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Examining why trends in very heavy precipitation should not be mistaken for trends in very high river discharge

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Abstract It is firmly established in the hydrologic literature that flooding depends on both antecedent watershed wetness and precipitation. One could phrase this relationship as "heavy precipitation does not necessarily lead to high stream discharge", but rarely do studies directly affirm this statement. We have observed several non-hydrologists mistake trends in heavy precipitation as a proxy for trends in riverine flooding. If the relationship between heavy precipitation and high discharge was more often explicitly presented, heavy precipitation may less often be misinterpreted as a proxy for discharge. In this paper, we undertake such an analysis for 390 watersheds across the contiguous U.S. We found that 99th percentile precipitation only results in 99th percentage discharge 36 % of the time. However, when conditioned on soil moisture from the Variable Infiltration Capacity model, 62 % of 99th percentile precipitation results in 99th percentile discharge during wet periods and only 13 % during dry periods. When relating trends in heavy precipitation to hydrologic response, precipitation data should, therefore, be segregated based on concurrent soil moisture. Taking this approach for climate predictions, we found that CMIP-5 atmosphere–ocean global circulation model (AOGCM) simulations for a RCP 6.0 forcing project increases in concurrence of greater than median soil wetness and extreme precipitation in the northern United States and a decrease in the south, suggesting northern regions could see an increase in very high discharges while southern regions could see decreases despite both regions having an increase in extreme precipitation. While the actual outcome is speculative given the uncertainties of the AOGCM's, such an analysis provides a more sophisticated framework from which to evaluate the output as well as historic climate data.

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1 Introduction

Figure 2.18 in the Third National Climate Assessment (http://nca2014.globalchange.gov/report/our-changing-climate/heavy-downpours-increasing) presents the percentage increase in precipitation falling in the 99th percentile of daily precipitation events across eight geographic regions in the United States from 1958 to 2012 (Walsh et al. 2014, p. 37). The figure shows a 71 % increase in precipitation falling in heavy events in the Northeast from 1958 to 2012, a 27 % increase in the Southeast, a 34 % increase in the Midwest, and lesser changes across the rest of the contiguous U.S. These findings were corroborated by DeGaetano (2009), Groisman et al. (2012), and Karl and Knight (1998).

We – the authors – have been at several recent regional workshops in the Northeastern U.S. focused on climate change impact assessment where Figure 2.18 from the National Climate Assessment Report has been presented to provide background context on changes in recent climate. These workshops have had audiences comprised of academics, staff from governmental agencies, and citizen groups. The figure has been shown at these workshops as evidence of not only an intensification of precipitation, but also as justification for likely increases in flooding, with little distinction whether this may be localized flooding or large scale riverine flooding. While we admittedly have a small observational sample of how people interpret National Climate Assessment Figure 2.18, we have found that – of those we have observed - many non-hydrologists have been inclined to see changes in heavy precipitation and flooding (of all kinds) as closely linked.

Indeed, in small and steep or urban catchments, heavy precipitation and flooding are most likely closely linked. Similarly, for exceptionally heavy precipitation (e.g., return periods of more than 100 years for annual maximums) the role of antecedent moisture also diminishes (Smith et al. 2013). However, the linkage between precipitation and flooding is more nuanced at larger scales, in non-urban areas, and for all but the most extreme precipitation events. In addition, the hydrology literature itself has numerous studies investigating controls on flooding, with most indicating that a primary control besides precipitation is antecedent watershed wetness (e.g., Li et al. 2009; Tramblay et al. 2010; Shaw and Riha 2011; Radatz et al. 2013; Georgakakos et al. 2014). Furthermore, nearly all rainfall-runoff models track antecedent watershed wetness such that the fraction of rainfall converted to runoff increases as stored water increases (e.g., Massari et al. 2014). Needless to say, the role of antecedent moisture conditions in controlling watershed outflow is well-established.

Therefore, the object of this paper is as much one of science communication as the investigation of fundamental scientific principles. In short, despite the well-established fact that riverine flooding is dependent on watershed wetness nearly as much as precipitation intensity, this concept appears to often be overlooked by non-hydrologists when interpreting precipitation data. We suggest that this gap in hydrologic intuition results from a discrepancy in how discharge and precipitation are discussed.

Precipitation is a fundamental measures of climate. Precipitation data are plentiful both in terms of spatial and temporal density. In the U.S. alone, there are many thousands of stations at which hourly precipitation data are available and tens of thousands at which daily precipitation data are available. In contrast, there are approximately half as many stream discharge measurements in the U.S. as there are precipitation measurements. Discharge on many streams is influenced by dams, water withdrawals, or land use changes (Villarini and Smith 2010). Additionally, differences in variables such as watersheds areas and land cover among others make large scale comparisons difficult. While there are indeed analyses of changes in

discharge over time (Villarini and Smith 2010; Hirsch and Ryberg 2012; Vogel et al. 2011; Lins and Cohn 2011; Douglas et al. 2000, and Mallakpour and Villarini 2015), such analyses have reported inconsistent trends in high discharge.

Thus, quite reasonably, precipitation data are more prominently discussed in most assessments of climate change. This would be fine if the linkage between precipitation and discharge was widely understood. But, the same limitations that keep discharge from being as broadly discussed as precipitation also keep the relationship between discharge and precipitation from being studied in a universal way. In part because of the need to carefully select watersheds with minimal human influences, hydrologic studies are often more focused on a small number of watersheds (e.g., Shaw and Riha 2011; Tramblay et al. 2010; Radatz et al. 2013). Additionally, the studies often include a modeling component (e.g., Tramblay et al. 2010; Van Steenbergen and Willems 2013; Berthet et al. 2009). Consequently, the conclusions from such hydrologic studies more often read as a case study of localized hydrologic processes or an assessment of modeling techniques rather than a universal statement on hydrologic function across wide geographic regions.

As a result, there is asymmetry in the type of information available regarding precipitation, discharge, and the linkage between precipitation and discharge. While it is typical to present precipitation trends for wide geographic areas (e.g., DeGaetano 2009; Groisman et al. 2012, and Karl and Knight 1998), there are very few papers that match this geographic reach while focusing on the linkage between discharge and precipitation (e.g., Mallakpour and Villarini 2015). Thus, while there are many hydrology papers that demonstrate that discharge is not dependent on precipitation alone, there are few papers that present the concept in the same geographically expansive (and broadly relevant) way that changes in precipitation are presented (i.e., Figure 2.18).

In this paper, we parallel the approach taken in presenting trends in heavy precipitation to more definitively demonstrate the connection between extreme precipitation and flooding. Namely, we use a set of 390 watersheds spread across the contiguous U.S. We first evaluate the trend in extreme precipitation at these watersheds reproducing the analysis in Figure 2.18. Then, we evaluate the trend in high flow events at these same watersheds and, more critically, directly assess how many high flow events at each watershed are caused by very heavy precipitation. Additionally, we evaluate how the strength of the linkage between precipitation and discharge changes with antecedent watershed wetness. Finally, we also evaluate the relationship between heavy precipitation and antecedent wetness projected for the end of the 21st century by climate models.

One of the few studies to evaluate the linkage between precipitation and high flows across many watersheds is Small et al. (2006). For 218 basins in the eastern U.S., Small et al. (2006) reported that significant increases in precipitation occurred between 1948 and 1997 in 78 of the basins, with this increase mainly occurring in the fall. Only at nine sites did these significant increases in fall precipitation coincide with significant increases in annual maximum flow. Thus, despite an upward trend in rainfall amounts across many of the watersheds, there was no commensurate increase in high flow. Small et al. (2006) hypothesized that dry conditions in the fall minimized increases in discharge despite increases in fall precipitation. This evaluation was limited by the fact that Small et al. (2006) used mean seasonal precipitation and annual maximum flow. Here we expand on the findings of Small et al. (2006) by evaluating streamflow and precipitation data at an event scale as well as explicitly quantifying the relationship of high discharges to soil moisture following intense precipitation events.

2 Methods

Daily discharge and precipitation volume data were taken from the Model Parameter Estimation Experiment (MOPEX) along with basin boundary data (Duan et al. 2006). Basins used in the MOPEX data set are assumed to experience minimal upstream regulation. Of 438 basins in the MOPEX database, 390 basins having more than 30 years of complete daily precipitation and discharge data between 1950 and 2000 were retained. Basin sizes range from 67 to 10,329 km^2 and represent a mix of land cover. 380 of the basins are less than 10 % urban based on the North American section of the Global Land Cover 2000 dataset (Latifovic et al. 2002).

Consistent with the Third National Climate Report (Georgakakos et al. 2014), we define a very heavy precipitation event ($P_{99\%}$) at a watershed as any daily event greater than the 99th percentile of wet days (any measured precipitation) computed across the historic period of record. While the exact 99th percentile value varied geographically, the median value across all watersheds was 3.5 cm. Other studies that have evaluated intense rainfall have used fixed higher thresholds such as 5.1 cm (Karl and Knight 1998) or 12.7 cm (Groisman et al. 2001). These studies used single station data whereas our values are spatial averages utilizing between 2 and 12 stations within a basin. Therefore, in our study the magnitude of each event is suppressed due to spatial averaging. Our lower watershed specific value also allows more storm events to be analyzed leading to more robust results. To evaluate whether multi-day precipitation has a different outcome than single day precipitation, we also evaluate high discharge resulting from very heavy precipitation periods. We define a very heavy precipitation period ($P7_{99\%}$) to be a 7 day period with greater than the 99th percentile of 7 day precipitation across the historic period of record. Finally, very high discharges in a watershed are considered to be any discharges greater than the 99th percentile discharge across the entire period of record.

Trends were determined in the number of very heavy events recorded per water year (the 12 month period beginning October 1st) for both discharge and precipitation using two different methods. First, the trends in each study watershed were assessed using Poisson regression. Second, we applied a test that evaluated regional trends. Past work has noted that trend tests on individual sites often overlook spatial-correlations between nearby sites that keep individual sites from being statistically independent. We computed cross-correlation corrected regional field significance (Douglas et al. 2000) using a nonparametric measure, a regional Mann-Kendall test, for the regions used in the Third National Climate Assessment (Walsh et al. 2014): the Northeast (NE), Southeast (SE), Midwest (MW), North Central (NC), South Central (SC), Northwest (NW), and Southwest (SW). The regional boundaries are indicated in Fig. 1. By computing a regional value, this method accounts for the multiple testing problem. It also accounts for cross correlation by recognizing the increased likelihood of converging trends due to correlated datasets. Possible autocorrelation in the time series were corrected for with prewhitening.

We also calculated the probability of both very heavy precipitation events resulting in a very high discharge event, $Pr(Q_{99\%}|P_{99\%})$, and very heavy precipitation periods resulting in a very high discharge event, $Pr(Q_{99\%}|P7_{99\%})$, using two different approaches to grouping the precipitation data. In one approach, precipitation data was grouped by season (MAM, JJA, SON, DJF) as in Small et al. (2006). In the second approach, we grouped events using modeled watershed soil moisture. To assess causation of discharge from precipitation, very heavy precipitation events were paired to daily discharge values that occurred within a site specific time window after the precipitation event. This time period was set so as to allow travel time in the watershed but to not be so large as to allow for significant discharge from subsequent precipitation events. To calculate unique travel times for each basin, we determined
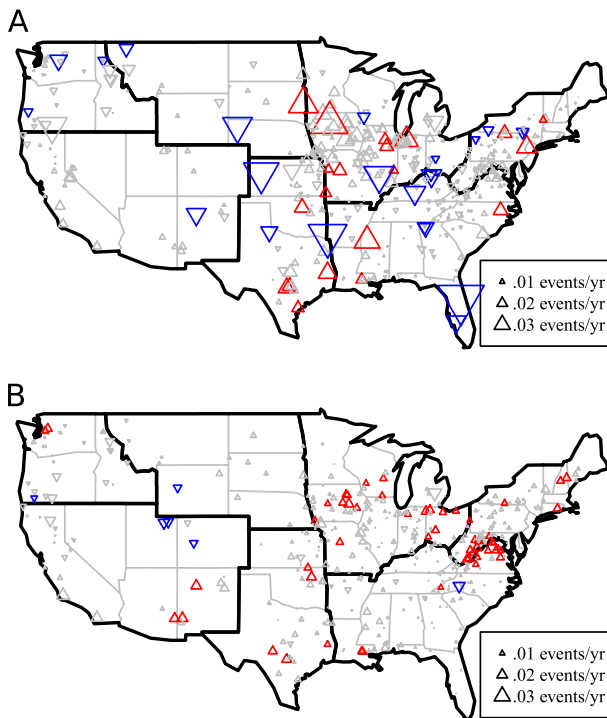
Fig. 1 Significant trends in number of very high flows (**a**), and very heavy precipitation events (wet days) (**b**) per water year between 1950 and 2000 determined by Poisson regression for all studied watersheds. Colored symbols (*red*: positive, *blue*: negative) represent statistically significant points ($p < .05$) and are scaled to show the local trend in number of events per year with *arrow* direction indicating the direction of trend. Regions analyzed in the text are highlighted

the largest cross-correlation coefficient between daily precipitation and discharge. 93 % of the sites had lags of 5 days or less with larger watersheds having longer lag times. Some sites had lag times as long as 40 days. However, these sites were nearly all located in high elevation mountain regions where discharge is likely dependent on snow melt and not direct precipitation. Because sites with lags >5 days were most likely reflecting snow melt and not rainfall, we held the maximum expected lag at all sites to 5 days.

Gridded monthly soil moisture data for the continental U.S. was retrieved from the University of Washington Variable Infiltration Capacity hydrological model retrospective run for 1950–2000 (Maurer et al. 2002). This model and run adequately matched the time frame of MOPEX discharge and precipitation data and had a spatial resolution (grid size of 1/8°) appropriate to the watershed sizes used in this study. While there has not been validation soil moisture simulation within the model across our entre study area, previous work indicates that the model reasonably matches relative seasonal soil moisture values when verified using observed Illinois data (Maurer et al. 2002). The gridded time series is converted to watershed specific time series. This is accomplished by weighting the percent of each soil moisture grid cell encompassed by the watershed and evaluating a weighted average at each time step to generate a time series specific to the watershed. 99th percentile precipitation events were segregated based on whether they occurred above or below the watershed median soil moisture value. $Pr(Q_{99\%}|P_{99\%})$ and $Pr(Q_{99\%}|P7_{99\%})$ were computed for each subset.

Finally, atmosphere–ocean general circulation model (AOGCM) daily precipitation and monthly soil moisture values were taken from the fifth phase of the Coupled Model Intercomparison Project (CMIP 5) multi-model ensemble repository for the RCP 6.0 scenario for a selection of models where it was available: bcc_csm1, CSIRO, GFDL−CM3, GFDL −ESM2G, GFDL−ESM2M, HadGEM_ES, IPSL−CM5A−LR, IPSL−CM5A−MR, MIROC5, MIROC−ESM, MIROC−ESM−CHEM, MRI_CGCM3, and NorESM1−M. We only used the first run in any multi-run ensemble. Model output covered two periods, the start of the century (2006–2036) and the end of the century (2070–2100). Precipitation events from both periods that exceeded the 99th percentile precipitation value at the start of century were again segregated based on whether they occurred above or below the regional mean soil moisture value from the start of the century. The general results were similar among models. For instance, of the 13 models, there was agreement in the change of number of 99th percentile precipitation in the NE among 12 models for wet conditions and 11 for dry conditions. The least model agreement in change of 99th percentile precipitation was found in the SE under wet conditions; in these cases there was agreement among 8 of the 13 models. Because of the general consistency across models, the probability of each precipitation/soil moisture pairing was averaged regionally across all models.

3 Results and discussion

3.1 Trends in occurrence of very high discharge and very heavy precipitation

Trends in the number of very heavy precipitation events per year determined by Poisson regression for each site are shown in Fig. 1a. Of the 390 watersheds, there are 283 upward trends, 54 of which are statistically significant at $p<0.05$. There are 108 downward trends of which 6 are statistically significant. While trend tests on individual sites indicate there are many more significant upward trends than downward trends, individual tests can be complicated by cross-correlation among sites. As an additional and more robust assessment, we also calculated regional trends. We found that the Northeast (NE), Southeast (SE), and Midwest (MW) United States show significant increases ($p<0.05$) in the number of very heavy precipitation events per year. All other regions, the North Central (NC), South Central (SC), Northwest (NW), and Southwest (SW) show no significant regional trend. Although we use a somewhat different measure of trend in very heavy precipitation than Karl and Knight (1998), we for the most part show agreement across our results with Karl and Knight (1998). Both of us found strong positive trends in very heavy precipitation in the NE, SE, and MW as well as mixed to negative trends in the NC, SC, and NW. The one discrepancy exists in the SW; Karl and Knight (1998) found positive trends in the SW where this study does not. This disagreement could be due to a lack of stations in our study since even though we examined 29 sites in the SW, many of which cluster along the coast or in the Mountains.

Very high discharge trends (Fig. 1b) display a different pattern. Even though Poisson regression found 20 significant upward and 23 significant downward trends, there is little geographic consistency to the direction of trends. Regional trend analysis showed neutral to negative insignificant trends in all regions. This lack of trends in very high discharge is consistent with Douglas et al. (2000) and Hirsch and Ryberg (2012).

These trend analyses indicate that the 390 sites in this study are generally representative of meteorological stations (i.e., Karl and Knight 1998; Groisman et al. 2012) and watersheds (Douglas et al. 2000; Hirsch and Ryberg 2012) used in prior studies and that the evaluation of

the linkage between precipitation and discharge presented below is also evaluating a representative collection of watersheds.

3.2 Connection of very heavy precipitation to very high discharge

In addition to evaluating trends, the probability of very heavy precipitation events resulting in very high discharge, $Pr(Q_{99\%}|P_{99\%})$, was directly assessed. As seen in Fig. 2a, the distribution of $Pr(Q_{99\%}|P_{99\%})$ appears to be bimodal. The primary peak is centered at around a 40 % probability. A second lower peak at zero is due to sites with lag periods >5 days. When sites are aggregated, $Pr(Q_{99\%}|P_{99\%})=35$ %. 161 individual sites have a $Pr(Q_{99\%}|P_{99\%}) > 35$ % although very few have $Pr(Q_{99\%}|P_{99\%}) > 60$ %. In essence, at the vast majority of the 390 sites we evaluated, less than half of very heavy precipitation results in very high discharge. This analysis directly indicates that large precipitation events are not solely responsible for the entire spectrum of high discharge events and that other factors, namely soil moisture, must be important in controlling discharge.
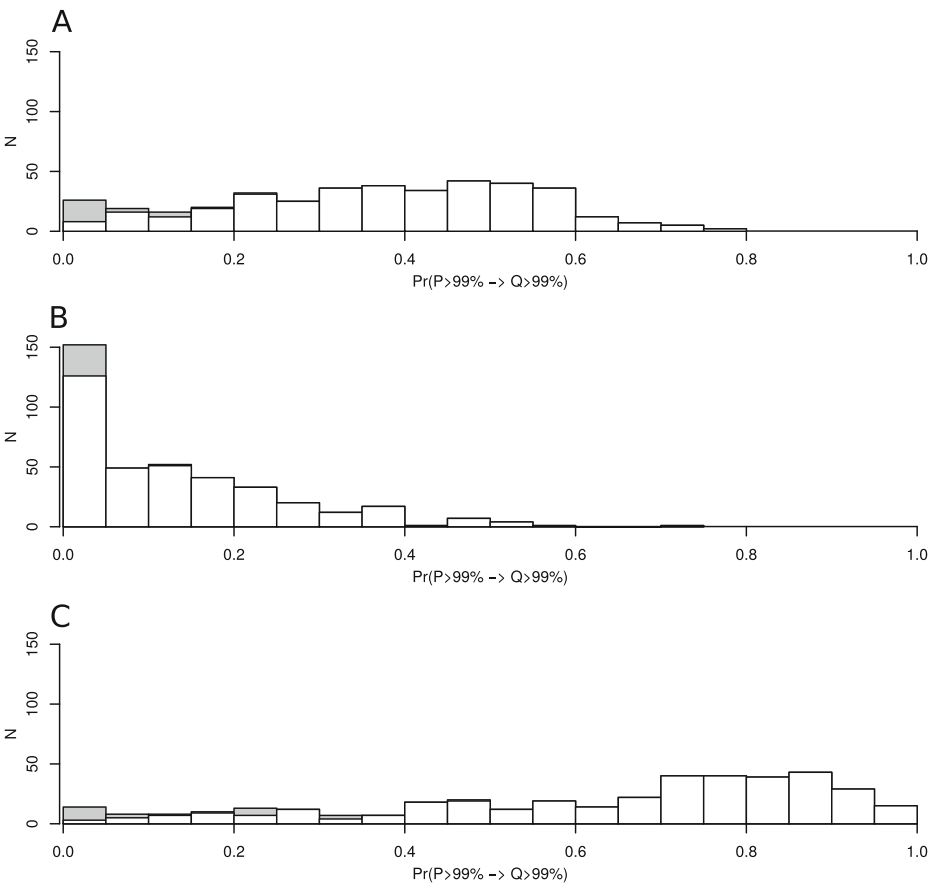

Fig. 2 Number of sites with the probability that a 99th percentile precipitation event results in a 99th percentile discharge for all events (**a**), events when moisture is less than the median value (**b**), and events when moisture is greater than the median value (**c**) between 1950 and 2000. The number sites with expected lag > 5 are highlighted in *gray*

One might ask whether $Q_{99\%}$ is too high a threshold and whether $P_{99\%}$ might nearly always result in high flows, just not at the 99th percentile. To assess this question, we considered the probability of discharges less than 99th percentile resulting from 99th percentile precipitation (Fig. 3). As might be expected, the linkage between heavy precipitation and discharge increases as the percentile for discharge decreases. Aggregated across all sites, the probability of 99th percentile discharge from 99th percentile P is only 36 % but the probability of 95th percentile discharge is upwards of 60 %. This is a relatively sizable increase. However, 95th percentile flow occurs in 5 out of 100 days and on more than 18 days in an average year. Thus, while 95th percentile flow is certainly high, it is within a realm that would not usually be associated with flooding.

The seasonal data as shown by regional average in Table 1 provides some insight into control by soil moisture. It was found that higher linkages between very heavy precipitation and very high discharge occur during DJF (on average $Pr(Q_{99\%}|P_{99\%})$ =52 % across all sites with 191 over 60 %) and MAM (58 % with 203 over 60 %). In contrast JJA (29 % with 31 over 60 %) and SON (33 % with 65 over 60 %) showed much lower linkages. This behavior is most pronounced in the typically wetter NE and SE. In the mountainous NC and SC the signal is mixed due to a later snowmelt extending sometimes into JJA.

3.3 Soil moisture as a potentiator

Seasonal variations in gridded soil moisture generally agree with the standard assumption that DJF and MAM tend to be wetter than JJA and SON. However, the seasonal distribution of gridded soil moisture when compared across sites matches more accurately with the observed discharge distribution than with the precipitation distribution.

More notably, as seen in Fig. 2b and c, when grouped according to soil moisture, $Pr(Q_{99\%}|P_{99\%})$ can be seen to vary positively and dramatically with soil moisture across a majority of sites. When soil moisture is below its site-specific median value, $Pr(Q_{99\%}|P_{99\%})$
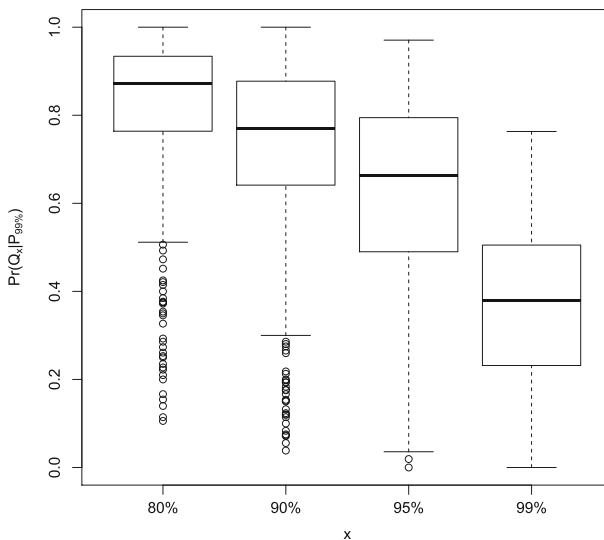

Fig. 3 Boxplots of the probabilities that 99th percentile precipitation events result in daily flows exceeding the given percentile across the 390 study sites. The central line in each *boxplot* denotes the median. The edges of the box separate the quartiles. The whiskers are either the extrema or 1.5 times the interquartile range. Outliers are denoted as *circles*

Table 1 Probability of extreme precipitation resulting in extreme discharge ($Pr(Q_{99\%}|P_{99\%})$)

Region	Season				Soil moisture	
	MAM	JJA	SON	DJF	Low	High
NE	0.56	0.21	0.28	0.53	0.12	0.58
SE	0.60	0.15	0.26	0.54	0.07	0.60
MW	0.37	0.20	0.15	0.28	0.06	0.44
NC	0.23	0.23	0.11	0.06	0.07	0.28
SC	0.44	0.40	0.39	0.26	0.13	0.59
NW	0.16	0.03	0.19	0.43	0.17	0.41
SW	0.35	0.04	0.18	0.48	0.06	0.46

tends to be low. In these dry periods, across all sites $Pr(Q_{99\%}|P_{99\%})=13\%$ with only one site (in Oregon) over 60 %. When soil moisture is above its site-specific median value, the distribution of $Pr(Q_{99\%}|P_{99\%})$ is centered around 80 %. However, some sites, especially those with expected lag periods of> 5 days, not unexpectedly maintain low probabilities of large flows in response to very heavy precipitation events. In wet periods, across all sites, $Pr(Q_{99\%}|P_{99\%})=62\%$. When wet, $Pr(Q_{99\%}|P_{99\%}) >60\%$ at 242 individual sites, and >80 % at 126 sites. Table 1 shows the geographic distribution of these probabilities. With the exception of mountainous sites in the NC and NW as well as some sites in the MW, the entire US shows an increase in $Pr(Q_{99\%}|P_{99\%})$ during high soil moisture periods. So, not surprisingly, during wet times (with respect to soil moisture) a similar rain event is likely to generate much higher discharges than during a dry time. This distinction is much clearer than the seasonal distinction (see Table 1). Namely, in using season alone, the connection between very heavy precipitation and discharge is underestimated during wet periods and overestimated during dry periods.

To evaluate whether variation in soil moisture could be predicted by antecedent rainfall, we also considered the degree to which very high discharge was related to prolonged heavy rainfall. Specifically, the average likelihood of very heavy 7-day precipitation periods resulting in high discharge, $Pr(Q_{99\%}|P7_{99\%})$, is 52 % across all sites. In terms of comparing to soil moisture, when considering the probability at individual sites, very high discharge occurs from very heavy precipitation >60 % of the time or more at 158 sites, and >80 % of the time or more at only 17 sites. Thus, prolonged heavy rainfall did not explain periods of closest alignment between precipitation and discharge as well as soil moisture.

3.4 Additional factors influencing runoff of very heavy precipitation

In addition to evaluating $Pr(Q_{99\%}|P_{99\%})$ in relation to soil moisture, we also evaluated $Pr(Q_{99\%}|P_{99\%})$ in relation to several other factors: geographic region, fraction of urban landcover, watershed area, fraction of precipitation falling as snow, and the expected lag period. These results are shown in Table 2.

Geographic region, while suggestive, was not a significant factor (at $p<0.05$) when testing the equality of the regional means by one way ANOVA. Specifically, despite a lack of statistical significance, the NC and NW have lower values than the rest of the country. These values are believed to be depressed by watersheds in the Rocky Mountains where flows peak in the spring or summer due to snowmelt rather than heavy rain events.

Table 2 Comparisons of the number of sites, N, and mean $Pr(Q_{99\%}|P_{99\%})$ conditioned on various factors

Factor/Region	N	$Pr(Q_{99\%}|P_{99\%})$	p-value
NE	71	38 %	0.08
SE	101	43 %	
MW	108	30 %	
NC	17	23 %	
SC	37	46 %	
NW	27	28 %	
SW	29	36 %	
>10 % Urban	10	45 %	0.02
≤10 % Urban	381	36 %	
Area > 1000 km^2	170	29 %	<.01
Area ≤ 1000 km^2	221	42 %	
≤30 % P as Snow	370	38 %	<.01
>30 % P as Snow	20	4 %	
Lag > 5	27	5 %	<.01
Lag ≤ 5	364	39 %	

p-values are determined by one way ANOVA for regions and by t-tests for the rest

Urban watersheds (>10 % urban) are found to have significantly higher $Pr(Q_{99\%}|P_{99\%})$. It is well recognized that urban watersheds demonstrate greater runoff due to decreased infiltration capacity. The impact of urban land cover is likely to increase as the land cover fraction increases. For example, the basin with the largest urban fraction (67 %) was located in Chicago and had $Pr(Q_{99\%}|P_{99\%})$=55 %.

Watershed area was also found to be a significant factor with basins >1000 km^2 having significantly lower average $Pr(Q_{99\%}|P_{99\%})$ (36 %) than smaller watersheds (45 %). This is reasonable as larger basins are more likely to have natural features (e.g., wetlands, valley bottoms, etc.) which attenuate inputs.

The fraction of precipitation falling as snowmelt was one of the most significant factors and resulted in $Pr(Q_{99\%}|P_{99\%})$ of 38 % for basins with less than 30 % of precipitation falling as snow versus only 4 % for basins with more than 30 % snow. In watersheds with sizable amounts of snowfall, peak flows are attributable to spring snowmelt and are largely disconnected in time from precipitation inputs. This finding is reinforced by consideration of the influence of the lag in basin response time to precipitation inputs. Basins with expected lags of under 5 days have an average $Pr(Q_{99\%}|P_{99\%})$ of 39 % whereas basins with longer lag times have an average $Pr(Q_{99\%}|P_{99\%})$ of only 5 %. The expected lag time is linked closely to both watershed area (large basins are more likely to have long lags than small ones are) and to snow fraction (mountainous watersheds with snowmelt sometimes occurring as late as JJA have the longest lag times).

3.5 Limitations to the analysis

In discussing the impact of daily precipitation on daily flow rates, we neglect to account for the impact of the distribution of sub-daily precipitation intensities. Specifically, large instantaneous peaks have been shown to result in greater runoff ratios even when the overall precipitation remains constant (Dunkerley 2012).

Secondly, peak instantaneous discharge is arguably a greater risk to flooding and associated damage than daily discharge. We do not address this here, but our methods could be modified in the future to determine to probability of extreme precipitation resulting in high instantaneous flow.

3.6 Future projections of interaction between very heavy precipitation and soil moisture

With respect to climate change, our analysis as well as the extensive hydrologic sciences literature suggests that increases in very heavy precipitation are most likely to impact very high discharge if the increase in precipitation occurs during wet periods. Figure 4 shows the projected change in concurrence of very heavy precipitation with both low and high moisture regimes according to 13 RCP6.0 AOGCM experiments. Concurrence of high (right side) or low (left side) moisture conditions with very heavy precipitation is represented in the length of the black (end of century) and gray (start of century) bars. So in the SE, for instance, a decrease in concurrence of high moisture and very heavy precipitation can be seen by the fact that the black high moisture bar decreases relative to the gray bar. For the majority of AOGCM projections explored in the southern US (i.e., in the SE, SC and to a lesser degree the SW) less very heavy precipitation is projected to occur concurrently with wet periods at the end of the century than at the beginning, presumably resulting in less favorable flooding conditions. This change is due to a negative change in soil moisture through time. In northern regions the concurrence of wet conditions and heavy precipitation and thus flood probability is predicted to increase due to greater amounts of very heavy precipitation in spite of unchanging or decreasing soil moisture profiles.

This analysis provides a novel interpretation of AOGCM output. While other studies have assessed future changes in CMIP-5 AOGCM output (Dirmeyer et al. 2014; Koirala et al. 2014), none that we are aware of have directly considered the joint relationship between soil moisture
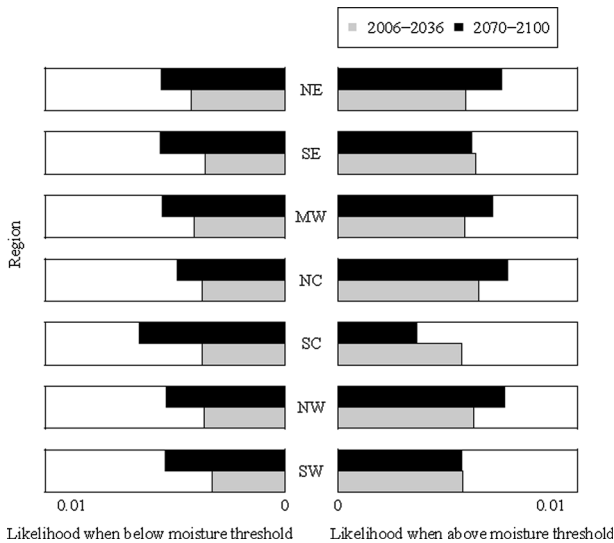

Fig. 4 Mean probability of heavy precipitation occurring concurrently with either dry (below median, *gray bars*) or wet (above median, *black bars*) soil moisture conditions for the start and end of the 21st century. Results are shown by region and averaged for 13 AOGCMs forced by RCP 6.0. *Left panels* – dry soil moisture conditions, *Right panels* – wet soil conditions

and very heavy precipitation at the event (i.e., daily) scale. Dirmeyer et al. (2014) evaluated "flood precipitation", using precipitation as a proxy for flow as well as discharge, but only considered mean annual values. Koirala et al. (2014) evaluated 95th percentile discharge from 11 AOGCMs but did not evaluate soil moisture or precipitation. In terms of direction of change in 95th percentile discharge, Koirala et al. (2014) found inconsistencies across the 11 models within the contiguous U.S. While this finding in part calls into question the meaningfulness of comparing AOGCM output, it also indicates the need to more closely investigate underlying differences in processes among models, a task partially addressed by looking at concurrence between heavy rainfall and high soil moisture in different AOGCMs as we have done here.

4 Conclusions

Despite very heavy precipitation sometimes being assumed to be a proxy for very high discharge, very heavy precipitation resulted in only 36 % of very high discharge days across the 390 watersheds studied here. This discrepancy can largely be explained by differences in concurrent soil moisture. For example, $Pr(Q_{99\%}|P_{99\%})$, rose to 62 % when soil was at its median wetness or greater as opposed to 13 % when drier. While the hydrologic literature frequently investigates how event precipitation and antecedent moisture conditions interact to influence discharge magnitude, such studies only implicitly address the question: "Do very heavy precipitation events lead to very high discharge events?" In this paper, we directly evaluate this question, providing a clear conclusion that precipitation should not be viewed as being directly related to discharge, and that trends in very heavy precipitation should be used cautiously to infer trends in very high discharge.

We suggest that any evaluation of precipitation intended to inform discharge should condition precipitation by concurrent watershed moisture status. Examining this concurrence of heavy precipitation and antecedent moisture can provide conclusions different from those provided by looking at precipitation alone. Other watershed characteristics such as land cover, total watershed area, and percent of precipitation falling as snow have a significant impact on $Pr(Q_{99\%}|P_{99\%})$, but with the exception of outcomes in mountainous, snow-dominate regions, antecedent moisture best explains variations in $Pr(Q_{99\%}|P_{99\%})$.

Very heavy precipitation is likely to be a useful indicator for the prevalence of flash flooding in urban or steep areas as well as direct effects such as crop damage. However, with respect to river flooding, this paper suggests that very heavy precipitation alone is often not a sufficient predictor of discharge and other variables may be required.

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