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Analysis of Rain-on-Snow Runoff Events in New York

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ABSTRACT

Rain-on-snow (ROS) runoff events are important hydro-meteorological phenomenon due to their association with flooding. The severity of ROS runoff events depends on the magnitude of the precipitation, air temperature elevation, snow water equivalent, and areal extent of the antecedent snowpack. Examining the consequences of these factors acting together creates challenges for both flood prediction and flood risk assessments. The purpose of this study is to provide information on the spatial patterns and variability of rain-on-snow events in New York. We examine the spatial and temporal variability of rain-on-snow events for water years 2004 to 2012 from SNOw Data Assimilation System (SNODAS) products for New York. Liquid and solid precipitation, snow depth, snow melt, snow water equivalent, maximum and minimum temperature, and streamflow characteristics are examined. Our study shows that rain-on-snow events are dominant in high elevation areas and their distribution varies with month. There is significant positive correlation of rain-on-snow days and rain-on-snow runoff events with elevation and negative correlation of these events with increasing air temperature.

Keywords: Runoff events, rain-on-snow, precipitation, temperature, elevation.

INTRODUCTION

Rain-on-snow (ROS) is an important winter and spring phenomenon that plays a significant role in generating high streamflow and has greater potential for generating serious floods than does radiation-induced snowmelt (Kattelmann, 1985). The term “rain-on-snow” is interpreted in many different ways. While the literal meaning of the term “rain-on-snow” would be snow melted by warm rain, many researchers have recognized that this is not entirely the case. Introduction of liquid water into snow weakens the bond between grains and alters the snow texture, which results in reduced mechanical strength of the snowpack. Rain-on-snow is an important process for flooding in the eastern United States as well (Graybeal and Leathers, 2006). For example, in January 1996, a combination of thaw with three days of very mild temperatures and intense rainfall increased the levels of streams and lakes causing massive flooding in many parts if Northeastern US (Leathers et al., 1998). In that case, the runoff from the snowmelt and the heavy rainfall, which may have been enhanced by orographic effects, combined to create the severe flooding.

In order to improve streamflow prediction for reservoir operation, flood control, and design of major structures, models are needed to estimate the timing, amount, and rate of outflow from the

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snowpack under rain-on-snow events (McCabe et al., 2007). Such knowledge is enhanced by a thorough understanding of processes associated with liquid water storage, natural and rain-induced melting, and transmission through the snowpack. Wankiewicz (1978) emphasized the quantitative effect of snow cover on the various runoff mechanisms, and Kattelmann (1985) discussed the necessity of accurate forecasting snowmelt particularly during rainy conditions. Peak flow that result from low values of precipitation are small and of little consequence in terms of erosional damage in upland areas or downstream flooding. But if rapid snowmelt occurs during rainfall, the erosional potential of storm runoff may increase. Because high daily rainfall rates cause high streamflow levels, even a small addition of snowmelt water during high daily rainfall most likely would increase storm runoff volume and the size of instantaneous peak flows, thereby increasing the chance of not only channel erosion and landslides in upland watersheds but also downstream flooding (Harr, 1981).

Limited documentation of rain-on-snow events makes anticipation and mitigation of potential hazards difficult. To help overcome the lack of useful information, this investigation provides basic information on the spatial and temporal patterns and temporal trends of rain-on-snow events in New York. This study, one of the first of its in the Northeastern US, will therefore provide important information on rain-on-snow events, including their frequency of occurrence, seasonal patterns, magnitude of snow water equivalent, and snowmelt generation; data necessary for water managers to improve their management plans.

METHODS

Streamflow and climate records for 31 watersheds in New York State (Figure 1; Table 1) were used to determine frequency of runoff events resulting from rainfall on snowpack or snowmelt. The area of these watersheds ranged from as small as 29 km^2 to 1574 km^2, and the mean elevation ranged from 105 m to 788 m.

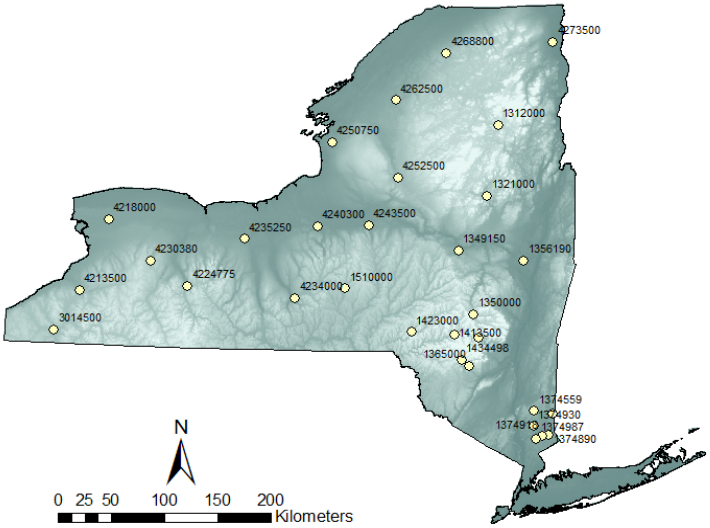


Figure 1. Map of New York State and USGS gage stations for rain-on-snow events study.

Table 1. Watershed area and average elevation of 31 USGS gages. The watersheds are arranged by regions and in ascending order of elevation

USGS Gage	USGS Gage	Area (sq. km)	Basin Mean Elevation (m)	Elevation Range (m)	Region
4262500	West Branch Oswegatchie River	668.2	399.9	181–538	Adirondack
4268800	West Branch Regis	442.9	474.9	89–838	Adirondack
4273500	Saranac at Plattsburgh	1574.7	499.5	29–501	Adirondack
4252500	Blackriver near Boonville	787.4	499.9	220–645	Adirondack
1321000	Sacandaga River near Hope	1271.7	581.4	235–668	Adirondack
1312000	Hudson River near Newcomb	497.3	660	456–1095	Adirondack
1423000	West Br Delaware River at Walton	859.9	592.1	350–777	Catskill
1365000	Rondout Creek near Lowes Corners	99.2	628.6	256–1173	Catskill
1350000	Schoharie Creek at Prattsville	613.8	652.6	344–956	Catskill
1413500	East Br Delaware R. at Margaretteville	422.2	667.3	390–1057	Catskill
1362200	Esopus Creek at Alaben	165	671.5	180–1042	Catskill
1434498	West Br. Neversink at Claryville	87.5	788.2	439–903	Catskill
1356190	Lishakill NW of Niskayuna	40.4	104.9	55–154	East
1349150	Canajoharie Creek at Canajoharie	154.6	310.5	86–703	East
4235250	Flint Creek at Phelps	264.2	338.1	139–654	Finger Lake
4240300	Ninemile Creek at Lakeland	297.9	272.2	110–582	Finger Lake
4243500	Oneida Creek at Oneida	292.7	312.3	112–162	Finger Lake
4234000	Fall Creek at Ithaca	326.3	414.7	116–575	Finger Lake
1510000	Ostellic River at Cincinnatus	380.7	483.2	286–636	Finger Lake
1374987	Kisco River below Mt. Kisco	45.6	137.8	63–245	Southeast
1374918	Stonehill River South of Katonah	48.4	146.2	66–265	Southeast
1374890	Cross River near Cross River	44.3	169.3	103–304	Southeast
1374930	Muscoot River near Baldwin Place	35	204.7	155–344	Southeast
13744980	East Br. Croton River near Putnam Lake	160.8	213.6	117–406	Southeast
1374559	West Br. Croton River at Richardsville	28.5	257.1	155–357	Southeast
4218000	Tonawanda Creek at Rapids	903.9	236.7	173–244	West
4250750	Sandy Creek near Adams	354.8	331.4	74–521	West
3014500	Chadokoin River at Falconer	502.5	454.6	377–568	West
4230380	Oatka Creek at Warsaw	101.3	468.7	156–588	West
4213500	Cattaraugus Creek at Gowanda	1129.2	492.1	174–709	West
4224775	Canaseraga Creek above Dansville	230.3	498.6	160–690	West

Streamflow data were downloaded from USGS National Water Information System for each of the 31 watersheds. The first step in hydrograph analysis entails separation of stream flow into surface runoff and base flow components. Baseflow separation is done using filter method outlined by Arnold et al. (1995). Event runoff is defined as the direct surface runoff component of the baseflow-separated daily hydrograph summed over a period that lasts from the first day of streamflow hydrograph rise (t_1) until the beginning of the next event (t_2) (Hewlett and Hibbert, 1967). The length of the runoff event is defined as the period between the first day of streamflow rise (t_1) until the beginning of the next event (t_2).

Snow accumulations prior to runoff events were determined from snow depth from SNOw Data Assimilation System (SNODAS) (NOHRSC, 2010). The SNODAS is a modeling and data assimilation system has been developed by the National Weather Service's National Operational Hydrologic Remote Sensing Center (NOHRSC) to provide estimates of snow cover, snow water equivalent, snowmelt, and associated snowpack variables at a 1-km spatial resolution to support hydrologic modeling and analysis. SNODAS includes procedures to ingest and downscale output from Numerical Weather Prediction (NWP) models; a physically based, spatially-distributed energy-and-mass-balance snow model; and procedures to assimilate satellite-derived, airborne and ground-based observations of snow covered area (SCA) and snow water equivalent. For this study, we analyzed liquid precipitation, snowpack depth, snowmelt, and snow water equivalent from October to April (2003–2012). To obtain averages or totals for desired parameters representative of the USGS basins, the gridded (~1 km) SNODAS data were extracted based on the areal extent of the watersheds. Since air temperature is not one of the output variables of SNODAS, we used spatially distributed air temperature data from the Northeast Regional Climate Center (NRCC) at Cornell University, Ithaca, NY (DeGaetano and Belcher, 2007). The 4-km-resolution air temperature data were spatially averaged for 31 watersheds.

Rain-on-snow runoff events were characterized based on snowmelt, snow depth, liquid precipitation (rain) and solid precipitation (snow) information obtained from SNODAS. Two ROS variables are calculated for each watershed:

- a ROS day for a site was defined as a day when precipitation occurred as rain and snowpack was present.
- a ROS runoff event was defined as a runoff event, as previously defined, with at least 1 ROS day occurring within the event.

The Spearman rank correlation test was used for exploratory data analysis. Correlation analysis was done to understand relationships between elevation, temperature, rain-on-snow, and precipitation characteristics. Spearman rank correlation is often used as a statistical tool to detect monotonic relationship. It is a non-parametric technique and, therefore, not affected by the statistical distribution of the population. Because the technique operates on ranks of the data, it is relatively insensitive to the outliers and there is no requirement that the data be collected over regularly spaced temporal intervals (Helsel and Hirsch, 1992) . The Spearman rank correlation coefficient (r) is calculated using equation 1:

$$r = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n^3 - n} \tag{1}$$

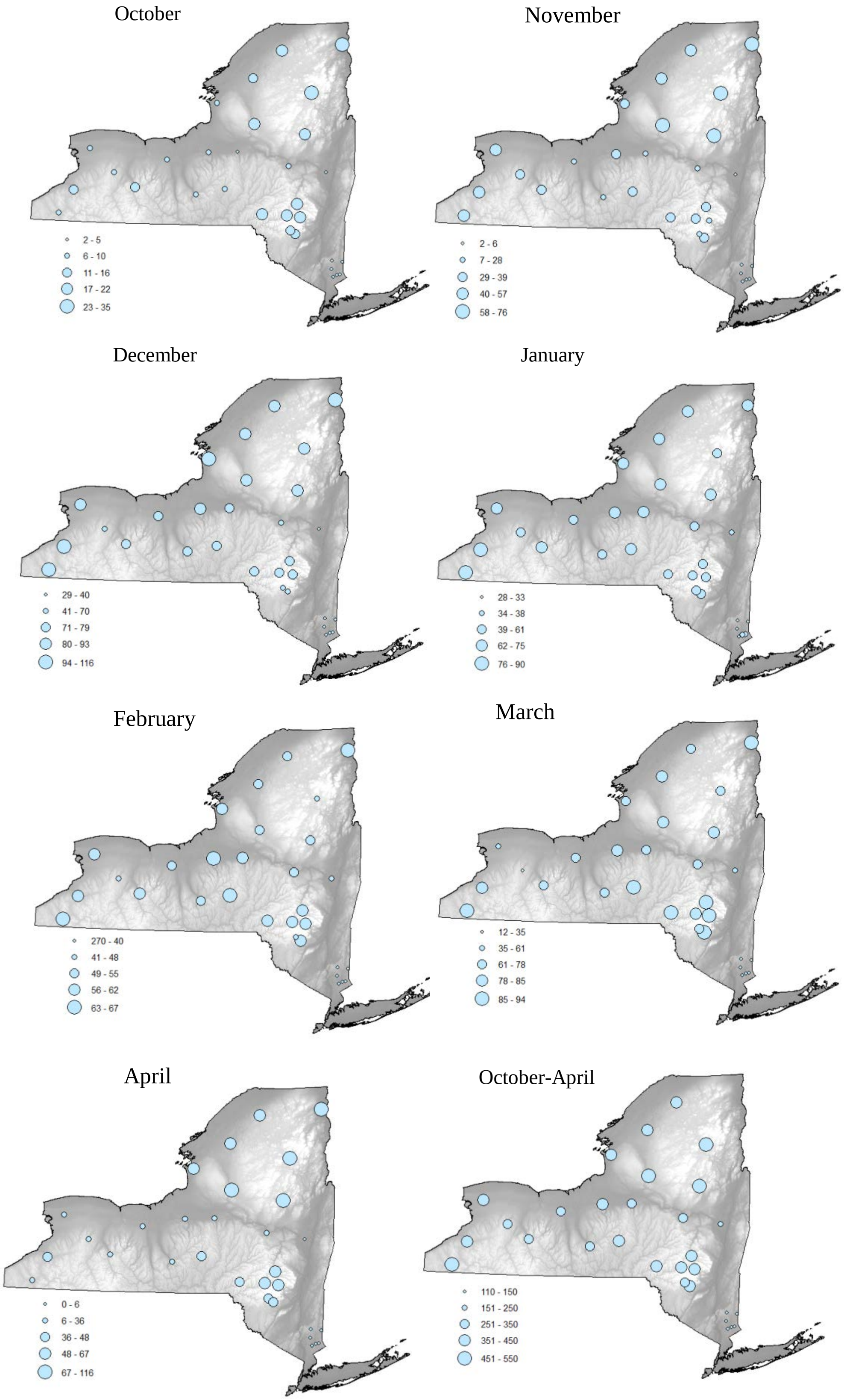
where, d_i is the difference between rank for each x_i, y_i data pair and n is the number of data pairs. The strength of the relation is indicated by r, which ranges from −1 (strong negative correlation) to +1 (strong positive correlation) with a value of 0 denoting no correlation. A two-tailed significance test ($\alpha = 0.05$) was done to assess significance of correlation between variables.

Annual peak flow for 31 basins was analyzed for the period of record when data were available. Peak flows were ranked by size for periods of records, and SNODAS were used where possible to separate peak flows caused by rainfall from peak flows caused by rain-on-snow. Peak flow sources were identified for 2003–2012 period using SNODAS model information by identifying the date of peak flow occurrence and the occurrence of runoff due rain-on-snow. Peak flow return period was calculated using Log Pearson Type III analysis (Graybeal and Leathers, 2006).

RESULTS AND DISCUSSIONS

Rain-on-snow runoff events and elevation relations

Daily precipitation as rain and snowfall, snow water equivalent and snowmelt of 31 USGS gage watersheds in New York were used to examine the spatial and temporal patterns of rain-on-snow runoff events for water year 2003 through 2012. Figure 2 shows the spatial and temporal pattern of runoff events with rain-on-snow on a monthly basis that occurred during the period of study. ROS runoff events are found to be most frequent in the Catskill and western region New York during December and varied spatially. The total number of ROS runoff events was the largest in the Adirondack, western, and Catskill regions of NY. In general, ROS runoff events are less frequent in southeast New York and Finger Lakes regions. The ROS runoff events generally occurs in most watersheds as early as October and as late as April. Although it is quite possible that some watersheds in the far north and west of New York may experience snowfall and subsequent runoff as early as September and as late as May, these earlier and later months were not investigated as these events generally represented a small fraction of ROS events.



October

November

December

January

February

March

April

October-April

Figure 2. ROS runoff events, October to April during 2003–2012**.**

During March and April, when rain-on-snow frequencies are the highest, decrease in snow water equivalent is greatest. In March and April, the largest snowmelt per ROS runoff event occurred in the Central and Northern New York. The magnitude of snow depth is largest in the northern NY during spring; thus, April ROS runoff events in these locations can still melt a significant amount of snow. The number of rain days at a site is an important precipitation characteristic related to the frequency of ROS runoff events. For the study period, the percentage of rain-on-snow days is about 19–24% of total rain days at the lowest elevation basins (located in the southeast region); and this percentage increases with increased elevation and locations of the watersheds (greater than 60% in the Adirondack Region) (Table 2). The proportion of ROS runoff events to the total number of runoff events was highest in the Adirondack region followed by the Catskills region. Another important condition for ROS runoff events is an accumulation of snow on the ground. Temperatures at the lower elevation sites are warmer, reducing the number of days with snowpack on the ground, and thus reducing the number of potential rain-on-snow days.

Table 2. Precipitation characteristics and rain-on-snow events in 31 USGS gage watersheds. The watersheds are arranged by regions and in ascending order of elevation. (2003–2012).

USGS Gage	Total Rain Days	ROS Days	Percent of Rain Days that are ROS days	Total number of runoff events (October–April)	ROS Runoff Events	Percent of runoff events that are ROS Runoff Events	Annual Peak Flow caused by rain-on-snow (2003–2012)
04262500	712	434	61	112	66	59	9
04268800	674	410	61	127	74	58	9
04273500	750	554	74	168	78	46	8
04252500	708	481	68	154	90	58	5
01321000	692	470	68	143	80	56	8
01312000	659	482	73	110	63	57	8
01423000	670	379	57	157	98	62	6
01365000	632	361	57	170	71	42	7
01350000	661	398	60	163	79	48	7
01413500	656	388	59	149	70	47	7
01362200	645	392	61	141	69	49	7
01434498	589	326	55	182	78	43	7
01356190	552	181	33	217	46	21	8
01349150	650	302	46	197	78	40	6
04235250	715	322	45	159	64	40	8
04240300	752	378	50	170	74	44	8
04243500	715	330	46	208	75	36	7
04234000	687	327	48	207	76	37	9
01510000	724	392	54	183	85	46	8
01374987	602	136	23	144	44	31	3
01374918	600	135	23	127	43	34	3
01374890	577	139	24	154	36	23	6
01374930	569	135	24	170	38	22	5
01374498	582	110	19	134	42	31	6

USGS Gage	Total Rain Days	ROS Days	Percent of Rain Days that are ROS days	Total number of runoff events (October–April)	ROS Runoff Events	Percent of runoff events that are ROS Runoff Events	Annual Peak Flow caused by rain-on-snow (2003–2012)
0							
01374559	577	136	24	140	44	31	6
04218000	776	356	46	146	68	47	9
04250750	725	408	56	156	86	55	9
03014500	868	457	53	95	57	60	5
04230380	679	259	38	207	68	33	7
04213500	799	436	55	200	103	51	7
04224775	702	338	48	138	58	42	8

During the late fall and winter, the frequencies of both ROS runoff events and ROS days increased with elevation. At the lowest elevation, the percentage of cool season precipitation days that are ROS days is close to zero for most of the sites. This elevation relationship with ROS runoff events and ROS days during the late March and April is primarily related to the number of days that snow is on the ground. The Spearman correlation analysis between elevation and rain days, ROS days, and ROS runoff events are presented in Table 2. The analysis was done for two seasons (i.e., OND [October–November–December], JFMA [January–February–March–April]) and for all months (October–April). All variables are positively correlated with elevations. ROS DAYS showed the highest positive correlation (0.72 for JFMA, 0.55 for OND, and 0.65 for October–April) with elevation and were significant at the 0.05 level. Similar significant positive correlations with elevation were observed for ROS runoff events for seasons. Snow on the ground days were positively correlated to elevation. Average snow water equivalent (SWE) increased with increasing elevation. The frequency of occurrence of ROS days and rain days also showed locational pattern. The number of ROS runoff events tended to increase in the Adirondack, Catskill, and western regions while there were less ROS runoff events in the southeast region. The relatively small differences in basin elevation may also mean that the observed differences in ROS days and ROS runoff events are better indexed by the location of these watersheds. There is little low elevation snow at these times and occasional precipitation causes a lower number of runoff events.

Rain-on-snow runoff events and temperature relations

Many studies have shown increasing temperature in Northeastern United States during the past several decades with subsequent effects on hydrological conditions, including decreasing snowpack and shifts to earlier snowmelt runoff (Burns et al., 2007; Hayhoe et al., 2008). Modeling studies in watersheds in New York have also indicated that climate change may result in decrease in snowpack and shift timing of annual peak and annual low flows (Pradhanang et al., 2011; Zion et al., 2011). The intensity and occurrence of runoff events are dependent on the development of snowpack and subsequent melt runoff event; we performed correlation analysis between ROS runoff events and average annual minimum and maximum temperature of each watershed under study.

The Spearman correlation analysis between the average maximum and minimum temperatures calculated over different seasonal time periods and rain days, ROS days, and ROS runoff events are presented in Table 3. The analysis was done for two seasons similar to the analysis of elevation (i.e., JFMA [January–February–March–April] and OND [October–November–December]). ROS days and ROS runoff events were negatively correlated with average maximum temperature during JFMA and were found to be significant at the 0.05 level. Average annual minimum temperature showed significant negative correlation with ROS days for JFMA. The results were not significant for OND except for ROS days. The correlation analysis of rain-on-snow variables with average maximum and minimum temperature for October–December, January–April, and October–April showed significant negative correlation (Table 3). The negative correlations between average temperature and ROS runoff event frequencies indicate that as temperature increases ROS runoff, events become less frequent. The negative correlations are most common for low elevation sites that are located in the southern part of NY.

Table 3. Spearman rank correlation coefficients for elevation, maximum and minimum temperature and rain-on-snow variables

Variables	Elevation			Average Maximum Temperature			Average Minimum Temperature		
	OND	JFMA	Oct–Apr	OND	JFMA	Oct–Apr	OND	JFMA	Oct–Apr
Rain Days	0.24	0.22	0.19	−0.47*	−0.25	−0.40*	−0.16	−0.34	−0.28
ROS Days	0.55*	0.72*	0.65*	−0.73*	−0.75*	−0.80*	−0.78*	−0.79*	−0.78*
ROS Runoff Events	0.68*	0.46*	0.57*	−0.78*	−0.49*	−0.67*	−0.54*	−0.71*	−0.64*
Snow on the ground days	0.79*	0.79*	0.79*	−0.91*	−0.79*	−0.90*	−0.89*	−0.91*	−0.92*
Average SWE	0.67*	0.54*	0.75*	−0.90*	−0.85*	−0.94*	−0.63*	−0.74*	−0.71*

OND: October–November–December

JFMA: January–February–March–April

Oct–Apr: From October to April

2-tailed test of significance is used

* Correlation is significant at the 0.05 level regions showed mixed results.

Streamflow characteristics

Rain-on-snow conditions produce streamflow hydrographs that generally differ from hydrographs caused by rain alone. Figure 3 shows examples of a typical hydrograph resulting from rain-on-snow, snowmelt and rain only runoff events. Rising limbs of rain-on-snow hydrographs are generally steeper than those associated with rain-only hydrographs. Differences in size of peak flows and rates of hydrograph rise might be expected due to differences in the amount and rate of water input. The combination of a ripened snowpack, snowmelt, and rain-on-snow generate large runoff compared to the runoff from snowmelt or rain alone. Peak flow sources were identified for 2003–2012 period using SNODAS model information. Ranking peak flow, as to whether or not snowmelt contributed substantially to the peaks, was done. The causes of peak flow were then identified based on rain and snow information from SNODAS. The results suggest that snowmelt during rainfall added to many annual peaks from 2003 to 2011. On average, 7 of 10 annual peaks were associated with *ROS* runoff events across all of the study sites. The sites that had less rain-on-snow related annual peaks were located in the southeast NY (Table 2). Most of rain-on-snow related peaks ranked highest in the record of study. Peak flow and return interval analysis showed that most of the highest annual peak flows occurred during mid- to late March. The comparison of the boxplots of event cumulative runoff identified as rain-on-snow generated and runoff generated by rain only is shown in Figure 4. The intensity of ROS runoff events compared to rain only runoff events tended to be greater in the Adirondack and Catskill regions of NY and increased with elevation. The southeast region showed greater cumulative runoff for rain only events. Other regions showed mixed results.

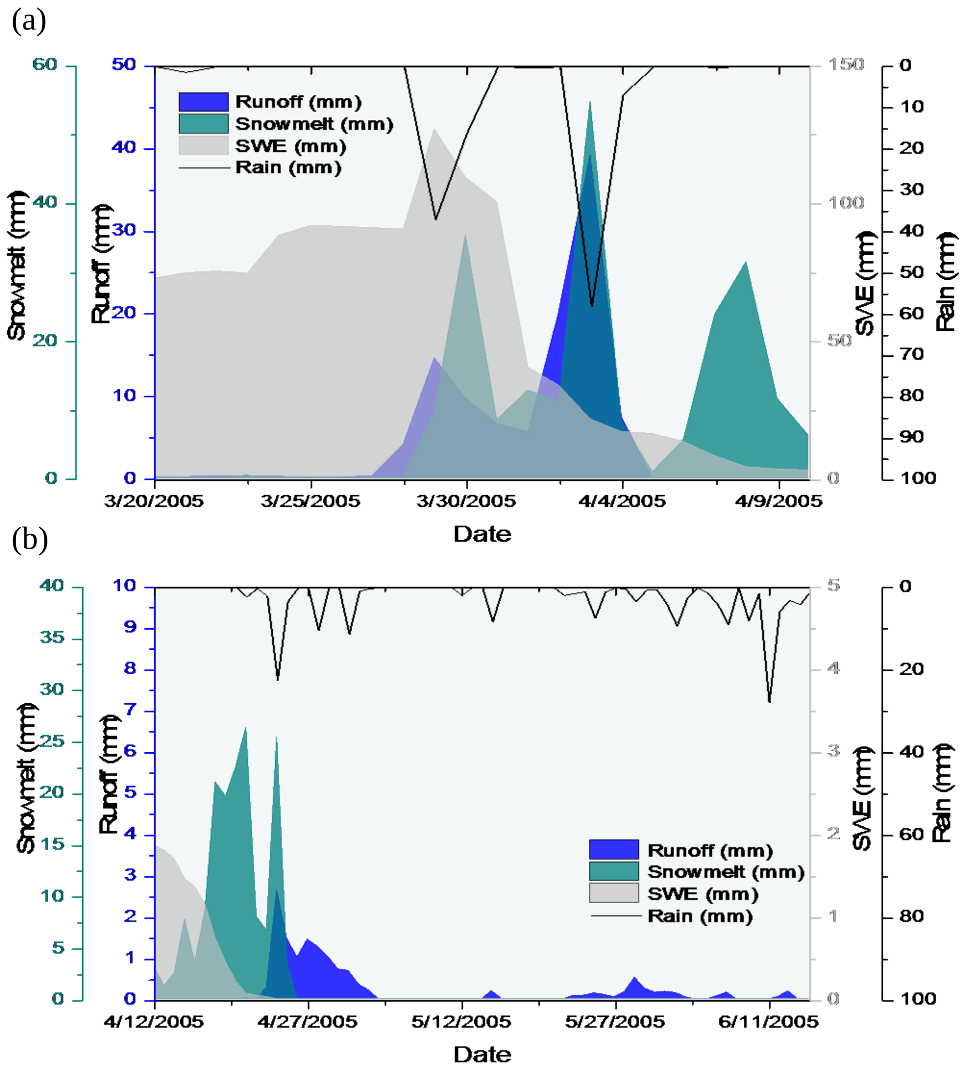
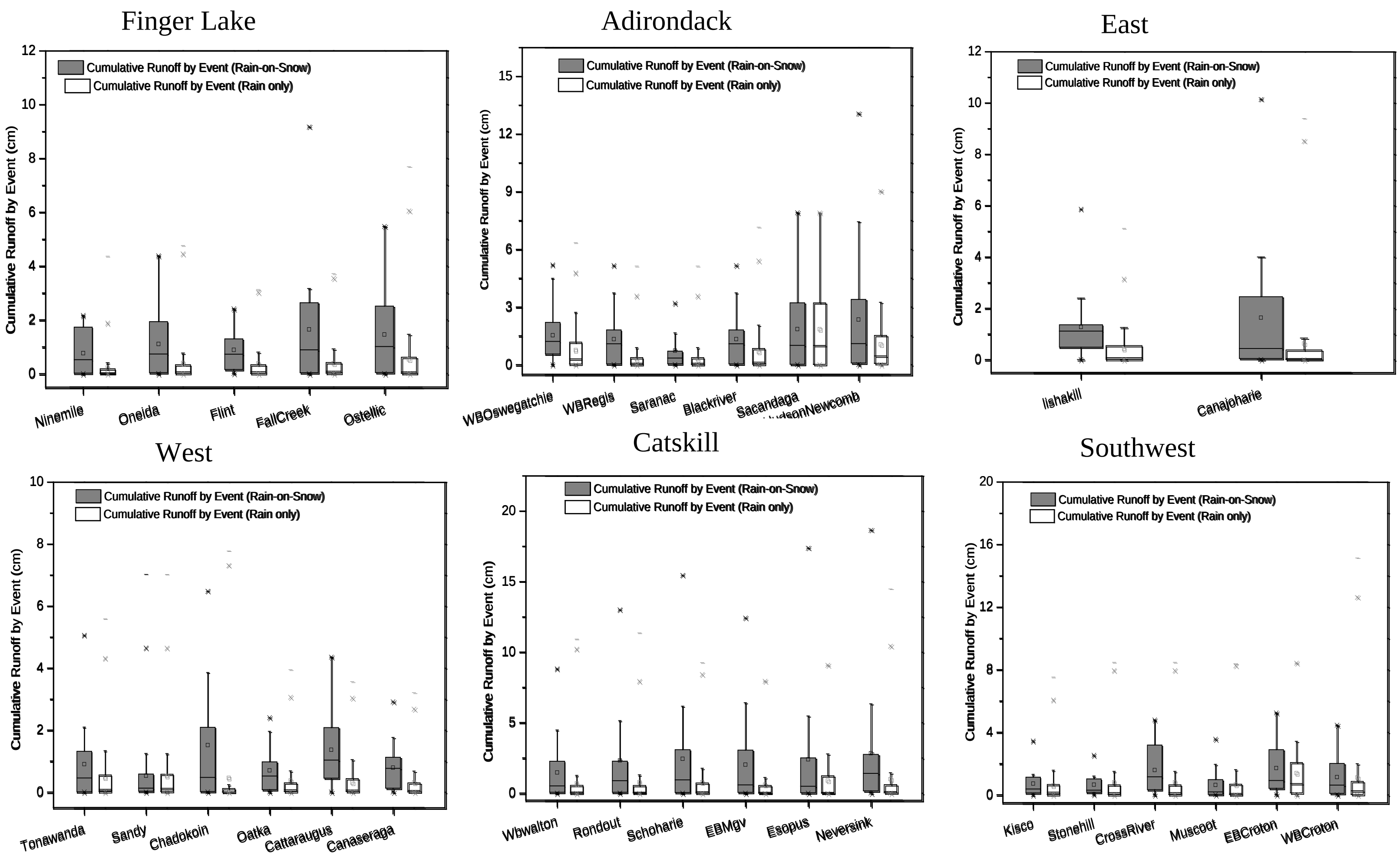


Figure 3. Hydrograph characteristics of a) rain-on-snow, and b) snowmelt and rain induced streamflow.

CONCLUSIONS

In conclusion, a first attempt has been made in documenting frequency of rain-on-snow events and their spatial and temporal distribution in New York. The period of 2003–2012 was selected to establish spatial and temporal patterns of ROS days and ROS runoff events, their correlation with elevation and temperature, and to compare hydrograph characteristics of ROS runoff events and rain only events. Seasonal snowfall amounts, rain on snowpack, or snowmelt were found to possibly play an important role in flooding in most of the areas in NY during 2005, 2007, and 2010. Flooding events caused by rain-on-snow can be devastating from human and economic perspectives and also present fascinating hydrologic phenomena in which climatological preconditioning and the occurrence of an unusual weather condition combine to create disastrous results. Our analyses on ROS days and ROS runoff events appear to follow logical climate relations and provide one of the first inventories of the magnitude of these relations, as well as description of elevation and regional differences in the relations. This information is useful as a base for additional research into rain-on-snow events, which should improve both flood forecast and assessments of flood risks.



Finger Lake

Adirondack

East

West

Catskill

Southwest

Figure 4. Boxplots of cumulative runoff by event for events due to rain-on-snow (grey shaded box) versus events due to rain-only. The boxes indicate the range of values between the 25th and 75th percentiles, the dark horizontal lines indicates the median, the ends of the dashed lines indicate the 1st and the 99th percentiles of the distribution and the small squares show the average

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