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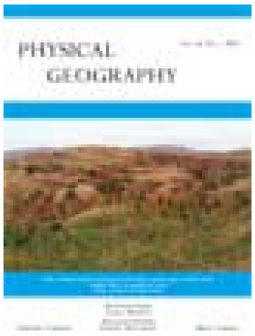

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ARTICLE

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Discharge responses associated with rapid snow cover ablation events in the Susquehanna and Wabash River basins

Zachary J. Suriano[a], Gina R. Henderson[b] and Daniel J. Leathers[c]

[a]Department of Geography & Geology, University of Nebraska Omaha, Omaha, NE, USA; [b]Oceanography Department, U.S. Naval Academy, Annapolis, MD, USA; [c]Department of Geography, University of Delaware, Newark, DE, USA

ABSTRACT

In the mid-latitudes, snow plays a critical role in regional hydroclimate, with snow ablation variability in ephemeral regions representing an area of essential research. Due to a lack of historical snow-water-equivalent data in the eastern United States, recent research has substituted daily snow depth changes for ablation. These studies, however, do not explicitly examine if such a substitution yields a snowmelt hydrological signal, an important component of water resource management. As such, this study evaluates if ablation events, as defined as a daily snow depth decrease, subsequently result in increased river discharge within two similarly sized watersheds in the eastern United States: the Wabash and Susquehanna River basins. For both basins, >75% of snow ablation events resulted in a positive river discharge response (increase in discharge) at a 3-day lag. Furthermore, results show a significant and positive relationship between ablation event frequency and seasonal discharge response, such that an increase (decrease) in seasonal snow ablation event frequency yields an increase (decrease) in associated seasonal river discharge at a 3-day lag. These relationships indicate that inter-diurnal decreases in snow depth do carry hydrological implications, adding confidence that such a definition of ablation is appropriate for climatological applications.

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Streamflow; snow depth change; snowmelt; Susquehanna; Wabash; cold-season hydroclimatology

Introduction

Snow cover ablation can greatly influence regional hydroclimatology, impacting streamflow, soil moisture, and groundwater supplies. In regions with ephemeral snow cover, the variable release of water from the snowpack can pose challenges to predicting and preparing for multiple events each year. In the United States from 1972–2006, 48 major snowmelt-related floods occurred, causing over $3.3 billion (2007 dollars) in losses (Changnon, 2008). One of the most prominent snowmelt floods occurred within the Susquehanna River drainage basin in January 1996; over 7.5 cm of liquid precipitation and an unseasonably warm and moist synoptic-scale system rapidly ablated over 0.5 m of snow, resulting in some 30 fatalities (Leathers, Kluck, & Kroczynski, 1998).

CONTACT Zachary J. Suriano zsuriano@unomaha.edu

In an effort to further the understanding of snow ablation processes in ephemeral regions, recent research has investigated the variability and forcings of ablation events in eastern North America (Dyer & Mote, 2007; Grundstein & Leathers, 1998, 1999; Leathers, Graybeal, Mote, Grundstein, & Robinson, 2004; Suriano, 2019; Suriano & Leathers, 2017, 2018). Across all of these studies, decreases in snow depth are used as a proxy for ablation. While care is taken to account for factors such as compaction and measurement bias, the link between snow depth decrease and stream discharge is not directly stated.

To begin establishing a link between snow depth change and stream discharge, this study examines two basins in the eastern United States: the Susquehanna River and Wabash River basins. The basins are of similar size and at a similar latitude, yet their respective snow covers are significantly different; snow cover in the Wabash River basin is less prevalent. The magnitude of snowmelt runoff can be dependent on more than just the magnitude of snow depth decrease, and is also influenced by antecedent soil moisture, snow-cover, river ice, and meteorological conditions. Due to these antecedent conditions, it is hypothesized that the magnitude of a snow depth decrease event will not be directly related to the magnitude of stream discharge for an individual event, but rather significant relationships will be apparent at monthly and seasonal time scales between ablation frequency and stream discharge. Such relationships would prove useful in supporting the conclusions of previous and future work (e.g. Suriano & Leathers, 2017), and in developing a climatology of discharge-causing ablation events within the basins.

A thorough description of the two drainage basins and the means of detecting snow ablation events that result in stream discharge are within the data and methodology section of the paper. In the results section, a brief climatology of discharge-causing ablation events is presented for both basins, followed by a detailed analysis of ablation–discharge relationships and their inter-annual variability. Finally, the summary and discussion section reiterates the key findings of the study and speaks to its implications.

Data and methodology

Snow data and basin definition

Daily snow depth data are obtained from a quality-controlled gridded North American dataset of snowfall, snow depth, precipitation, and temperature variables (Mote et al., 2018). The dataset is currently available at the National Snow and Ice Data Center (NSIDC; https://nsidc.org/data/g10021). Surface observations from the United States' Cooperative Observer Network and the Meteorological Service of Canada undergo quality control and are interpolated onto a 1-degree grid daily (Dyer & Mote, 2006; Kluver et al., 2017; Robinson, 1988; Suriano & Leathers, 2017). While the dataset currently terminates at the end of 2009, the historical snow ablation perspective it provides makes the dataset more advantageous for this study compared to other snow products, many of which are model-based (i.e. National Operational Hydrologic Remote Sensing Center data; NOHRSC).

The drainage basins of the Susquehanna and Wabash Rivers are based on the Hydrological Units from the United States Geological Survey's "Watershed Boundary Dataset" (http://nhd.usgs.gov/wbd.html), and gridded to a 1-degree resolution by a centroid method. If a grid cell's centroid falls within the spatial boundary of the watershed, that cell is considered within the basin at the 1-degree resolution. The two basins are of similar size at the 1-degree resolution, with the Wabash consisting of ten 1-degree grid cells and the Susquehanna consisting of nine (Table 1). The Susquehanna and Wabash River basins are bounded approximately by 40-43°N latitude, 75-79°W longitude and 38-41°N latitude, 84-89°W longitude, respectively (Figure 1).

The Susquehanna River basin includes portions of south-central New York state, east-central Pennsylvania, and a small region in northern Maryland. Collectively, the basin contains a population of approximately 4 million people, including the cities of Binghamton, NY, Harrisburg, PA, Wilkes-Barre, PA, and Williamsport, PA. Topography is highly variable due to the presence of the Appalachian Mountains; elevation ranges in the basin from nearly 300 m to sea level. As noted from USGS/Chesapeake Bay 2006 Land Use

Table 1. Descriptive information regarding the two studied watersheds: the susquehanna river basin (left) and the Wabash River basin (right). The percentage of Approved-Estimated data is based on the data-value qualification code provided by USGS. This value denotes data that may have been originally missing, but have been supplemented by the USGS. All data used, estimated or otherwise, has been deemed publication worthy and received the USGS Director's approval.

	Susquehanna River Basin	Wabash River Basin
Drainage Basin (km^2)	71,225	103,500
Drainage Basin (1-degree cells)	9	10
River Length (km)	747	810
Discharge Station	USGS 01570500 Harrisburg, PA	USGS 03377500 Mt. Carmel, IL
Datum of gage	290.01 feet above NGVD29	368.98 feet above NAVD88
Available Data Record	1 October 1890-present	1 October 1927-present
Percentage of Approved-Estimated Data	3.4%	0.9%

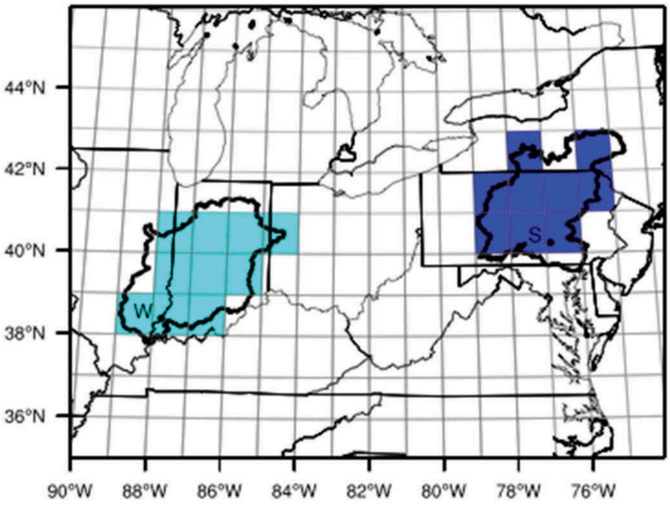

Figure 1. Map depicting the two studied watersheds: the Susquehanna River basin (dark blue) and the Wabash River basin (teal). The thick dark lines represent the basins' respective boundaries while the colored grid cells represent the basins' boundaries at a 1-degree resolution. Labeled points W and S indicate the locations of the Mt. Carmel (W) and Harrisburg (S) discharge stations for the Wabash and Susquehanna basins, respectively.

Data (from Susquehanna River Basin Commission, 2016), the majority of land cover within the basin is forest (64%), approximately 26% agricultural land, and 7% developed land. The river drains into the Atlantic Ocean via the Chesapeake Bay, where it is the largest tributary, contributing about half of the Bay's freshwater input.

The Wabash River basin sits approximately 750 km west of the Susquehanna, and covers much of central and western Indiana (some 75% of the state), eastern Illinois, and a small region in western Ohio. The basin, as of 2010, contained a population of approximately 4.4 million people, which includes the cities of Indianapolis, IN, Bloomington, IN, Urbana, IL, and Terre Haute, IN. In contrast to the Susquehanna, land cover in the Wabash River basin is predominately agriculture-based, with nearly 62% of land representing cultivated crops, 19% deciduous forest, 8% developed land, and 6% pasture (WRIWA, 2011). The river drains into the Ohio River at the southwest corner of Indiana, eventually draining into the Gulf of Mexico via the Mississippi River.

Ablation definition and calculation

Snow data in the Cooperative Observer Network (COOP), and thus the 1-degree dataset, contain no information on snow water equivalent. As such, changes in daily snow depth under specific conditions have been defined in prior work as ablation (Dyer & Mote, 2007; Grundstein & Leathers, 1998; Leathers et al., 2004; Suriano, 2019; Suriano & Leathers, 2017, 2018). This study uses a similar definition of ablation as the prior work, and defines ablation as an inter-diurnal decrease in basin-wide, areal-weighted snow depth under the following conditions: (1) the snow depth change is at least 2.54 cm, and (2) the maximum daily temperature on the second day of the associated event is > 0°C.

The 2.54 cm (1 inch) threshold is chosen as it represents the first measurable (non-trace) quantity of snow depth for station observers in the COOP network where observations are rounded to the nearest inch. Utilizing the temperature threshold brings greater confidence that snow depth changes are due to ablation, and not other physical processes such as compaction. Snowpack compaction can reduce the depth of the snowpack without modifying its mass due to destructive metamorphism and overburden forces (Colbeck, 1983). In the mid-latitudes, when surface air temperatures reach above 0°C, it can be assumed the snowpack is relatively mature and isothermal, limiting the portion of snow depth change attributable to compaction as effectively as possible (Dyer & Mote, 2007).

The Susquehanna and Wabash River drainage basins are located along the southern edge of typical North American snow cover, thus snow cover is often ephemeral and depths can be spatially variable. When an ablation event as defined in this study occurs, it does not mean the same magnitude of snow (depth) is ablated equally across the basin; ablation may be spatially inhomogeneous based on the current snow depth and specific meteorological conditions.

It is important to note snow depth decreases can occur due to sublimation and wind erosion. However, for a single ablation event, these factors are generally minimal (e.g. Dery & Yau, 2002) and are considered negligible in this study. Furthermore, in the event of missing data, a maximum of one (of nine/ten) grid cell within each respective basin may contain missing data in order for basin-wide snow depth and ablation to be calculated that particular day. If more than the maximum numbers of grid cells are missing, the day is not included in analysis.

Discharge data and methodology

River discharge data are obtained at one location for each drainage basin from the United States Geological Survey National Water Information System (Table 1). The Susquehanna River stream site at Harrisburg, Pennsylvania (USGS 01570500) and the Wabash River stream site at Mt. Carmel, Illinois (USGS 03377500) are selected (Figure 1). Both stream sites have sufficient periods of records, minimal missing data, and are considered the furthest points downstream in their respective rivers prior to human damming or river termination (Table 1). Data-value qualification for USGS stations are listed as either "A" for approved, "P" for provisional, "e" for estimated, or some combination of the previous. Only days in which the dataset is approved for publication, estimated or otherwise, are utilized in this study.

Discharge events are defined as a discharge response, or an inter-diurnal change in discharge (ft^3/s), calculated at multiple lags (i.e. a 3-day lag is the difference in the discharge of day three and day zero). In determining the appropriate lag between an ablation event and a potential corresponding river discharge event, a cross-correlation analysis is conducted for both drainage basins individually. Both drainage basins exhibit a peak cross-correlation between ablation and discharge at a three-day lag (Figure 2; Henderson, Arthur, Masters, Leathers, & Suriano, 2019), and thus represents the focus of this study. A discharge-causing ablation event is then defined as an ablation event that results in a positive (increasing) response in river discharge at a three-day lag. A brief climatology of the discharge-causing snow ablation events is presented for each drainage basin, followed by an analysis of the relationships between ablation and discharge at intra- and inter-seasonal time scales.

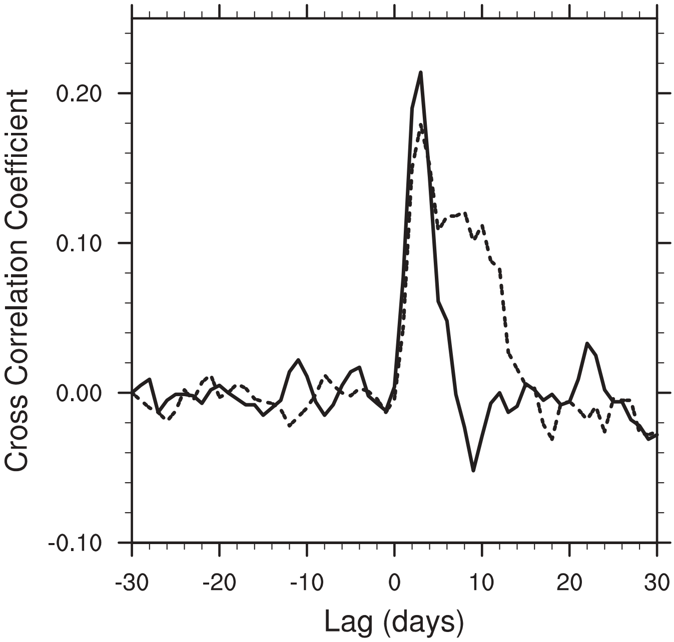

Figure 2. Cross-correlation coefficient of snow ablation magnitude and river discharge magnitude at various lags (in days) for the Susquehanna River basin (Solid) and the Wabash River basin (Dashed).

Results

Snow ablation climatology

Within the Susquehanna River basin from 1960–2009, a total of 441 snow ablation events occurred, resulting in a September–August snow season average of 8.8 events yr^{-1} (Standard Deviation (SD): 4.9 events). Of those 441 events, 334 (75.7%) resulted in an increase in river discharge at the Harrisburg, PA stream site at a 3-day lag (Table 2). Examining the seasonal cycle of ablation frequency (Figure 3(a)), events only occur during the 6 months of November–April, corresponding to a period of typical snow cover (Table 2). The frequency of ablation events steadily increases from a minimum in October to the maximum in March of approximately 2.2 events yr^{-1}; ablation events then rapidly decrease in frequency back to the minimum in May (Figure 3(a)). The discharge-causing ablation events have an average ablation magnitude of 4.3 cm event^{-1} (SD: 2.0 cm; Table 2). The seasonal cycle of ablation magnitude for the discharge-causing events is relatively constant, with the exception of April events, which exhibit a lower average magnitude than the months of November–March by approximately 1.0 cm (not shown).

Table 2. Summary statistics of snow depth, snow ablation events, and discharge-causing ablation events for both the Susquehanna and Wabash River basins. The snow season is defined as the period between the first and last occurrence of a basin-wide average snow depth in excess of 2.54 cm, whereas its snow depth is the average depth in cm for all days in the season. Ablation magnitude is reported as cm of snow depth.

	Susquehanna	Wabash
Total Ablation Events (days)	441	138
Ablation events leading to Discharge (days)	334	105
Ablation events leading to Discharge (%)	75.7	76.1
Average Ablation Magnitude (cm)	4.3	4.0
Average Snow Season (dates)	6 Dec–26 Mar	23 Dec–27 Feb
Average Snow Season Depth (cm)	8.8	3.0

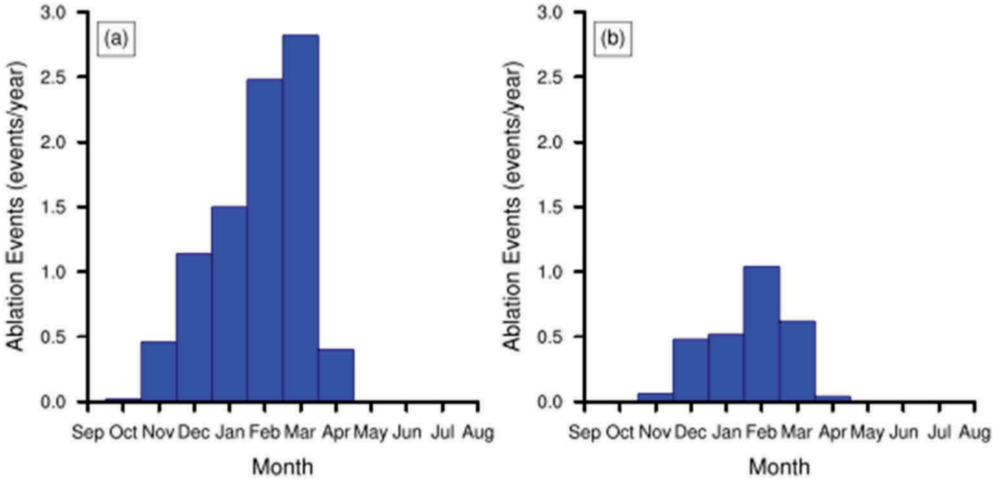

Figure 3. Seasonal cycle of discharge-causing snow ablation event frequency averaged from 1960–2009 for (a) Susquehanna River basin, and (b) Wabash River basin.

For the Wabash River basin, snow cover is less prominent compared to the Susquehanna basin, and thus ablation is less common. From 1960–2009, only 138 ablation events occurred (2.8 events yr^{-1}; SD: 2.4 events), of which 76.1%, or 105 events, resulted in an increase in discharge at Mt. Carmel, IL at a 3-day lag (Table 2). Only two events occurred in November and only one event in April, with no ablation occurring between May and October (Figure 3(b)). Across the remaining months of the seasonal cycle, approximately 0.4 events yr^{-1}, or 21 events per 50 years, occur in each December, January, and March, and a maximum of 0.8 events yr^{-1}, or 3.9 events per 5 years, occurs in February (Figure 3(b)). A discharge-causing ablation event has an average magnitude of ablation of 4.0 cm event^{-1} (SD: 1.7 cm) for the Wabash basin (Table 2), and exhibits a greater average seasonal range in ablation magnitude than that of the Susquehanna basin. For the Wabash, the maximum ablation magnitude occurs in December at 4.9 cm event^{-1}, followed by February, January, and March at 4.0, 3.8, and 3.5 cm event^{-1}, respectively (not shown).

Ablation and discharge

For both the Susquehanna and Wabash basins, >75% of ablation events result in a positive (i.e. increasing) response of river discharge (Table 2). The magnitude and seasonality of that response does differ between the basins, however. During 1960–2009, the average daily river discharge for the Susquehanna River was 34,597 cfs (979.68 m^3 s-^{1}). Following an ablation event, when there was a positive response in discharge, at a 3-day lag the average increase in river discharge was 53,529 cfs (1515.78 m^3 s-^{1}). Such an increase represents a 155% increase from the average flow, and an average increase of 133% from flow on the day of ablation. For the Wabash River, average daily discharge from 1960–2009 was 30,491 cfs (863.41 m^3 s-^{1}), with an increase in discharge of 13,829 cfs (391.6 m^3 s-^{1}) following an ablation event at a 3-day lag. This response was a 45% increase from the average daily flow, and a 51% increase in discharge when compared to the average discharge on the day of ablation.

Within the seasonal cycle, the percentage of ablation events that lead to a positive response in river discharge varies for both basins. In the Susquehanna basin, peak response rate occurs in February at 81%, followed by March and January at 78% and 77%, respectively. Moving away from the peak snow/cold season of January–March, the discharge response rate following ablation events declines, with only 55% of November and April ablation events resulting in increased discharge at a 3-day lag. This may be indicative of a lower probability of frozen soil and the higher potential for runoff to be retained in the soil during the non-winter months. The seasonal cycle of discharge response rate for the Wabash basin exhibits a slightly different pattern than that of the Susquehanna. For the Wabash, peak response rate occurs in December; where >87% of ablation events yield a positive response in river discharge at a 3-day lag. January, February, and March have discharge response rates of 73%, 75%, and 77%, respectively, while very few events occur in November and April. This feature may, however, be due to a general lack of snow cover in the Wabash during November and April.

To further support that a physical relationship exists between daily decreases in snow depth (i.e. ablation events, as defined in this study) and daily river discharge response, statistical relationships were drawn using linear regression. All days of ablation within the September–August season were regressed with their corresponding discharge responses at a 3-day lag for both basins (Figure 4). For the Susquehanna basin, snow ablation magnitude is significantly related to river discharge response, at a 3-day lag (F (1,438) = 5.917, $p < 0.05$), with an R^2 of 0.013 (after a single outlier was removed (18 January 1996: −23.72 cm ablation, 501,000 cft s^{-1})). While much of the variance in discharge response magnitude is not explained by ablation magnitude alone, the relationship does indicate the larger (smaller) the snow ablation magnitude, the larger (smaller) the river discharge response. Based on this linear fit, for every 1.0 cm more snow (depth) that is ablated, an additional 4600.0 cft s^{-1} of water is discharged by the river at a 3-day lag (95% confidence interval of 883.3–8316. 7). As such, there is a significant hydrological response to ablation when defined as only an inter-diurnal decrease in snow depth.

For the Wabash basin, there is an insignificant linear regression equation to predict 3-day lagged discharge response magnitude (in cft s^{-1}) from 1960–2009 when looking at all September–August ablation events (F(1,136) = 2.654, $p < 0.11$) where per 1.0 cm increase in ablation (depth), discharge increases 1371.4 cft s^{-1} (3036.1 – −293.3). Ablation magnitude and discharge response events were also regressed for each basin when ablation events were restricted to greater magnitudes (i.e. 5.0, 7.5, and 10.0 cm events). In all cases, explained variance remains similar to that of the reported 2.54 cm threshold events.

Ablation magnitudes and 3-day lag discharge responses were also regressed by month within each basin's respective snow season. For both basins, the magnitude of discharge response following an ablation event during the month of December is significantly related to the magnitude of ablation. For the Wabash basin, an increase in ablation (depth) of 1.0 cm increases the discharge response by 2003.8 cft s^{-1} (1209.4–2798.2 cft s^{-1}) during December (F(1,23) = 6.363, $p < 0.02$) with an R^2 of 0.22. For the Susquehanna basin, a similar increase in ablation of 1.0 cm yields an increase in discharge response of 14,310.1 cft s^{-1} (9,605.7–19,014.5 cft s^{-1}; F(1,55) = 9.253, $p < 0.01$, $R^2 = 0.14$). No other

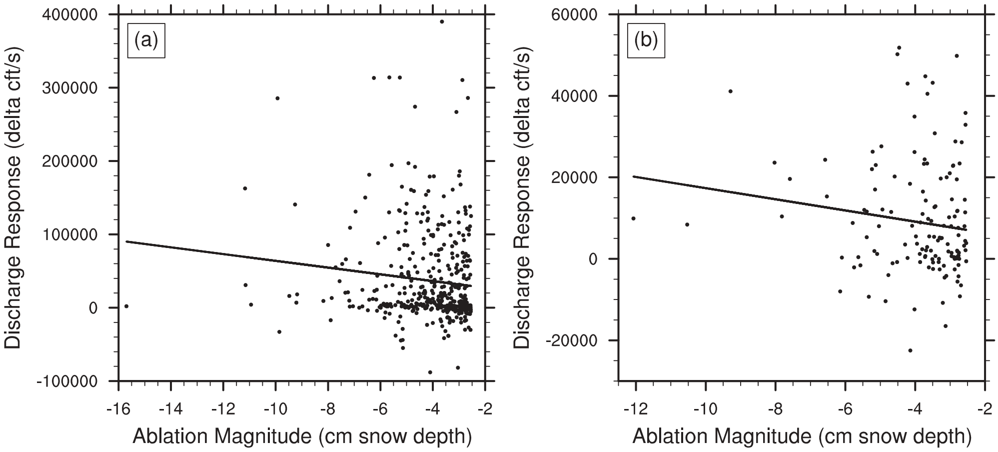

Figure 4. Relationship between individual ablation events' magnitude (in cm) and the corresponding 3-day lagged discharge response for (a) the Susquehanna River basin, and (b) the Wabash River basin. The relationship is statistically significant ($p < 0.05$) for the Susquehanna (a), while not significant for the Wabash ($p = 0.10$).

individual months' ablation events exhibited significant relationships with discharge response magnitude (after an outlier was removed; see above).

It is also hypothesized the magnitude of discharge response from ablation events at a seasonal scale (November – May) would be significantly related to the seasonal frequency of ablation events: A positive (negative) relationship would indicate the total seasonal discharge response from ablation events would be larger (smaller) when a higher (lower) frequency of ablation events occurred. Such a relationship would further support that ablation events defined as snow depth decreases do generate a hydrologic impact at longer temporal scales, and, specifically, at the scales often examined in climatological research (e.g. Dyer & Mote, 2007; Suriano & Leathers, 2017). In both drainage basins, the seasonal frequency of ablation events and seasonal discharge responses are significantly related (Figure 5(a,b)), suggesting in seasons with more (less) ablation events, the basins experience a greater (lesser) total discharge response. Linear regression determines that the seasonal total discharge response can be predicted significantly, based on seasonal ablation frequency for both basins. The significant regression equation for the Wabash ($F(1,48) = 41.577$, $p < 0.01$) has an R^2 of 0.464, while the equation for the Susquehanna ($F(1,48) = 14.784$, $p < 0.01$) has an R^2 of 0.235. For every additional ablation event, the seasonal discharge response increased by 5,580.6 (95% confidence interval: 3840.4–7320.7) and 11,357.8 (95% confidence interval: 5418.6–17,296.3) cfs (153.4–489.8 m^3s^{-1}) for the Wabash and Susquehanna basins, respectively.

Temporal variability

In light of previous findings (e.g. Dyer & Mote, 2007; Suriano & Leathers, 2017), the long-term variability of discharge-causing ablation events was investigated. A statistically significant decrease ($p < 0.05$) in the seasonal frequency of ablation events leading to positive discharge response is detected for the Susquehanna basin of 0.07 events yr^{-1} (Figure 6). The frequency of discharge-causing ablation events decreased from approximately 7.8 events yr^{-1} in the 1960s,

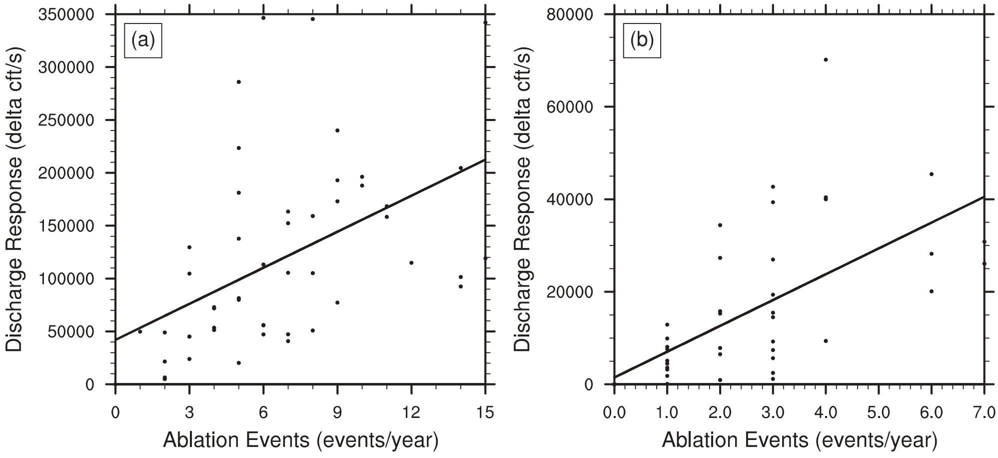

Figure 5. Correlation of seasonal (November–March) snow ablation event frequency (events yr^{-1}) and seasonal total discharge response (Δ cfs yr^{-1}) for (a) Susquehanna River basin, and (b) Wabash River basin. Both relationships are statistically significant at the 95% confidence interval ($p < 0.05$).

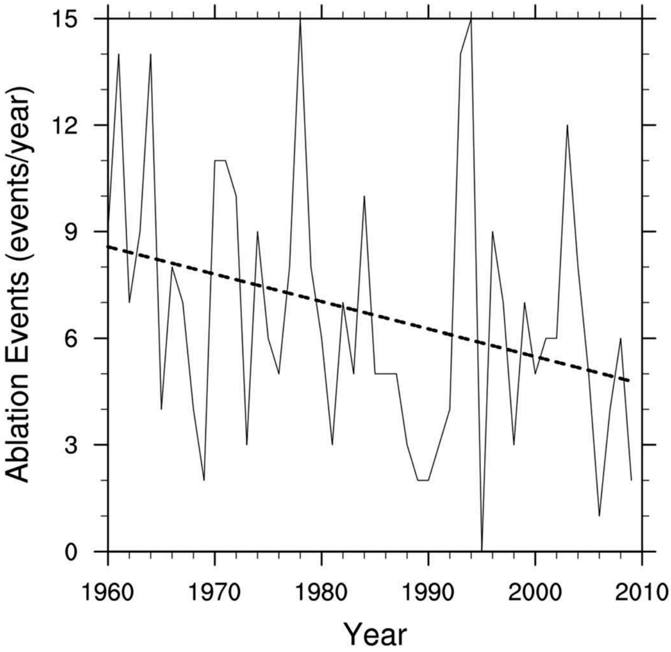

Figure 6. Interannual variability of September–August averaged discharge-causing snow ablation event frequency for the Susquehanna River basin from 1960–2009 (solid). The linear trend line (dashed) depicts the statistically significant decrease in frequency ($p < 0.05$).

to approximately, 5.5 events yr^{-1} in the 2000s, a linear-fit decrease of ~45% from 1960 levels. A similar decreasing trend is noted in the frequency of ablation events within the basin, regardless if they resulted in a positive discharge response or not. This indicates fewer ablation events are occurring within the basin. Future work examining the potential forcings of this trend is currently underway, with particular emphasis on the role of synoptic-scale circulation and its influence on ablation and discharge (Henderson et al., 2019). No significant trends in the frequency of ablation events (discharge-causing or not) are detected for the Wabash River basin.

Summary and discussion

Snow depth observations in the eastern United States, particularly over longer climatological periods, are usually not accompanied by snow water equivalent observations. As such, many studies examining snow ablation (e.g. Dyer & Mote, 2007; Grundstein & Leathers, 1998; Leathers et al., 2004; Suriano, 2019; Suriano & Leathers, 2017, 2018) define ablation as an inter-diurnal decrease in snow depth, and assume there is a hydrological signal. To establish a climatological-scale hydrological link between snow depth change and river discharge, this study examined river discharge responses in conjunction with inter-diurnal snow depth decreases in the basins of the Susquehanna and Wabash Rivers in the eastern United States.

Runoff generated from snowmelt is dependent on more than just the magnitude of snow depth loss, and includes factors such as the antecedent soil moisture, snow, river, and meteorological conditions. Without information on snow-water equivalent or antecedent soil moisture conditions, however, it was hypothesized that no significant relationships between individual-event ablation magnitude and the corresponding discharge response magnitude would exist for either basin. The results of this study partially disprove the hypothesis, suggesting there is a detectable positive relationship between exclusively snow depth changes and the river discharge response. For both basins examined, >75% of snow ablation events result in a detectable increase of river discharge, or positive discharge response, at a 3-day lag. For the Susquehanna basin specifically, a significant linear regression equation indicates that larger (smaller) ablation events lead to larger (smaller) discharge responses at a 3-day lag across the entire September–August snow season.

For the Wabash basin, the linear regression equation between all September–August ablation event magnitude and discharge response was not statistically significant at the 95% level. Given the relationships noted in the Susquehanna basin, it is possible that the statistical relationship between these two variables for the Wabash may be negatively impacted by other factors, and there is a credible and useful linkage between ablation and discharge. The authors propose the lack of significance may be derived in the topography of the basin. The Wabash basin is relatively flat, with a large portion of the basin existing in the glacial plain left behind by the Laurentide Ice Sheet. This less topographically variable landscape may not drain as quickly, when compared to the more topographically variable Susquehanna basin, with near-peak discharge levels after an ablation event in the Wabash basin persisting longer than a single day. Examining the cross-correlation for the Wabash (Figure 2-dashed), while the peak correlation occurs when stream discharge lags snow ablation by 3 days, there is an elevated plateau of relatively higher values that extends beyond the days immediately after a snow ablation event. This suggests runoff from an ablation event has an initial peak, followed by a prolonged and less intense signal of runoff that may have dampened the statistical relationship between ablation event and discharge magnitude for only the 3-day lag utilized in this study.

While less clear, a secondary explanation behind the differing signals between the basins could be due to the differences in land cover type, where open vs. canopy land cover has been shown to alter snow ablation rates (Musselman, Molotch, & Brooks, 2008). As noted previously, the Wabash basin has a majority land cover type of agriculture, compared to the majority forested Susquehanna.

For both basins, the magnitude of ablation events during specifically the month of December are able to significantly predict the magnitude of discharge response at a 3-day lag, while for all other months, linear regression equations are insignificant (i.e. $p > 0.05$). This begs the question, what is unique about December? For the Wabash basin, December is the month of peak discharge response rate for ablation events, thus one would then expect to see greater alignment between ablation and discharge response magnitudes. In the Susquehanna basin, December has a discharge response rate in excess of 70%, however, peak discharge response rate occurs in February and exhibits an insignificant regression equation between discharge response and ablation magnitude ($p < 0.1$; $R^2 = 0.01$). While the mechanisms behind this relationship are currently unclear, the authors suggest it is associated with other physical mechanisms that contribute to stream discharge. Soil moisture, river-ice concentration, and meteorological conditions conducive for ablation may be less influential on discharge during December, allowing for early-season snow depth variability to have more impact (Leathers et al., 1998). Future research could examine these additional mechanisms that control ablation-induced discharge, to assist in isolating potential causes of this December-oriented feature.

In many hydrologic and cryospheric research and management applications, snow water equivalent is the preferred variable to analyze. Despite this, the availability of observations over long time periods is limited, posing challenges in gaining critical climatological perspectives. Based on the findings of this study, the use of an inter-diurnal change in snow depth as a proxy for ablation is a viable alternative. This is particularly apparent when examining the linkages between ablation frequency and discharge at seasonal time scales. While the statistical relationships between snow depth change and discharge at the individual event level do not explain the majority of variance, >75% of ablation events lead to positive discharge responses, and, in turn, support a hydrological response to snow depth changes. Defining snow ablation as an inter-diurnal snow depth decrease yields a sufficient hydrological signal for use in climatological studies focused on snow ablation variability and its forcings.

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ORCID

Zachary J. Suriano http://orcid.org/0000-0001-7574-0191

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