0.3

RESULTS and DISCUSSIONS

Table 5 is a summary of the best-fit Horton equation parameter values based on measured infiltration test for some sites at Millburn, NJ for different rains. Also, Figure 2 shows the fitted Horton and Green-Ampt equations to observed data for some sites of the project

Table 5 Horton's parameters summaries

Site Address	Date	Horton's parameters			Akan (1993)	Pitt et al. (1999)*		
		f_0(in/hr)	f_c(in/hr)	k (1/hr)	f_0(in/hr)	f_0(in/hr)	f_c(in/hr)	k (1/hr)
Linda's Flower	06-17-2010	5.7	1.9	0.0065	2-3.3	1.5-12	0.25-1.3	0.05-0.2
	07-14-2010	5.6	2.2	0.011				
	08-01-2010	5.3	2.5	0.0055				
258 Main St.	06-17-2010	35	5.3	0.06	1-1.7	1.5-12	0.25-1.3	0.05-0.2
	07-14-2010	75	6.8	0.07				
	08-01-2010	75	4.7	0.045				
2 Undercliff	10-02-2009	3.9	0.57	0.013	2-3.3	1.5-12	0.25-1.3	0.05-0.2
383 Wyoming Ave.	7-26-2009	3.2	0.66	0.005	2-3.3	1.5-12	0.25-1.3	0.05-0.2
	7-29-2009	10	1.1	0.0035				
	8-02-2009	5.5	0.93	0.003				
	8-22-2009	3.6	1.2	0.03				
	10-02-2009	5.6	1.2	0.0045				

* 25th and 75th percentile values for compact sandy conditions

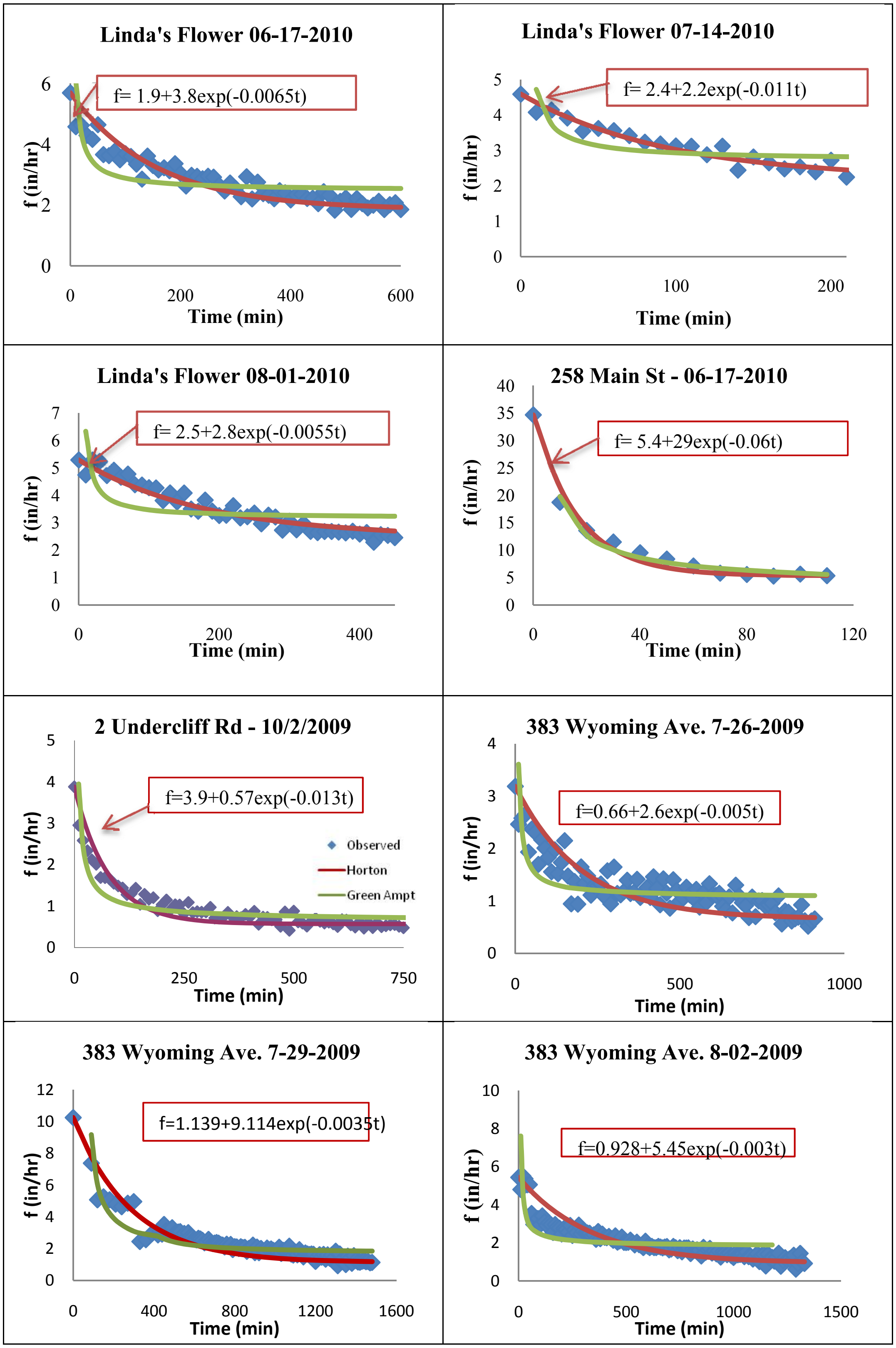

Figure 2 Horton and Green-Ampt fitted curves for observed data. (dots: observed data, Red line: Horton and Green line:Green-Ampt. The Horton equation is written on each graph)

As it is shown in figure 2, the Horton equations indicated better fits to the data than the Green-Ampt model to the Millburn data. However for some sites, the Table 5 fitted Horton's parameters also don't compare well to the values available from the literature. As noted previously, a linear relationship between f_t and $(1/F_t)$ is needed based on the Green-Ampt equation. Figure 4 presents linear regressions of f_t vs $(1/F_t)$ for the monitored sites. The only visually acceptable linear regression is associated with the observations from the 258 Main St. site, which also shows the best Green-Ampt fitted equation in Figure 3 as well.

Table 6 Green-Ampt parameters

Site Address	**Date**	**Hydraulic conductivity K (in/hr)**	
		estimated	**Rawls et al. (1983)**
Linda's Flower	06-17-2010	2.435	0.429
	07-14-2010	2.685	
	08-01-2010	3.131	
258 Main St.	06-17-2010	1.018	1.17
2 Undercliff	10-02-2009	0.557	0.429
383 Wyoming Ave.	7-26-2009	1.039	0.13-0.43

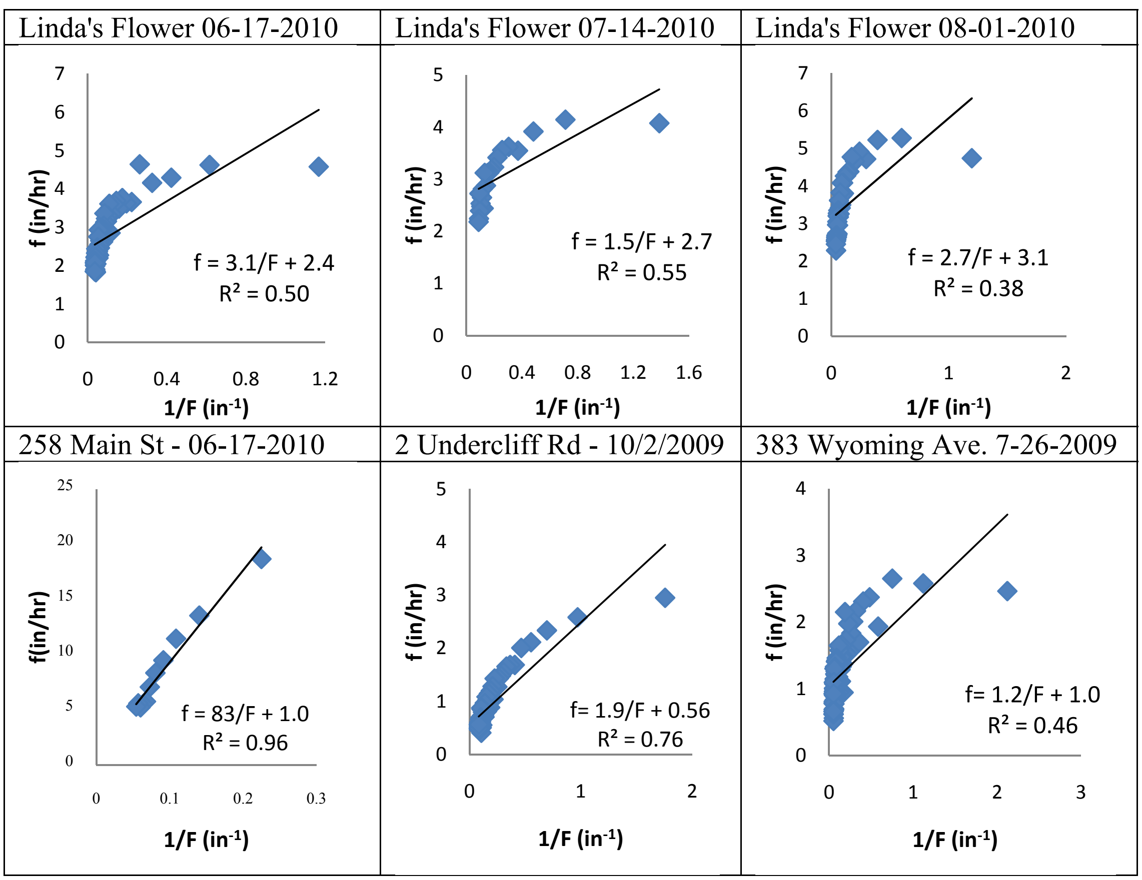

Figure 3 Linear regression of f_t vs $(1/F_t)$ for some sites in Millburn, NJ.

Conclusion

Different aspects of beneficial use of stormwater are considered due to lack of water in different parts of the world. Groundwater recharge to augment local groundwater resources, is also a suitable beneficial use of stormwater. Tow commonly used infiltration models; Horton and Green-Ampt was used to calculate groundwater recharge potential at a case study location currently collecting data in Millburn, NJ.

The fitted graphs and resulting derived parameters of each mentioned equations indicate that although the fitted Horton curve is fitted better to observed data of the case study area than Green-Ampt curve, the calculated parameters of both used infiltration models don't compare to the literature.

Later project activities will involve extensive modeling of stormwater beneficial use opportunities at many US locations, including Millburn, NJ with WinSLAMM model, resulting sustainable water management to make top-level evaluations of this water source.

References

Akan, A. O. (1993), *Urban Stormwater Hydrology: A Guide to Engineering Calculations*. Lancaster. PA: Technomic Publishing Co., Inc.

Green,W.H.,Ampt, G.A., (1911). Studies on soil physics: I. Flow of air and water through soils. Journal of Agricultural Science 4, 1–24.

Horton, R.E., (1940). An approach toward a physical interpretation of infiltration capacity. Soil Science Society of America Proceedings 5, 399–417.

Kostiakov, A.N.,(1932). On the dynamics of the coefficient of water percolation in soils and on the necessity for studying it from a dynamic point of view for purposes of amelioration. Trans 6, 17–21.

Rawls, W.J. and Brakenseik D.L. (1983). "A procedure to predict Green-Ampt infiltration parameters". Advances in Infiltration, Am. Soc of Agr. Eng, 102-112.

Philip, J.R., (1957). The theory of infiltration: 4. Sorptivity and algebraic infiltration equations. Soil. Sci. 84, 257.

Pitt, R., J. Lantrip, R. Harrison, C. Henry, and D. Hue. (1999), *Infiltration through Disturbed Urban Soils and Compost-Amended Soil Effects on Runoff Quality and Quantity*. U.S. Environmental Protection Agency, Water Supply and Water Resources Division, National Risk Management Research Laboratory. EPA 600/R-00/016. Cincinnati, Ohio. 231 pgs. December 1999.