GREENROOFS FOR STORMWATER RUNOFF CONTROL: EXPERIENCES FROM TWO SITES

LA 222 Hydrology for Planners

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Abstract

As cities expand and encroach onto rural lands, large impervious surfaces in the form of buildings, parking lots and roads cover the landscape. These impervious surfaces generate increased quantities of stormwater runoff which flow rapidly into municipal conveyance systems bypassing the natural infiltration processes resulting in polluted water and altered natural hydrologic systems. By replacing the footprint area of a building with a rooftop garden, greenroofs may offer an opportunity to control runoff and remove pollutants from rainwater. In this report we examined two greenroofs, one in Petaluma, California and the other in Portland, Oregon to determine their hydrological characteristics and how they perform as stormwater management techniques. We found that both roofs reduce the volume of stormwater runoff by an average greater than 60% while also reducing peak flows and increasing runoff time. Our results show that greenroofs are viable on-site stormwater control devices.

Introduction

Historically roofs have acted as a mediator between ground and sky, forming a protective enclosure and incorporating the natural world into landscape and architectural design. Roof gardens date back as far as 2250 BC in the Ziggurat of Ur and have been used through the 20th century by influential architects such as Le Corbusier and Frank Lloyd. (Jellicoe, 1995) Today roof gardens, now called greenroofs, are commonly used as part of the sustainability movement among design professionals. This movement focuses on the health of cities and the impact of urban development practices on the environment.

Greenroofs provide aesthetic, practical and ecological benefits for buildings and landscape. Aesthetically, vegetative roofs add visual access to green areas in otherwise built urban environments. Changing colors, falling leaves and new growth remind inhabitants of the seasonal change and awareness of natural processes. As cities continue to grow and expand, large open green space has become increasingly rare. Greenroofs help to restore some of the precious open space lost to urban development.

On the practical side, the layers of vegetation and substrate protect the underlying waterproofing membrane from damaging outdoor influences such as ultraviolet exposure, human traffic, and wind deterioration. Greenroofs are composed of six to seven layers including a waterproof membrane, root barrier, and optional layer of insulation, protection / retention mat, drainage layer, growing medium and vegetation. (figure 1) Greenroof technology can extend the lifespan of a normal roof from 10-15 years to 30-40 years (Kiers, 2002). An increased life span reduces maintenance and re-roofing cost. Extreme temperatures can damage a roof and drastically reduce its life span. Vegetative roofs prevent damaging ultra-violet rays from absorbing into layers below. Conventional asphalt and bitumen roofs can reach up to 170 degrees F on a hot 95 degree summer day while vegetative roofs stay under 80 degrees F under the same conditions (Curtis, 1987). By providing a natural system of plants and soil between the sun and the roof surface cooler temperatures result. Cooler roofs create cooler buildings that require less air conditioning and create a reduction in overall energy consumption. In some climates a greenroof may completely eliminate the need for air conditioning. The energy efficiency of the building is also improved by a layer of air trapped in the planting mass, which limits air exchange between the indoor and outdoor temperatures. The outside of the building is therefore cooled in the summer and warmed in the winter.

Ecologically, the most important benefit of greenroofs is their ability to reduce urban storm water runoff and improve water quality. When rain falls on open land it enters the natural hydrologic cycle. In this natural cycle sixty percent of rainwater is absorbed into the ground and forty percent returns to the air through evaporation and transpiration (Scholz-Barth, 2001). In an urban environment, impermeable pavement occupies 75% of surfaces creating a cycle were 15% of rainfall evaporates, 5% infiltrates into the ground and 75% becoming stormwater runoff (Scholz-Barth, 2001). The resulting stormwater runoff is then managed through gutters, curbs, storm drains and treatment facilities. Greenroofs provide opportunities for rainwater to return to a more natural hydrologic cycle through retention, peak runoff reduction and improved water quality.

Stormwater retention on greenroofs is achieved through the plant's capture of precipitation in their foliage as well as their absorption of water in the root zone. Further absorption also takes place in the actual soil materials and often in the undersoil roof construction, which contains plastic cellular grids that trap water. (figure 1) Retention amounts are expressed as a volume such as cubic feet (ft^3). Stormwater retention rate is calculated by dividing the amount of roof runoff by the amount of roof run-on and multiplying by 100. Stormwater peak reduction is the slowed velocity of runoff as it infiltrates the layers of vegetation, soil and roof membrane. For short or small storm events very little runoff may leave the vegetation and soil as runoff and ultimately be used by the plants through evapotranspirtation or be directly evaporated from the greenroof. Larger and longer storm events fill the storage capacity of the greenroof system and rely on the reduced velocity of runoff through the assembly to delay and attenuate the discharge from the roof. Runoff rates are determined by dividing the volume of runoff by the time it takes for the runoff to pass through the roof. This expressed as a flow such as cubic feet per second (cfs). Water quality of runoff from greenroofs is also improved through volume reductions and pollutant removal as runoff is cycled through the greenroof system and the vegetative materials (Hutchinson, 2003).

European cities currently lead the world in the number of greenroofs. Germany has the highest number of roofs covering about 10% of all flat roofs in the country. Along with Germany other European city governments in Austria, France, Norway and Holland have passed regulations and policies to encourage greenroof projects. America has also begun to introduce greenroofs in urban environments with Chicago recently completed a vegetative roof on top of City Hall and policy makers in Portland, Oregon implementing greenroofs into the city's master plan to reduce stormwater runoff. As Portland's policy suggests, greenroofs have become increasingly important as a guidelines in the mitigation of stormwater runoff.

As architects and urban planners, who are interested in sustainability, we wish to understand the hydrologic characteristics of greenroofs as a means of controlling stormwater runoff. We believe that greenroofs offer the best on-site device to control stormwater by reducing actual runoff, reducing peak runoff and delaying runoff after a storm event.

Study Approach

To understand the actual hydrological processes that characterize greenroofs we measured and observed the greenroof located on the Artaurus Veterinary Clinic in Petaluma, California as well as performing an analysis of data collected by the City of Portland on the Hamilton Apartments greenroof in Portland, Oregon.

Site Selections and Descriptions

Artaurus Veterinary Clinic was built in 1974, so its roof provides an opportunity to examine the performance of greenroofs over time. Although it did not benefit from current greenroof technology and construction methods, the clinic has used the roof for 30 years without serious problems. Sited at the base of a grassy hill in Petaluma adjacent to Highway 101, the clinic stands one story tall and measures approximately 4,000 ft^2 with a flat roof. (figure 2) Its roof is a flat, timber-framed structure with wood sheathing, covered with tarpaper, aluminum sheets, 2 inches of drainage stone, and 6-8 inches or earth. (figure 3) Native Californian grasses grow the full area of the roof, blending the building into the landscape. Based on the date and type of construction, this style of greenroof is often referred to as a sod roof. Built and occupied by the same owner since its construction, the Artaurus Veterinary Clinic has had no major maintenance performed on the roof and the roof had no leaks until approximately 5 years ago (J. Steele, D.V.M., personal communications, April 2004).

The Hamilton Apartments is a ten-story building located in Portland, Oregon on which 8,700 ft^2 of greenroof was installed in 1999. (figure 4) The City of Portland Bureau of Environmental Services is monitoring this greenroof to determine characteristics of planting methods; viability of substrate and vegetation; effluent water quality and stormwater characteristics. The design and construction of the Hamilton greenroof is characteristic of current greenroof technology with a 4-inch substrate composed of fiber, compost, perlite and loam and plant species that include a variety of succulents such as sedum, selosperma and sempervivum, grasses and herbaceous species. (figure 5) To monitor the roof runoff, the Bureau of Environmental Services installed flow-monitoring equipment immediately upstream of each primary roof drain. (figure 6) A tipping bucket rain gauge is also installed at the center of the roof to collect site-specific rain data (Hutchinson 2003). (figure 7)

Rainfall Simulation Field Measurements

We performed two measurements of the effectiveness of the greenroof at the Petaluma site to manage stormwater using a hose to simulate rainfall. One measurement was made at a high flow to simulate an intense rainfall, and a second at a moderate flow to simulate an average rain event. A portion of the roof at the southeast corner of the building was chosen as the best location for these measurements: sloping gently to the east, this point of the roof drains into an aluminum gutter. (figure 8) Before applying water to the roof, we calculated the flow rate of the hose by running the water into a bucket and timing its fill rate. We then applied the same flow rate to an approximately 4 square foot area (ft^2) at the corner of the roof above an aluminum gutter and captured the runoff in a bucket at the gutters' downstream downspout. (figure 9, 10) When the bucket was half full the time was recorded and the flow to the roof was shut off. The time from this moment to the end of flow of runoff from the roof was also recorded along with the total amount of runoff collected. Due to the steepness of the gutter and its proximity to the downspout measurement point, all the roof runoff was collected into our measurement bucket.

Our simulation of the high intensity rainfall at the Artaurus Veterinary Clinic in Petaluma used a flow rate of 0.017 cubic feet per second (cfs) applied for a total of 1.19 cubic feet of run-on to the roof. In order to simulate an average rainstorm, the rate of flow was lowered to 0.002 cfs and another section of the roof was watered with a total of 0.415 cubic feet of water sprayed on the roof

Analysis of Long-term Greenroof Data

To examine the detailed stormwater retention and stormwater peak reduction qualities of greenroofs we analyzed data from the Hamilton greenroof project in Portland, Oregon. The study data includes roof run-on and run-off rates as well as rainfall data provided at 5-minute intervals beginning in December 2001. We analyzed data from the West study area; 3,655 square feet of greenroof. (Appendix 1, 2 & 3) We limited our examination to the water year 2003 (October 2002 through September 2003) and plotted the stormwater retention rate by month as well as individual hydrographs for a winter storm and a summer storm.

Results & Discussion

In our simulation of the high intensity rainfall at the Artaurus Veterinary Clinic in Petaluma we recorded an immediate runoff rate of 0.005 cfs; a reduction of 70% from the rate applied. Having applied a total of 1.19 cubic feet of water onto the roof only 0.60 cubic feet of water flowed off the roof, a retention of 0.59 cubic feet or a 50% reduction of discharge. The runoff continued for a period of 6 minutes after the water was stopped. In the simulation of an average rainstorm, water absorbed into the soil at a much slower rate than the first trial and runoff from the roof did not begin until after 25 seconds of continuous application. At this flow the runoff rate was measured at 0.0006 cfs, a 75% decrease in the rate of runoff. We applied a total of 0.415 cubic feet of water onto the roof for the second trial of which 0.203 cubic feet was measured as runoff while 0.199 cubic feet was retained on the roof, resulting in a 50% reduction of discharge. The runoff continued for a period 8 minutes and 45 seconds after the water was turned off. (figure 11)

Conventional roofs have runoff coefficients of 90-100% with rainfall leaving the roof as runoff immediately (Dunne, 1978). This high reaction rate is also repeated at the end of a rainfall when runoff stops within seconds of the last run-on. In our test of a high intensity rainfall at the Petaluma site, the greenroof did not show a marked delay in runoff, which was most likely due to the high volume of water we applied to a dry roof system. This resulted in a form of sheet runoff until the vegetation and soil became moistened. The runoff time was increased after the high intensity flow was stopped indicating that after sufficient wetting the greenroof did attenuate the flow. Our results from a moderate rain event simulation show that the runoff coefficient of greenroofing is much lower than that of conventional roofs demonstrated by the delay in runoff and the increased runoff time after flow was stopped. The moderate rain event simulation with its gradual wetting of the roof performed better at both pre- and post-storm runoff delay than the high intensity simulation.

The total rainfall recorded at the Hamilton Apartments site in Portland for the water year 2003 was 33 inches (Hutchinson, 2003). With a conventional roof and a 90% runoff coefficient the apartment roof would have created a calculated runoff of over 8,961 ft^3 of stormwater runoff. The greenroof installation reduced the stormwater runoff by a total measured stormwater retention of 3,291 ft^3 for the year; a reduction of 5,670 ft^3 of water, a 63% rainfall retention rate. (Figure 12) Due to Portland's climate, with moderate but near-continuous winter rainfall, dry summers, and occasional low-elevation snowfall, the rainfall retention rate varied throughout the year with a 100% retention rates in drier months and a 58% retention rates in wet months. (figure 13) As a comparison, the Artaurus Clinic with its 4,000 ft^3 roof area, a 50% retention rate, and 17 inches of rain in the water year 2003 would be calculated to reduce runoff by 2,728 $ft^{3.}$ (NCDC, 2004).

The manner in which a greenroof responds as a peak stormwater reduction device is demonstrated in the storm hydrographs from the Hamilton Apartments. Figures 14 and 15 show the delayed release of runoff after rainfall and the elimination of the high runoff peaks as the greenroof stabilized flow into a smooth gradually descending curve. Normal impervious roof runoff is equal to the rain run-on graphed in the figures 14 and 15 as the time of concentration is nearly instantaneous and would have immediate runoff. As mentioned earlier, conventional roofs also stop runoff within minutes of the last rainfall, unlike the runoff shown in figures 14 and 15 with continued runoff for 30 minutes or more. While the winter storm hydrograph (figure 14) demonstrates peak reduction in high intensity storms, the summer storm hydrograph (figure 15) illustrates the ability of greenroofs to completely eliminate peaks during low intensity storms. These results confirm that the measurements on the Artaurus greenroof are consistent with typical greenroof characteristics and that both sites greenroofs perform well at reducing runoff amounts, runoff rates and decrease peak runoff flows.

Conclusion

The continued introduction of greenroofs as a stormwater management technology is growing in the United States. The hydrologic aspects of the performance of vegetative roofing are proving beneficial to building owners, local municipalities, water management agencies and larger ecological systems. While minimal actual monitoring of installed greenroofs in the American climates is established to date, greater amounts of research are beginning. Our examination of the data we measured at the Artaurus Veterinary Clinic in Petaluma and the data we analyzed from the Hamilton Apartments in Portland show that greenroofs provide stormwater retention as well as peak storm runoff reduction and increased runoff time. These characteristics prove that greenroofs are a viable on-site stormwater control system.

In order that greenroof technology becomes more accepted by owners, developers, and homeowners, greater confidence must be earned in the value of the benefits of greenroofs, particularly stormwater runoff. When government agencies allow part or all of stormwater treatment requirements to be met using greenroofs, the acceptance of greenroofs will grow, their financial benefits increase and their aesthetic qualities will be enjoyed in more and more settings.

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http://www.greenroofs.com

Figure Captions

Figure 1: Typical Greenroof Construction Section

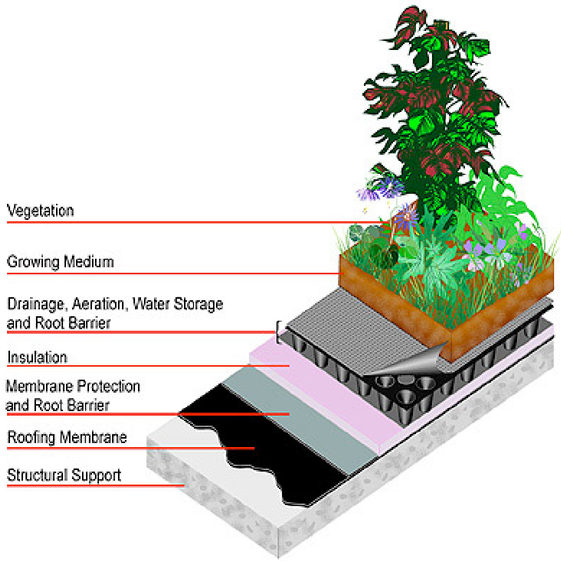


Figure 2: Artaurus Veterinary Clinic — Overview Photo

Figure 3: Artaurus Veterinary Clinic — Close-up of roof construction seen at roof edge

Figure 4: Hamilton Apartments — Overview Photo (courtesy City of Portland Bureau of Environmental Services)

Figure 5: Hamilton Apartments Greenroof Section Diagram (courtesy City of Portland Bureau of Environmental Services)

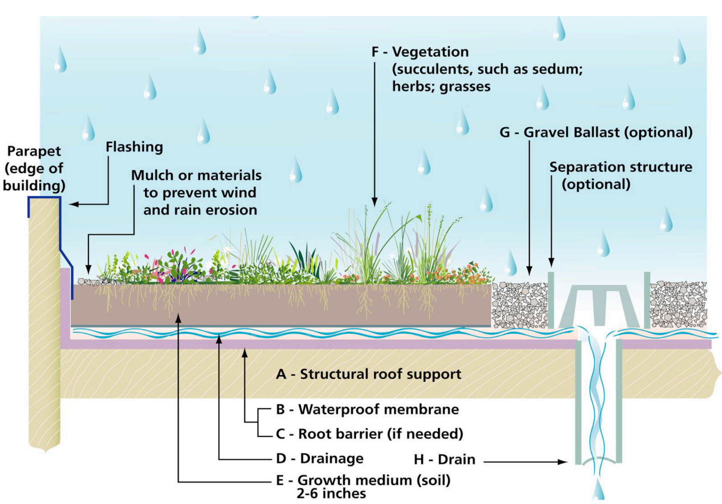


Figure 6: Hamilton Apartments — Roof Runoff Measuring Flume (courtesy City of Portland Bureau of Environmental Services)

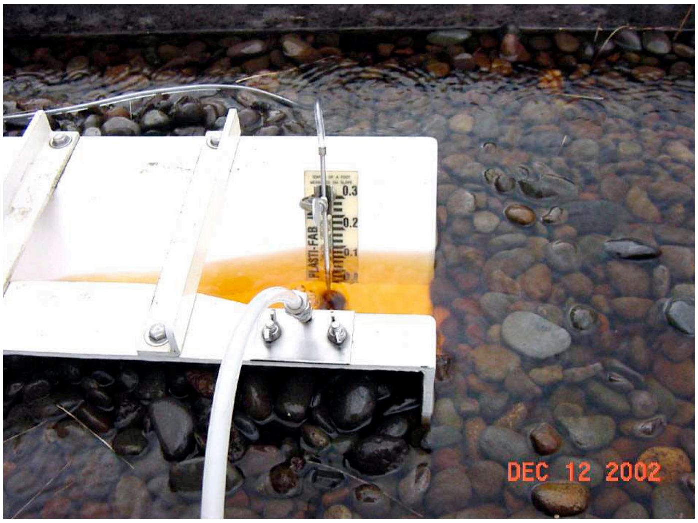


Figure 7: Hamilton Apartment — Tipping Rain gauge Station (courtesy City of Portland Bureau of Environmental Services)

Figure 8: Artaurus Veterinary Clinic — Measurement Location

Figure 9: Artaurus Veterinary Clinic — Application of Simulated Rainfall

Figure 10: Artaurus Veterinary Clinic — Collection of runoff from gutter into bucket

Figure 11: Artaurus Veterinary Clinic — Runoff Results

Artaurus Veterinary Clinic: Petaluma, CA		
	Intense rainfall	**Average rainstorm**
Flow		
Applied Run-on Flow Rate	.017 cfs	.002 cfs
Measured Runoff Rate	.005 cfs	.0006 cfs
% Reduction	70%	75%
Volume		
Total Applied	1.19 ft^3	.415 ft^3
Measured Runoff	.6 ft^3	.203 ft^3
Amount Retained	.59 ft^3	.199 ft^3
% Retention	50%	48%

Figure 12: Hamilton Apartments measured stormwater retention; Artaurus Veterinary Clinic calculated stormwater retention

Hamilton Apartments: Portland, OR	
	Water Year 2003
Total Rainfall	33 in
Stormwater Volume	
Total	8,961 ft^3
Flow into drains	3,291 ft^3
Retained	5,670 ft^3
% Retention	63%

Artaurus Veterinary Clinic: Petaluma, CA	
	Water Year 2003
Total Rainfall	17.05 in
Projected Stormwater Volume	
Total	5,683 ft^3
Predicted Flow into drains	2,955 ft^3
Predicted Retained	2,728 ft^3
% Retention	48%

Figure 13: Hamilton Apartments — Rainfall and Retention

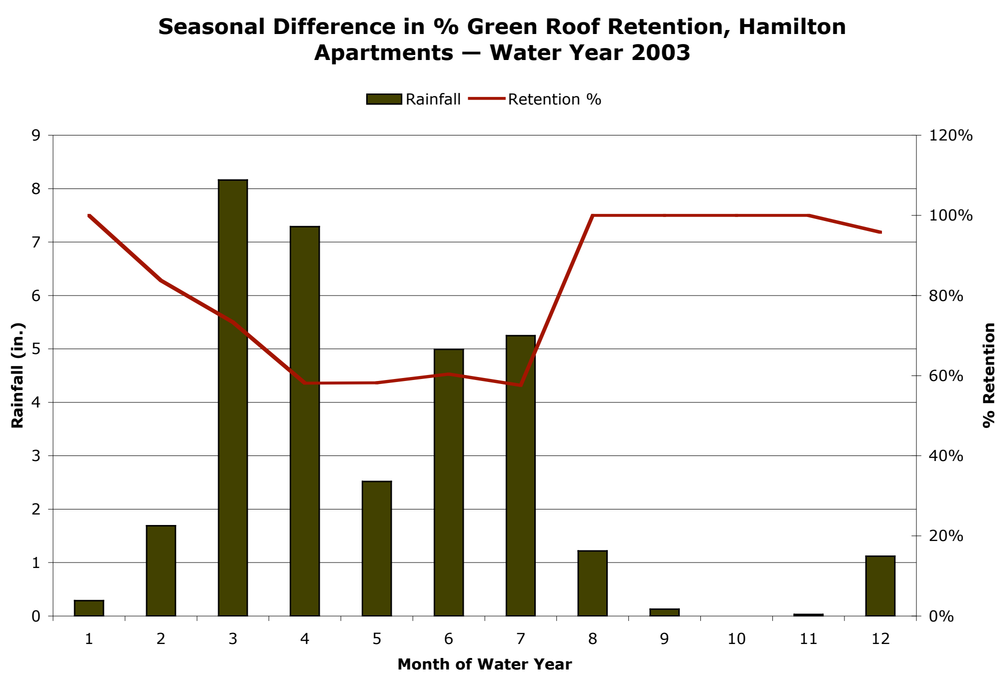


Figure 14: Hamilton Apartments — Winter Storm Hydrograph

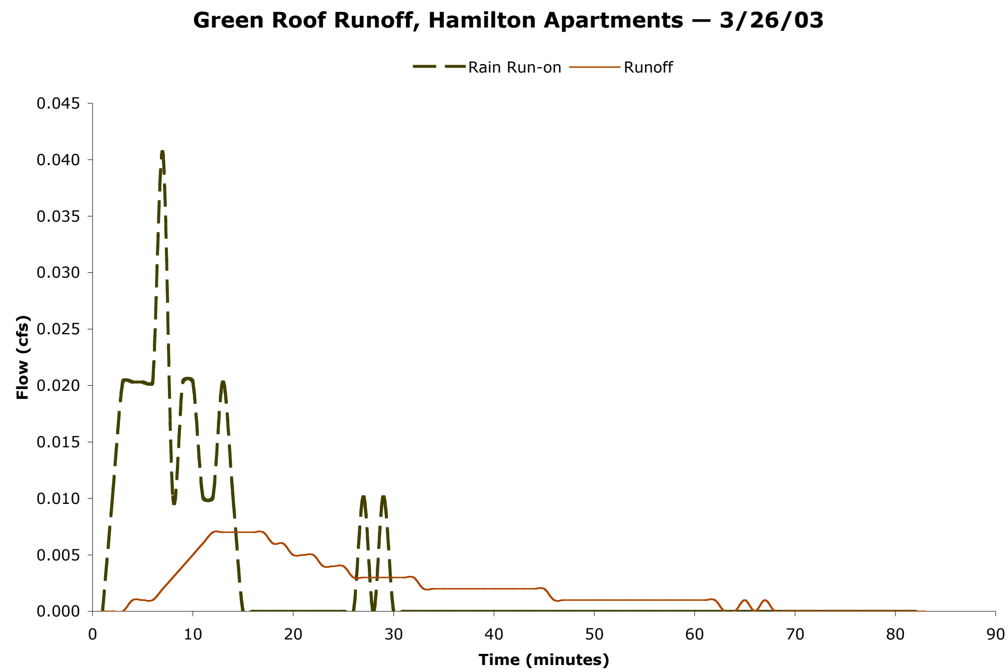
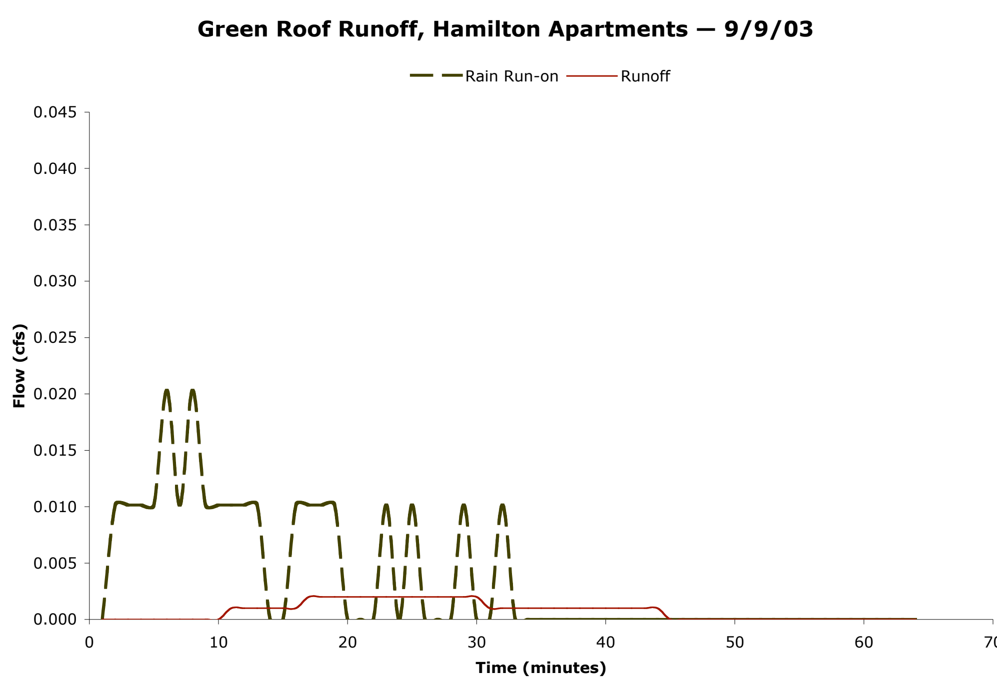


Figure 15: Hamilton Apartments — Summer Storm Hydrograph



Appendices

Appendix 1: Hamilton Apartments — Monthly Rainfall and Retention Data (courtesy City of Portland Bureau of Environmental Services)

	Rainfall (in.)	% Retention
October	0.29	100%
November	1.69	84%
December	8.16	73%
January	7.29	58%
February	2.52	58%
March	4.99	60%
April	5.25	58%
May	1.22	100%
June	0.13	100%
July	0	100%
August	0.03	100%
September	1.12	96%

Appendix 2: Hamilton Apartments — Winter Storm Data 3/26/03 (courtesy City of Portland Bureau of Environmental Services)

Time	Rain (inches)	Rain (Feet)	Rain Volume (cf)	Run-on (cfs)	Run-off (cfs)
5:30	0	0	0.00	0.000	0
5:35	0.01	0.00083333	3.05	0.010	0
5:40	0.02	0.00166667	6.09	0.020	0
5:45	0.02	0.00166667	6.09	0.020	0.001
5:50	0.02	0.00166667	6.09	0.020	0.001
5:55	0.02	0.00166667	6.09	0.020	0.001
6:00	0.04	0.00333333	12.18	0.041	0.002
6:05	0.01	0.00083333	3.05	0.010	0.003
6:10	0.02	0.00166667	6.09	0.020	0.004
6:15	0.02	0.00166667	6.09	0.020	0.005
6:20	0.01	0.00083333	3.05	0.010	0.006
6:25	0.01	0.00083333	3.05	0.010	0.007
6:30	0.02	0.00166667	6.09	0.020	0.007
6:35	0.01	0.00083333	3.05	0.010	0.007
6:40	0	0	0.00	0.000	0.007
6:45	0	0	0.00	0.000	0.007
6:50	0	0	0.00	0.000	0.007
6:55	0	0	0.00	0.000	0.006
7:00	0	0	0.00	0.000	0.006
7:05	0	0	0.00	0.000	0.005
7:10	0	0	0.00	0.000	0.005
7:15	0	0	0.00	0.000	0.005
7:20	0	0	0.00	0.000	0.004
7:25	0	0	0.00	0.000	0.004
7:30	0	0	0.00	0.000	0.004
7:35	0	0	0.00	0.000	0.003
7:40	0.01	0.00083333	3.05	0.010	0.003
7:45	0	0	0.00	0.000	0.003
7:50	0.01	0.00083333	3.05	0.010	0.003
7:55	0	0	0.00	0.000	0.003
8:00	0	0	0.00	0.000	0.003
8:05	0	0	0.00	0.000	0.003
8:10	0	0	0.00	0.000	0.002
8:15	0	0	0.00	0.000	0.002
8:20	0	0	0.00	0.000	0.002
8:25	0	0	0.00	0.000	0.002
8:30	0	0	0.00	0.000	0.002
8:35	0	0	0.00	0.000	0.002

8:40	0	0	0.00	0.000	0.002
8:45	0	0	0.00	0.000	0.002
8:50	0	0	0.00	0.000	0.002
8:55	0	0	0.00	0.000	0.002
9:00	0	0	0.00	0.000	0.002
9:05	0	0	0.00	0.000	0.002
9:10	0	0	0.00	0.000	0.002
9:15	0	0	0.00	0.000	0.001
9:20	0	0	0.00	0.000	0.001
9:25	0	0	0.00	0.000	0.001
9:30	0	0	0.00	0.000	0.001
9:35	0	0	0.00	0.000	0.001
9:40	0	0	0.00	0.000	0.001
9:45	0	0	0.00	0.000	0.001
9:50	0	0	0.00	0.000	0.001
9:55	0	0	0.00	0.000	0.001
10:00	0	0	0.00	0.000	0.001
10:05	0	0	0.00	0.000	0.001
10:10	0	0	0.00	0.000	0.001
10:15	0	0	0.00	0.000	0.001
10:20	0	0	0.00	0.000	0.001
10:25	0	0	0.00	0.000	0.001
10:30	0	0	0.00	0.000	0.001
10:35	0	0	0.00	0.000	0.001
10:40	0	0	0.00	0.000	0
10:45	0	0	0.00	0.000	0
10:50	0	0	0.00	0.000	0.001
10:55	0	0	0.00	0.000	0
11:00	0	0	0.00	0.000	0.001
11:05	0	0	0.00	0.000	0

Appendix 3: Hamilton Apartments — Summer Storm Data 9/10/03 (courtesy City of Portland Bureau of Environmental Services)

Time	Rain (Inches)	Rain (Feet)	Rain Volume (cf)	Run-on (cfs)	Run-off (cfs)
4:15	0	0	0.00	0.000	0
4:20	0.01	0.000833333	3.05	0.010	0
4:25	0.01	0.000833333	3.05	0.010	0
4:30	0.01	0.000833333	3.05	0.010	0
4:35	0.01	0.000833333	3.05	0.010	0
4:40	0.02	0.001666667	6.09	0.020	0
4:45	0.01	0.000833333	3.05	0.010	0
4:50	0.02	0.001666667	6.09	0.020	0
4:55	0.01	0.000833333	3.05	0.010	0
5:00	0.01	0.000833333	3.05	0.010	0
5:05	0.01	0.000833333	3.05	0.010	0.001
5:10	0.01	0.000833333	3.05	0.010	0.001
5:15	0.01	0.000833333	3.05	0.010	0.001
5:20	0	0	0.00	0.000	0.001
5:25	0	0	0.00	0.000	0.001
5:30	0.01	0.000833333	3.05	0.010	0.001
5:35	0.01	0.000833333	3.05	0.010	0.002
5:40	0.01	0.000833333	3.05	0.010	0.002
5:45	0.01	0.000833333	3.05	0.010	0.002
5:50	0	0	0.00	0.000	0.002
5:55	0	0	0.00	0.000	0.002
6:00	0	0	0.00	0.000	0.002
6:05	0.01	0.000833333	3.05	0.010	0.002
6:10	0	0	0.00	0.000	0.002
6:15	0.01	0.000833333	3.05	0.010	0.002
6:20	0	0	0.00	0.000	0.002
6:25	0	0	0.00	0.000	0.002

6:30	0	0	0.00	0.000	0.002
6:35	0.01	0.000833333	3.05	0.010	0.002
6:40	0	0	0.00	0.000	0.002
6:45	0	0	0.00	0.000	0.001
6:50	0.01	0.000833333	3.05	0.010	0.001
6:55	0	0	0.00	0.000	0.001
7:00	0	0	0.00	0.000	0.001
7:05	0	0	0.00	0.000	0.001
7:10	0	0	0.00	0.000	0.001
7:15	0	0	0.00	0.000	0.001
7:20	0	0	0.00	0.000	0.001
7:25	0	0	0.00	0.000	0.001
7:30	0	0	0.00	0.000	0.001
7:35	0	0	0.00	0.000	0.001
7:40	0	0	0.00	0.000	0.001
7:45	0	0	0.00	0.000	0.001
7:50	0	0	0.00	0.000	0.001
7:55	0	0	0.00	0.000	0
8:00	0	0	0.00	0.000	0
8:05	0	0	0.00	0.000	0
8:10	0	0	0.00	0.000	0
8:15	0	0	0.00	0.000	0
8:20	0	0	0.00	0.000	0
8:25	0	0	0.00	0.000	0
8:30	0	0	0.00	0.000	0
8:35	0	0	0.00	0.000	0
8:40	0	0	0.00	0.000	0
8:45	0	0	0.00	0.000	0
8:50	0	0	0.00	0.000	0
8:55	0	0	0.00	0.000	0
9:00	0	0	0.00	0.000	0
9:05	0	0	0.00	0.000	0
9:10	0	0	0.00	0.000	0
9:15	0	0	0.00	0.000	0
9:20	0	0	0.00	0.000	0
9:25	0	0	0.00	0.000	0
9:30	0	0	0.00	0.000	0