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Rain-on-Snow Project

Brandon Morgan, Colin Huber[1], Keegan Pedersen
Department of Civil Engineering Technology, Environmental Management & Safety
Rochester Institute of Technology
78 Lomb Memorial Drive
Rochester, New York 14623 USA

[1]Chemical Engineering Department
Rochester Institute of Technology
One Lomb Memorial Drive
Rochester, New York 14623 USA

Faculty Advisor: Professor Scott Wolcott, P.E.

Abstract

The effects of rain-on-snow events are typically neglected during stormwater management design in Monroe County, NY and climatically similar regions. A study was conducted to examine the validity of this methodology by analyzing the combination of meltwater and precipitation over impermeable frozen ground. Studies were conducted using historical meteorological data for March and a theoretical test site located in Monroe County, NY for return periods of: 1, 2, 5, 10, 25, and 100 years. Meltwater flowrates and equivalent depths were calculated from March precipitation data using equations derived from thermodynamic principles. The March meltwater depths were compared to annual precipitation depths typically used in rainfall runoff analyses. It was determined that March rain-on-snow runoff depths were significantly less than annual precipitation rates for each of the return periods. Sensitivity analyses were conducted in order to determine the effects of snow pack depth and air temperature. Additionally, sensitivity analyses of the soil type and land use on the pre and post-development peak flows for the test site were conducted. The study confirmed that the runoff from rain-on-snow events is minimal in terms of percentage and overall magnitude compared to annual precipitation depths. Therefore, the current practice of neglecting rain-on-snow events during stormwater management design is valid in Monroe County, NY and climatically similar regions.

Keywords: Stormwater Management, Rain-on-snow, Northeast United States

1. Introduction

There are many factors that are considered when designing stormwater management facilities. The primary concern is controlling the amount of precipitation runoff from the developed site. Stormwater management facilities are designed to meet criteria established by regulatory agencies. A common regulatory requirement is that the post-development peak flowrate leaving the site must not exceed the pre-development peak flowrate for a range of return periods. There are also regulations limiting the amount of impervious cover allowed on a given site. Impervious improvements such as asphalt and concrete pavement cause more runoff than unimproved surfaces such as grass and woodland because no rainwater infiltrates into the soil subsurface. Soil type and precipitation rates are two other factors considered during stormwater management. Soils are classified into four main hydrologic soil groups (HSG): A, B, C and D. The HSG types range from granular sandy type “A” soils to cohesive clayey type “D” soils. Cohesive soils result in more runoff because less water permeates into the soils. Precipitation is a key factor in stormwater design because it is the major source of surface runoff on. Stormwater management facilities in New York are sized according to design frequency precipitation for a particular location[1]. Design storms typically range from 1 year to 100 year return periods. Runoff estimates in the northeast United States do not typically account for melting snow pack. However, intuitively, residents of this region "know" that flooding is most severe in the spring. Steady rain, melting snow and frozen ground combine and lead to the frequent spring flooding. In other parts of the world, runoff may result in serious flooding during rain-on-snow (ROS) events[2]. Rain-on-snow may cause rapid melting of snowpack which leads to large amounts of runoff. Late-winter rain events are common in mountainous regions of the world such as the Austrian Alps and lead to high stream flows at the base of those areas[2]. As water penetrates the snowpack on the ground, the bonds between the snow grains weaken and reduce the mechanical strength of the snow[2]. In dryer regions where much of the annual precipitation comes from snowfall, consideration of melting snow to size storm water management systems is very important. In Upstate New York and other parts of the Northeastern United States, these ROS events are often ignored or not taken into consideration during the stormwater management design process. This research was completed in order to scientifically examine the current rainfall runoff regulatory ideology and determine if ROS events produce higher average runoff flowrates than the existing precipitation models.

2. Methodology

A reasonable worst case scenario was created for estimating ROS event runoff in Monroe County, New York. Meteorological data was collected for March which included air temperature[2], snow pack depths[3], wind speed[2], and precipitation[2] rates. The weather data was used to calculate the 1, 2, 5, 10, 25, and 100 year recurrence intervals for air temperature, 24-hour rainfall depth, and snowpack depth for the month of March (Equation 1). Recurrence intervals are used to classify the frequency of storm event. For example: a 1 year storm event has a 100% chance of happening at least once every year while there is only a 1% chance that a 100 year storm event will occur within that same year.

$$\text{Reccurence Interval: } \frac{\text{number of years of record used} + 0.12}{\text{magnitude of rank} - 0.44} \qquad (1)$$

It was necessary to make several assumptions in this research. The assumptions can be categorized as either runoff or thermodynamics related. The following assumptions were used for the runoff calculations:

- The ground is frozen, no infiltration occurs.
- The snow is saturated at the beginning of the precipitation event; the rain will no longer be absorbed into the snow pack.
- No additional depression storage, all puddles are filled.

The runoff related assumptions ensure that the calculations yield the highest possible ROS runoff rates by limiting infiltration and maximizing surface runoff.

For the thermodynamic calculations, the following assumptions were made:

- The surface snow temperature and the melt water temperature are 0° Celsius (°C).
- The rainwater is the same temperature as the air temperature.
- All the energy absorbed from the rain contributes to melting the snow.
- No heat transfer occurs between the ground and the snow as the ground is frozen.
- No radiation heat transfer to or from the snow.

The thermodynamic assumptions enable the calculation of melt water runoff for any given air temperature and rainfall intensity with Equations Two (2) through Nine (9) obtained from *Singh et al*[4]. The following equations also carry the assumption that the volume of snow melted is less than the total volume of snow present.

$$K_h:\ \frac{C_{pa} * k^2 * \rho_0}{P_0 * \ln\left(\frac{z}{z_{0W}}\right) * \ln\left(\frac{z}{z_{0T}}\right)} \quad (2)^4$$

Where:

- K_h is the sensible heat exchange coefficient
- C_{pa} is the specific heat of air (1,005 kJ kg^{-1} $°C^{-1}$)
- k is Karman's Constant (0.41)
- ρ_0 is the standard density of air (1.29 kg m^{-3})
- P_0 is standard atmospheric pressure (101.3 kPa)
- z is height of instruments (2m based on *Singh's* experiment)
- z_{0W} is the roughness parameter for logarithmic wind profile (1.0×10^{-4} m)
- z_{0T} is the roughness parameter for temperature wind profile, (6.0×10^{-6} m)

$$K_e:\ \frac{L * k^2 * \rho_0 * 0.623}{P_0 * \ln\left(\frac{z}{z_{0W}}\right) * \ln\left(\frac{z}{z_{0e}}\right)} \quad (3)^4$$

Where:

- K_e is the latent heat exchange coefficient
- L is the latent heat of evaporation (2.514×10^3 kJ kg^{-1})
- k is Karman's Constant (0.41)
- ρ_0 is the standard density of air (1.29 kg m^{-3})
- P_0 is standard atmospheric pressure (101.3 kPa)
- z is height of instruments (2 m based on *Singh's* experiment)
- z_{0W} is the roughness parameter for logarithmic wind profile (1.0×10^{-4} m)
- z_{0e} is the roughness parameter for logarithmic vapor pressure profile (6.0×10^{-6} m)

$$Q_h:\ K_h * P * \Delta T * V \quad (4)^4$$

Where:

- Q_h is sensible heat flux (W m^{-2})
- P is the atmospheric pressure (variable, Pa)
- ΔT is the difference in temperature between snow and air (variable, °C)
- V is the mean wind speed (variable, m s^{-1})

$$Q_e:\ K_e * \Delta e * V \quad (5)^4$$

Where:

- Q_e is latent heat flux (W m^{-2})
- K_e is the latent heat exchange coefficient
- Δe is difference in air and snow surface vapor pressure (Pa)
- V is mean wind speed (variable variable, m s^{-1})

$$Q_r:\ 0.001 * \rho_w * C_{pw} * \Delta T * R \quad (6)^4$$

Where:

- Q_r is rain heat flux (W m^{-2})
- ρ_w is the density of water (1,000 kg m^{-3})
- C_{pa} is the specific heat of water (4.2 kJ kg^{-1} $°C^{-1}$)

- ΔT is the difference in temperature between snow and air (°C)
- R is the rate of rainfall (m s^{-1})

$$Q_{flux}:\ Q_h + Q_e + Q_r \tag{7}$$ [4]

Where:

- Q_{flux} is heat flux, total energy gained by the snowpack (W m^{-2})
- Q_h is sensible heat flux (W m^{-2})
- Q_e is latent heat flux (W m^{-2})
- Q_r is rain heat flux (W m^{-2})

$$Q_{flux}:\ \left(\frac{\dot{m}}{a}\right) * \Delta \mathrm{H}_{\mathrm{Vw}} \tag{8}$$ [4]

Where:

- Q_{flux} is heat flux, total energy gained by the snowpack (W m^{-2})
- m is mass of meltwater (kg)
- a is area of site (m^2)
- ΔH_{Vw} is the energy change of the meltwater (J)

$$Equivalent\ Depth_{Snow\ Melt}:\ \frac{\dot{m}}{a \times \rho_w} \tag{9}$$ [4]

Where:

- $Equivalent\ Depth_{Snow\ Melt}$ is the depth of meltwater caused by heat flux (m)
- m is mass of meltwater (kg)
- a is area of site (m^2)
- ρ_w is the density of water (1,000 kg m^{-3})

The equivalent depth of meltwater (EDMW) is the depth of snow melted during a ROS event per unit area. Air temperature, snowpack depths and precipitation values were varied between the minimum and maximum values in order to determine the greatest EDMW for each recurrence interval. Average runoff flowrates from ROS events are calculated by multiplying the EDMW by the total area of a given site by the duration of the rainfall event.

In order to assess the relative contribution of meltwater to total runoff during a rain event *TR-55* rainfall/runoff methodology and *WinTR-55* software were utilized. TR-55 methodology was chosen for the rainfall/runoff analysis because it is state-of-the-practice in the stormwater management field and is able to estimate runoff from various soil types and land uses. The peak runoff discharge rates for the 1, 2, 5, 10, 25, and 100 year annual rain events were determined on hypothetical 10 acre test sites located in Monroe County, NY. One site was undeveloped with a land use of "meadow" while the other site was developed with a land use of "commercial and business". These two land uses provide the most contrast in runoff rates in the TR-55 method. "Typical" 24-hour rainfall-runoff events were analyzed for return periods of 1, 2, 5, 10, 25, and 100 years and hydrologic soil groups (HSG) A (sands) through D (clays). Sandy soils (HSG A) cause lower runoff rates than clayey soils (HSG D) because coarser grained soils have a higher infiltration rate, which decreases the amount of water available for runoff. The annual peak runoff flowrates from rain, only events were compared to the combined meltwater and rainfall flowrates generated during March ROS events.

3. Results And Discussion

Table 1 shows the input values for snowpack, temperature, and 24-hour rainfall totals at the Rochester International Airport in the month of March. The average 24-hour hour rainfall totals used in typical stormwater design are shown in the sixth column. The data in the second through fifth columns of Table 1 are used to determine the EDMW. The average 24-hour rainfall totals are used in the sensitivity analyses shown in Tables 3 and 4, below.

Table 1: Input Values

Recurrence Interval (Years)	March Snowpack (Inches)	Maximum March Temperature (°Fahrenheit)	Mean March Temperature (°Fahrenheit)	March 24-Hour Rainfall Total (Inches)	Annual 24-Hour Rainfall Total (Inches)
1	0.0	45.0	22.3	0.15	1.83
2	13.0	68.6	33.3	0.73	2.13
5	22.4	75.0	37.2	1.08	2.60
10	30.1	78.9	39.4	1.20	3.03
25	38.1	82.2	42.5	1.27	3.70
100	46.7	83.5	45.0	1.30	5.01

The annual 24-hour rainfall totals are higher than the March only rainfall totals because the annual totals include all of the heavy rain-only precipitation events that typically occur in late spring, summer, and early autumn.

Table 2 shows the results of the thermodynamic calculations and depth of runoff for each recurrence interval. The total runoff contributed from snow melt is less than 1% for each recurrence interval and decreases as the recurrence interval increases. Also, between the 1 and 100 year recurrence intervals, the increase in runoff depth from meltwater and rainfall is 172 percent and 793 percent, respectively. The relative contribution of meltwater is small under the worst case scenario (e.g. 1 year recurrence) and decreases as the recurrence interval increases. This indicates that in Monroe County, NY, the relative impact of precipitation depths on runoff rates is much greater than air temperature and snowpack depth.

Table 2: Runoff Depths During 24-Hour Rain on Snow Events in March

Recurrence Interval	Runoff Depth from Snow Melt (Inches)	Runoff Depth from Rainfall (Inches)	Combined Runoff Depth/Equivalent Depth of Meltwater (Inches)	Percentage of Combined Runoff That is Snow Melt
1	0.0011	0.1459	0.1470	0.75%
2	0.0020	0.7304	0.7324	0.27%
5	0.0026	1.0811	1.0837	0.24%
10	0.0028	1.1980	1.2008	0.23%
25	0.0029	1.2681	1.2710	0.23%
100	0.0030	1.3032	1.3062	0.23%

Table 3 shows the peak runoff rates of the 10 acre test sites used in the sensitivity analysis. The annual 24-hour rainfall totals for each recurrence interval were used to calculate the peak runoff rates on the test sites because those values would be used in the actual design of the sites. The bottom row of Table 3 shows the average 24-hour runoff rates from March ROS events. The March ROS depths and flowrates are independent of soil type and land use because the soil beneath the snowpack is assumed to be frozen and therefore impermeable in all cases. The March ROS runoff rates were calculated by multiplying the 24-hour rainfall total by the site area and converting to cubic feet per second (cfs).

Table 3: Traditional Rain-Only 24-Hour Event Flowrates

		Design Storm Frequency					
		1-yr	2-yr	5-yr	10-yr	25-yr	100-yr
Condition	HSG	Peak Flow (cfs)					
Traditional Rain-Only 24 Hour Precipitation Event, Pre-Development Conditions	A	0.00	0.00	0.00	0.00	0.00	0.00
	B	0.00	0.07	0.31	0.79	1.96	5.38
	C	0.62	1.19	2.37	3.69	6.07	11.42
	D	1.73	2.67	4.36	6.08	8.96	15.03
Traditional Rain-Only 24 Hour Precipitation Event, Post-Development Conditions	A	6.95	8.94	12.16	15.22	19.95	29.32
	B	8.56	10.70	14.00	17.12	21.97	31.32
	C	9.75	11.90	15.28	18.33	23.07	32.38
	D	10.35	12.45	15.80	18.95	23.70	32.90
Rain-on-Snow (ROS) Runoff Rate, cfs		0.06	0.31	0.46	0.50	0.53	0.55

Table 4 compares the peak runoff rates for the test sites under “typical conditions” to the average runoff rates from March ROS events.

Table 4: Ratio of Rain-on-Snow (ROS) Flowrates to Traditional Rain-Only Event Flowrates

		Design Storm Frequency					
		1-yr	2-yr	5-yr	10-yr	25-yr	100-yr
Condition	HSG	Ratio of Average ROS Runoff Rates to Test Site Peak Runoff Rates					
Pre-Development	A	Undefined[1]	Undefined[1]	Undefined[1]	Undefined[1]	Undefined[1]	Undefined[1]
	B	Undefined[1]	442.86%	148.39%	64.56%	27.55%	10.22%
	C	9.68%	26.05%	19.41%	13.82%	8.90%	4.82%
	D	3.47%	11.61%	10.55%	8.39%	6.03%	3.66%
Post-Development	A	0.86%	3.47%	3.78%	3.35%	2.71%	1.88%
	B	0.70%	2.90%	3.29%	2.98%	2.46%	1.76%
	C	0.62%	2.61%	3.01%	2.78%	2.34%	1.70%
	D	0.58%	2.49%	2.91%	2.69%	2.28%	1.67%

1: The peak flowrate ratios are “undefined” in Table 2 because the corresponding flowrates in Table 1 are zero (0).

March ROS runoff rates exceed annual runoff rates only under pre-development conditions in granular soils. In these cases, much of the annual precipitation at lower recurrence intervals infiltrates into the soil rather than becoming surface runoff. Conversely, the ground is frozen and impermeable in the March ROS events. Therefore, 100 percent of meltwater converts to surface runoff. As annual precipitation rates increase a greater percentage of rainfall turns into surface runoff and the ratio of ROS to annual runoff rates decreases. The ROS runoff rates are minimal compared to the post-developed flow rates experiencing traditional rain-only events.

4. Conclusion

The results of the rain-on-snow calculations confirm that March rain-on-snow events in Monroe County, NY are typically insignificant compared to annual rain-only events traditionally used in estimate runoff in stormwater management. Therefore, the current of standard of not considering rain-on-snow events during the stormwater management design phase is valid. The heavy flooding that occasionally occurs during the spring melt in Monroe County and surrounding area is likely due to ice dams and other types of clogging in stormwater collection systems.

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