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Research article

Riverine discharges to Chesapeake Bay: Analysis of long-term (1927–2014) records and implications for future flows in the Chesapeake Bay basin

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ABSTRACT

The Chesapeake Bay (CB) basin is under a total maximum daily load (TMDL) mandate to reduce nitrogen, phosphorus, and sediment loads to the bay. Identifying shifts in the hydro-climatic regime may help explain observed trends in water quality. To identify potential shifts, hydrologic data (1927–2014) for 27 watersheds in the CB basin were analyzed to determine the relationships among long-term precipitation and stream discharge trends. The amount, frequency, and intensity of precipitation increased from 1910 to 1996 in the eastern U.S., with the observed increases greater in the northeastern U.S. than the southeastern U.S. The CB watershed spans the north-to-south gradient in precipitation increases, and hydrologic differences have been observed in watersheds north relative to watersheds south of the Pennsylvania—Maryland (PA-MD) border. Time series of monthly mean precipitation data specific to each of 27 watersheds were derived from the Precipitation-elevation Regression on Independent Slopes Model (PRISM) dataset, and monthly mean stream-discharge data were obtained from U.S. Geological Survey streamgage records. All annual precipitation trend slopes in the 18 watersheds north of the PA-MD border were greater than or equal to those of the nine south of that border. The magnitude of the trend slopes for 1927–2014 in both precipitation and discharge decreased in a north-to-south pattern. Distributions of the monthly precipitation and discharge datasets were assembled into percentiles for each year for each watershed. Multivariate correlation of precipitation and discharge within percentiles among the groups of northern and southern watersheds indicated only weak associations. Regional-scale average behaviors of trends in the distribution of precipitation and discharge annual percentiles differed between the northern and southern watersheds. In general, the linkage between precipitation and discharge was weak, with the linkage weaker in the northern watersheds compared to those in the south. On the basis of simple linear regression, 26 of the 27 watersheds are projected to have higher annual mean discharge in 2025, the target date for implementation of the TMDL for the CB basin.

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1. Introduction

Chesapeake Bay (CB), located along the east coast of the United States (U.S.), is the Nation's largest estuary and is one of the most ecologically productive estuaries in the world (*e.g.*, Boynton et al., 1982). Like other estuaries throughout the world, CB is plagued by excess nitrogen, phosphorus, and suspended sediment transported from contributing watersheds (*e.g.*, Bricker et al., 2008). Delivery of these pollutants to CB over many decades has had detrimental effects on living resources as a result of eutrophication, loss of submerged aquatic vegetation (SAV), and a myriad of chain-reaction effects. In 2009, President Barack Obama signed Executive Order 13508, which directs the federal government to lead the effort to restore and protect the bay. In 2010, the U.S. Environmental Protection Agency mandated the development of a total maximum daily load (TMDL) for the CB watershed as part of a continued effort to reduce nitrogen, phosphorus, and suspended-sediment loads delivered to the bay. The expected improvement in the aqueous habitat as a result of the TMDL is to be measured by increases in water clarity, dissolved oxygen concentrations, and the spatial

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extent of SAV. The Chesapeake Bay Program (CBP), comprising federal, state, and local governments, academic institutions, and non-profit organizations, has agreed to implement 60% of the nutrient and sediment-reduction strategies required to meet the TMDL by 2017 and implement 100% of the strategies by 2025. In 2017, a "midpoint assessment" of the CB cleanup plan is scheduled. Consequently, the CBP is to review the latest science and incorporate new insights into the cleanup plan as appropriate.

The amount, frequency, and intensity of precipitation increased from 1910 to 1996 in the eastern United States (U.S.) (Karl and Knight, 1998). In addition, precipitation in the heaviest 1% of daily events increased from 1985 to 2012 in the eastern U.S. (Karl et al., 2009; Melillo et al., 2014). Overall increases in annual precipitation are expected to be associated with increases in the higher end of the precipitation distribution. Increases in the lowest percentiles alone are unlikely to produce significant trends in *overall* precipitation. Karl and Knight (1998) showed that the proportion of total precipitation caused by "extreme" and "heavy" events (defined by Karl and Knight (1998) as those greater than the 90th percentile) in the eastern U.S. has, indeed, increased relative to "moderate" events (defined by Karl and Knight (1998) as those around the median). The observed increases in heavy events, however, has been greater in the northeast compared with the southeast (Karl et al., 2009; Melillo et al., 2014). The CB basin spans the north-to-south gradient in observed precipitation increases in the heaviest 1% of daily events (Fig. 1).

An open question, then, is how is the observed precipitation increase, particularly in the highest percentiles, affecting stream discharge? In other words, where in the distribution of streamflow is the increasing precipitation causing higher flows, *i.e.*, are low flows, midflows, or stormflows increasing? With increased precipitation, the resulting pattern of changes in stream discharge will affect the pollutant load from the watershed. Where, when, and how those changes occur ultimately will determine the quantity of nitrogen, phosphorus, and suspended sediment that reach the bay. A concern of the CBP, therefore, is how will the observed changes in precipitation patterns affect attainment of the TMDL and desired improved conditions in the CB? In order to address the CBP's concern, and to determine the extent of coupling of precipitation and streamflow in the highly heterogeneous CB region, we examined and compared precipitation and streamflow trends for 88 years, from 1927 through 2014.

Whether stationarity is dead (Milly et al., 2008) or alive (*e.g.*, Montanari and Koutsoyiannis, 2014), variability is inherent in natural systems, making examination of long-term hydrologic records mandatory to understand how hydrologic processes are changing (Milly et al., 2015). Despite the perpetual lack of ideal datasets for studying the environment, we must recognize the variability of natural systems and the difficulties associated with interpreting responses of disturbed systems. Accordingly, for this study, we used the maximum period of record available, which was for calendar years 1927–2014, for the maximum number of watersheds (27) within and near the CB basin.

Several studies have examined changes in the maximum annual flow in watersheds in the UK (Robson et al., 1998), China (Yang et al., 2004), the U.S (*e.g.*, Berghuijs et al., 2016; Hirsch and Ryberg, 2012; Vogel et al., 2011). and, more specifically, the northeast U.S. (Armstrong et al., 2014). Another study in the UK analyzed flow regimes on a seasonal basis (Hannaford and Buys, 2012). We examined the entire flow regime, from the minimum to the maximum flow, to identify long-term changes in flow and the distribution of flow in watersheds within and near the CB basin. That examination motivated four lines of inquiry related to identifying spatial and temporal patterns in historical precipitation and discharge across the CB basin during the period 1927–2014. First, we sought to determine if there were any trends in precipitation or discharge over the period of record within groups of northern and southern watersheds and for each of the 27 watersheds individually. Secondly, we sought to determine how the distribution of precipitation was manifested in stream-discharge distribution for each of the 27 watersheds throughout the period of record. For example, do long-term changes in the 60th percentile of precipitation result in similar patterns in the 60th percentile of flow? (*i.e.*, does $\Delta\ P^{60th} = \Delta\ Q^{60th}$)? The third objective was to determine if there were any trends in the distribution of precipitation or discharge into percentiles over the period of record within each watershed. For example, is there a linear trend in the 30th percentile of precipitation or discharge for the period 1927–2014 in any of the watersheds? The final objective was to use the observed trends to project the annual mean discharge for each watershed for 2025, which is the year of the TMDL endpoint.

2. Methods

2.1. Study area

The CB basin encompasses 166,319-square kilometers (km^2), extends from New York to Virginia, and includes parts of six states as well as the District of Columbia (Fig. 2). Previous research that examined stream runoff (discharge normalized by watershed area) for the period 1930–2010 indicates that some flow metrics, for example, the mean one-day maximum runoff, show differences in trends between northern and southern watersheds (Rice and Hirsch, 2012). The north-south dividing line determined in that study is approximately the Pennsylvania—Maryland border (Rice and Hirsch, 2012). Using this designation, approximately 45% of the CB basin lies in the "north" and 55% lies in the "south." For the present study, 27 non-tidal watersheds either within or near the CB basin were chosen for analysis on the basis of nearly complete daily mean discharge records for 88 years (1927–2014). Eighteen of the watersheds examined lie north of the Pennsylvania—Maryland border and nine lie south of that border (Fig. 2). Within the dataset are several streamgages that lie upstream from other streamgages, especially in the north. Thus, a degree of redundancy is present in some of the results, but the difference in drainage area between upstream and downstream sites warrants the inclusion of both. The 27 watersheds have areas from 303 to 62,419 km^2 (Table 1) and have diverse land use, which includes various mixtures of forested, cultivated, and developed areas. The discharge trends presented incorporate the cumulative effects of climate and land-use changes in each watershed over the 88-year study.

2.2. Data

To obtain the most accurate precipitation data with the longest continuous record for the 88 years, Precipitation-elevation Regression on Independent Slopes Model (PRISM) precipitation data (http://www.prism.oregonstate.edu/historical/) (Daly et al., 2008) were downloaded for calendar years 1927–2014. The official climatological data for the U.S. Department of Agriculture, PRISM spatial climate data are considered to be the highest quality available in the U.S. (Daly et al., 2008). The downloaded data (in millimeters, mm) were averaged spatially (*i.e.*, across each watershed) and temporally to obtain monthly mean precipitation for each of the 27 watersheds for 88 years. The number of precipitation values in the dataset is 28,512. Although PRISM data were not designed for trend calculations, they have been used for such (*e.g.*, Small et al., 2006; Velpuri and Senay, 2013), and Small et al. (2006) effectively used PRISM data for identifying trends in specific watersheds. We have no choice but to assume that any error in the

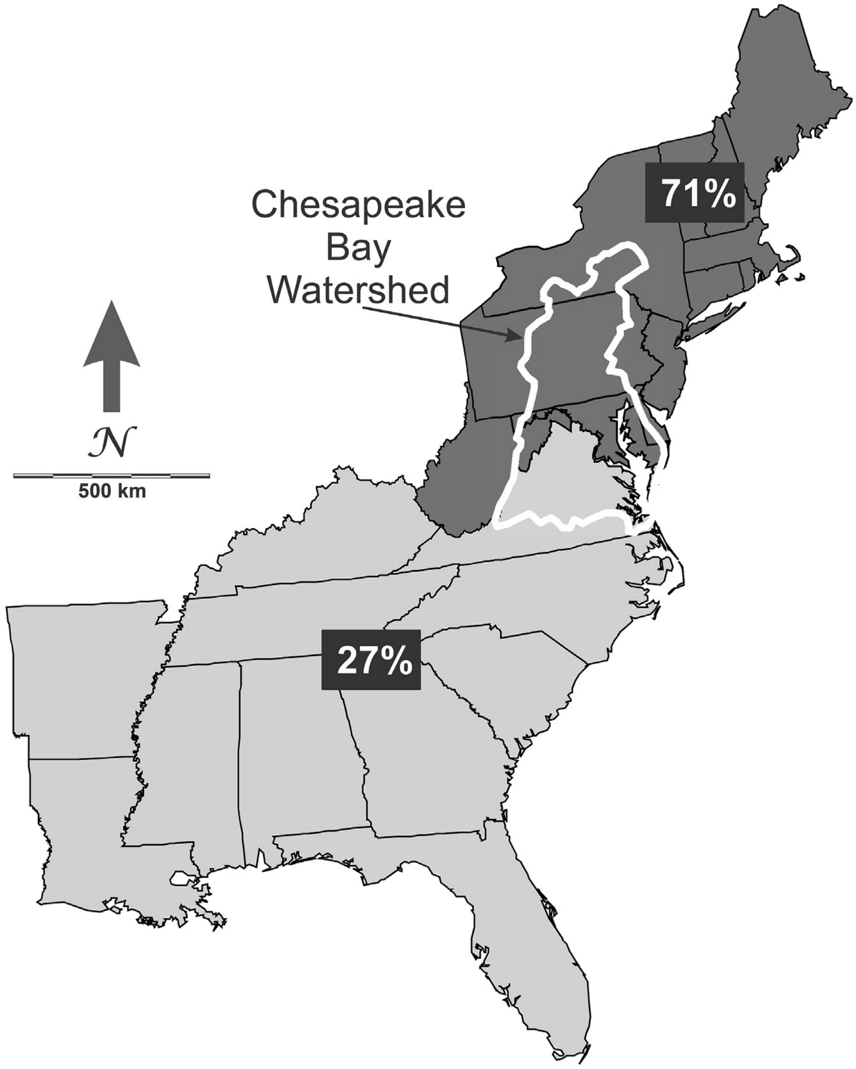

Fig. 1. Location of the Chesapeake Bay basin superimposed on a map of the eastern United States showing the observed change in the heaviest 1% of daily events from 1958 to 2012 (redrawn from Melillo et al., 2014).

precipitation data is random and unbiased, and spatially and temporally averaging the data across each watershed helps with this assumption.

Daily mean discharge data (the average of the instantaneous measurements, expressed as cubic meters per second, m^3s^{-1}) were downloaded for each of 27 U.S. Geological Survey (USGS) streamgages for calendar years 1927–2014 (http://nwis.waterdata.usgs.gov/nwis). Site 4 (station ID 01531000) is missing 4 days because of ice. Sites 21, 22, and 23 (station IDs 01606500, 01608500, and 01636500) are missing 541, 585, and 578 days, respectively, at the beginning of their records. The missing record represents 1.8% or less of the dataset for each of these three sites. Daily mean discharge values were averaged to obtain monthly mean discharge to correspond with the precipitation dataset. The number of discharge values in the monthly mean dataset is 28,457. As with the precipitation data, we assume that any error in the discharge data is random and unbiased.

2.3. Data analysis

The monthly mean datasets were examined for normal distribution of the values. As expected, the large number of months with little precipitation or with low flow yielded histograms with the highest density at small values and a long tail comprising small numbers of high values, *i.e.*, the distributions are skewed to the right. Therefore, the data were transformed ($\log_{10}$) to achieve a normal distribution with similar variance prior to carrying out the regressions. The transformed data were used only to compute slopes of trendlines and the significance of that slope.

For the first objective, to determine if there have been any trends in annual precipitation or discharge during the study period, we used simple linear regression (SLR) as the most parsimonious means of expressing a trend. For each group of watersheds (north, $n = 18$; south, $n = 9$), and for each watershed individually, the logarithm of monthly mean precipitation in mm was regressed against time using monthly data (*i.e.*, January 1927 = 1927.0000; February 1927 = 1927.0833; March 1927 = 1927.1667; *etc.*) to obtain the annual rate of change over the 88 years. Likewise, the logarithm of monthly mean discharge in m^3s^{-1} was regressed against time. Regression lines were fitted for the period 1927–2014 by time for both precipitation and discharge. Slopes and p-values were recorded for the SLR equations for the two groups of watersheds and for each watershed individually. Slopes are reported in logarithmic units (precipitation in $\log_{10}$ mm and discharge in $\log_{10}$

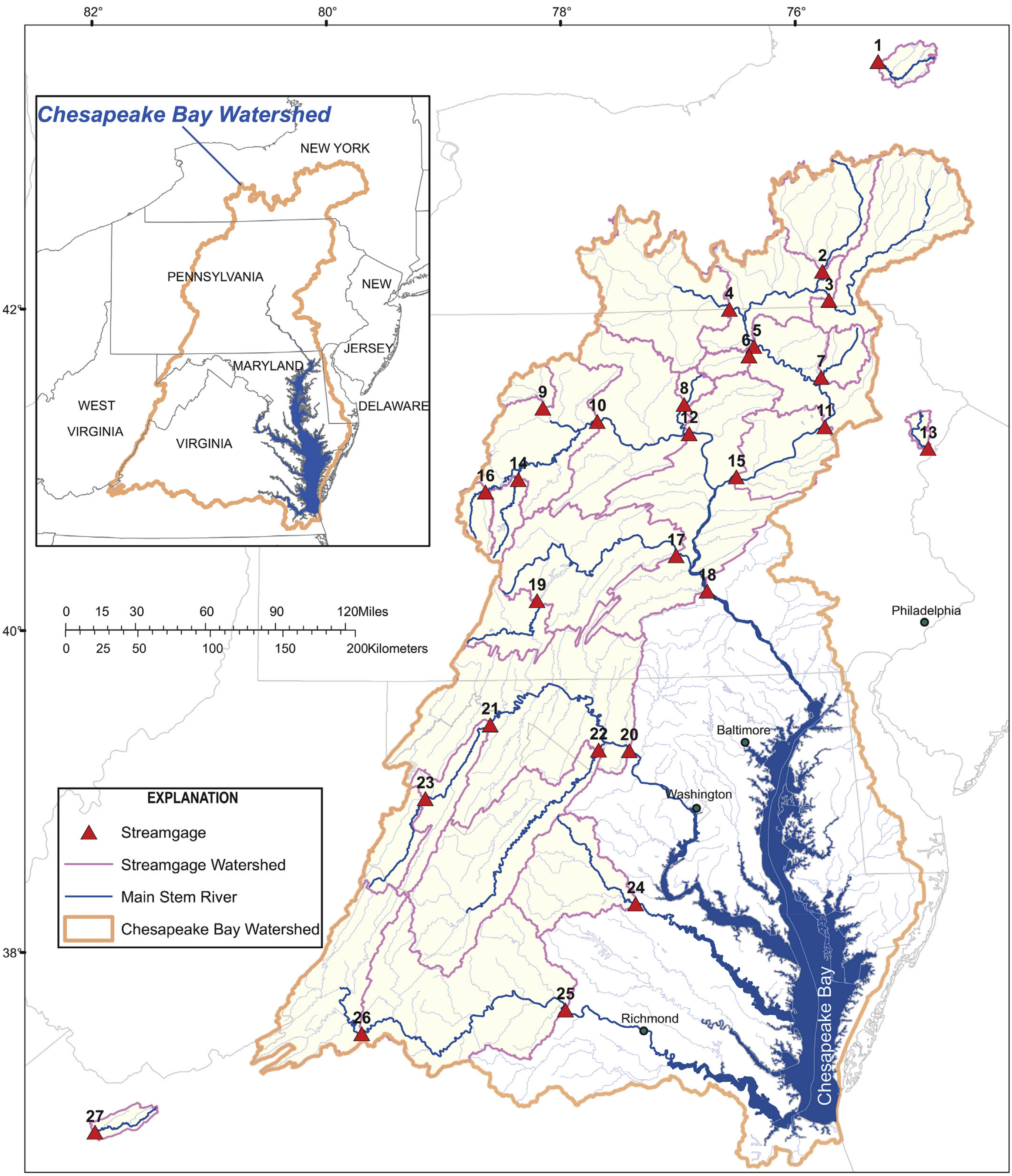

Fig. 2. The Chesapeake Bay basin showing locations of streamgages and outlines of the watersheds analyzed in this study.

m^3s^{-1}). Significance of linear relationships (in logarithmic space) was determined at $\alpha = 0.05$. An analysis of residuals for the data (not shown) indicated that all 27 watersheds had residuals with means near zero and that lacked any discernible pattern in their distributions (*i.e.*, white noise residuals), thus, the linear model was appropriate for the monthly mean discharge data.

The second objective was to determine the relationship between precipitation and discharge in the watersheds from 1927 to

Table 1
Locations of streamgages with the maximum 88-year record and areas of non-tidal watersheds upstream of streamgages within or near the Chesapeake Bay basin. Latitude and longitude given in decimal degrees. Sites are listed in order from north to south. [ID, identification number; km^2, square kilometers].

Streamgage Location				
Site number	USGS station ID	North Latitude	West Longitude	Area, km^2
1	04252500	43.51	75.31	787
2	01512500	42.22	75.85	3841
3	01503000	42.04	75.80	5781
4	01531000	42.00	76.63	6491
5	01531500	41.77	76.44	20,194
6	01532000	41.71	76.48	557
7	01534000	41.56	75.89	992
8	01550000	41.42	77.03	448
9	01543000	41.41	78.20	704
10	01545500	41.32	77.75	7705
11	01536500	41.25	75.88	25,796
12	01551500	41.24	77.00	14,716
13	01439500	41.09	75.04	303
14	01541500	40.97	78.41	961
15	01540500	40.96	76.62	29,060
16	01541000	40.90	78.68	816
17	01567000	40.48	77.13	8687
18	01570500	40.25	76.89	62,419
North-South Split				
19	01562000	40.22	78.27	1958
20	01638500	39.27	77.54	24,996
21	01608500	39.45	78.65	3784
22	01636500	39.28	77.79	7876
23	01606500	38.99	79.18	1686
24	01668000	38.31	77.53	4131
25	02035000	37.67	78.09	16,193
26	02019500	37.53	79.68	5369
27	03488000	36.90	81.75	572

2014. To the monthly mean precipitation and to the monthly mean discharge, we fitted distributions to obtain 11 percentiles for each year. The percentiles are the 10th, 20th, *etc*., increasing by units of 10 through the 90th percentile, along with the minimum and maximum values. Thus, single values for both precipitation and discharge were obtained for each percentile for each year for each watershed for the 88 years. The 22 × 2376-value matrix was divided into north and south, and precipitation and discharge percentiles for all of the northern watersheds were correlated; likewise, the same percentiles corresponding to the southern watersheds were correlated.

For the third objective, to determine any trends in the distribution of precipitation or discharge during the study period, regression lines were fitted to each set of data for the whole period of record by year for each percentile for each watershed (see Fig. 3 for an example). The slopes of the fitted lines were recorded.

To pursue the third objective further, we sought to determine if trends in any of the precipitation and discharge percentile values differed in the north as compared with the south. The percentile data were transformed to the $\log_{10}$ of each value to help with assumptions of normality and homogeneity of variance necessary for the analysis. Because the watersheds are of widely differing sizes, even the log transformation did not produce a homogeneous variance among the watersheds. To achieve homogeneity of variance, and to allow comparison of the watersheds across the spatial gradient, the data in each watershed were scaled. The scaling in each watershed was achieved by dividing every transformed discharge value for each percentile series by the initial value, *i.e.*, the corresponding log-transformed percentile value for 1927 for the individual watershed. Thus, the data represented the relative change from year-to-year from the initial value. The scaling resulted in a dataset in which the two groups (north and south) had similar variance. The scaling could also be achieved by dividing every transformed discharge value for each percentile series by the median (or mean) value, rather than the initial value. This would result in the same pattern of values, but on a different scale. The scaled values for each watershed were then regressed against year to obtain the slope of the trend for the period of record. The slopes of the regression for each watershed were grouped into north or south, and a mean slope was calculated for each group. A simple *t*-test was used to determine if the differences in the mean slopes for the north and south were significantly different.

The final objective was to project annual mean discharge out to the year 2025 in each watershed. To obtain projections of annual discharge rates (in m^3s^{-1}), the monthly averaged discharge data ($\log_{10}$ transformed) for each watershed for each year for 1927–2014 were regressed against time (*i.e.*, the same regressions as used for the first objective). The expected annual values of mean instantaneous discharge were then determined by extending the regression relationship 11 years, to 2025. Finally, the modeled (expected) values were converted back to the original data format by taking the antilogarithm of the values computed with the regression equations. The annual mean discharge values were computed for each watershed for the 3 years of interest (1927, 2014, and 2025), and the estimated percentage change in the time periods 1927–2014 and 2014–2025 were calculated.

3. Results

Monthly mean precipitation and discharge regressed against time indicated increases throughout the CB basin over the 88 years. The slopes of all log-transformed data are reported in logarithmic units. The average slopes of the regression lines indicated that the increase was slightly larger in the northern watersheds taken as a group (0.0005 mm yr^{-1}; $p < 0.0001$) as compared to the group of southern watersheds (0.0004 mm yr^{-1}; $p < 0.0001$). The results for regressions of monthly mean discharge were similar: for the group of northern watersheds, the average slope was slightly larger (0.0015 m^3s^{-1} yr^{-1}; $p < 0.0001$) than that of the group of southern watersheds (0.0010 m^3s^{-1} yr^{-1}; $p = 0.0323$).

When we looked at the individual watersheds within the two groups, there was a clear difference between the watersheds in the north relative to those in the south (Table 2). The slopes of precipitation trends for individual watersheds in the north were greater than those in the south, and 11 of the upward trends in the north were significant. Of the 11 significant trends in the north, the slopes ranged from 0.0005 to 0.0008 mm yr^{-1} (Table 2). None of the slopes in the south were significant. Progressing by individual watershed from north to south, the magnitude of the slopes for precipitation clearly decreased, and the number of significant trends also decreased (Table 2). As with precipitation, the magnitude of the discharge trends in individual watersheds was greater in the north than in the south. All but one watershed in the north had significant positive trends in discharge, with slopes that ranged from 0.0011 to 0.0021 m^3s^{-1}. Although trends in discharge for the nine southern watersheds nearly all were positive, none were statistically significant. The slopes ranged from −0.0001–0.0010 m^3s^{-1}. The lack of significance indicates that the slopes cannot be statistically distinguished from zero, *i.e.*, the mean of the values is the best estimator of the central tendency of the data.

Correspondence among precipitation and discharge percentiles for the 88-year period was tested by use of multivariate correlation. The Pearson correlation coefficients (r) (Table S1) among the northern watersheds were very low and ranged from −0.001 to 0.112, indicating little-to-no correspondence in precipitation and discharge in any percentile. Similarly, in the southern watersheds,

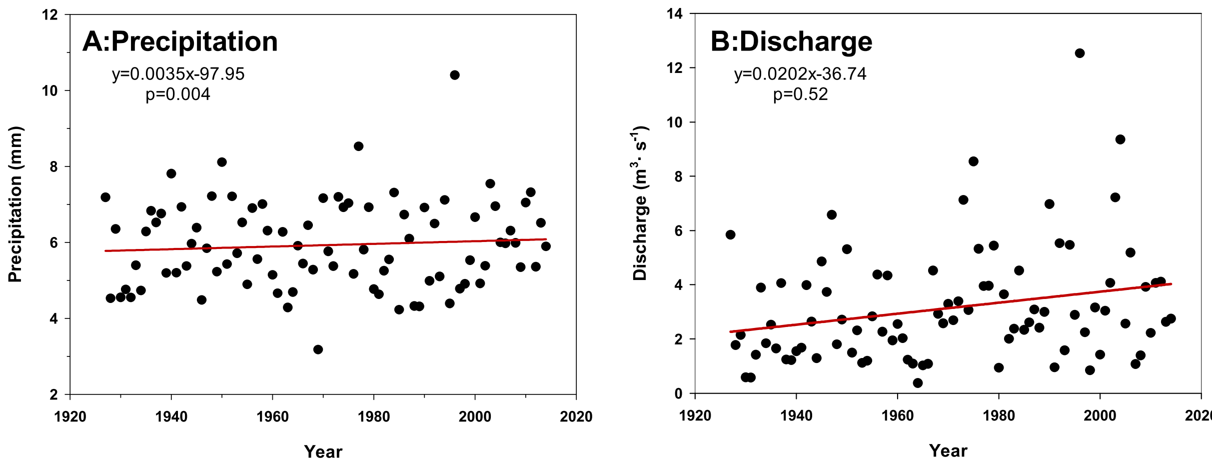

Fig. 3. Example of simple linear regression analysis of the monthly mean precipitation (A) and monthly mean discharge (B) values from 1927 through 2014 that correspond to the 30th percentile for each year at streamgage 01550000.

Table 2
Results of simple linear regression equations for precipitation and discharge, 1927–2014. Monthly mean precipitation and discharge were both regressed against time. Significant p-values (≤0.05) are in bold type. Slope of precipitation in logarithm$_{(10)}$ of millimeters per year; slope of discharge in logarithm$_{(10)}$ of cubic meters per second per year. Sites are listed in order from north to south. [ID, identification number; <, less than].

Site number	USGS station ID	Precipitation		Discharge	
		Slope	p-value	Slope	p-value
1	04252500	0.0007	**0.0011**	0.0021	**<0.0001**
2	01512500	0.0008	**0.0007**	0.0016	**0.0028**
3	01503000	0.0007	**0.0022**	0.0013	**0.0181**
4	01531000	0.0006	**0.0219**	0.0018	**0.0030**
5	01531500	0.0007	**0.0044**	0.0016	**0.0029**
6	01532000	0.0006	**0.0374**	0.0015	**0.0330**
7	01534000	0.0005	**0.0497**	0.0015	**0.0120**
8	01550000	0.0005	**0.0493**	0.0019	**0.0015**
9	01543000	0.0004	0.1000	0.0018	**0.0058**
10	01545500	0.0004	0.0953	0.0017	**0.0026**
11	01536500	0.0006	**0.0078**	0.0016	**0.0027**
12	01551500	0.0005	0.0612	0.0017	**0.0017**
13	01439500	0.0005	0.0972	0.0007	0.1661
14	01541500	0.0003	0.2357	0.0017	**0.0017**
15	01540500	0.0006	**0.0111**	0.0016	**0.0023**
16	01541000	0.0004	0.0985	0.0016	**0.0021**
17	01567000	0.0004	0.1577	0.0011	**0.0250**
18	01570500	0.0005	**0.0260**	0.0013	**0.0088**
		North-South Split			
19	01562000	0.0004	0.1693	0.0007	0.2082
20	01638500	0.0004	0.1150	0.0008	0.1026
21	01608500	0.0004	0.1725	0.0010	0.0833
22	01636500	0.0005	0.1245	0.0008	0.0624
23	01606500	0.0003	0.1958	0.0009	0.1108
24	01668000	0.0006	0.0794	0.0004	0.4727
25	02035000	0.0003	0.2653	−0.0001	0.8243
26	02019500	0.0002	0.4333	0.0003	0.4836
27	03488000	0.0003	0.2480	0.0006	0.2841

the r-values were low and ranged from 0.003 to 0.274.

Changes in the distribution of precipitation and discharge over the 88 years were examined by determining the value of each percentile plus the minimum and maximum values, then computing the regression parameters for each watershed at each percentile value (Table S2). The data in Fig. 4 represent the average slope at each percentile over the years for the precipitation and discharge trends of the 18 and nine watersheds in the north (Fig. 4A) and south (Fig. 4B), respectively, and indicates the rate of change of the precipitation or discharge over the 88 years. For precipitation in the north, the slopes were at their highest value at the minimum and decreased until P^{20th}; the values at the

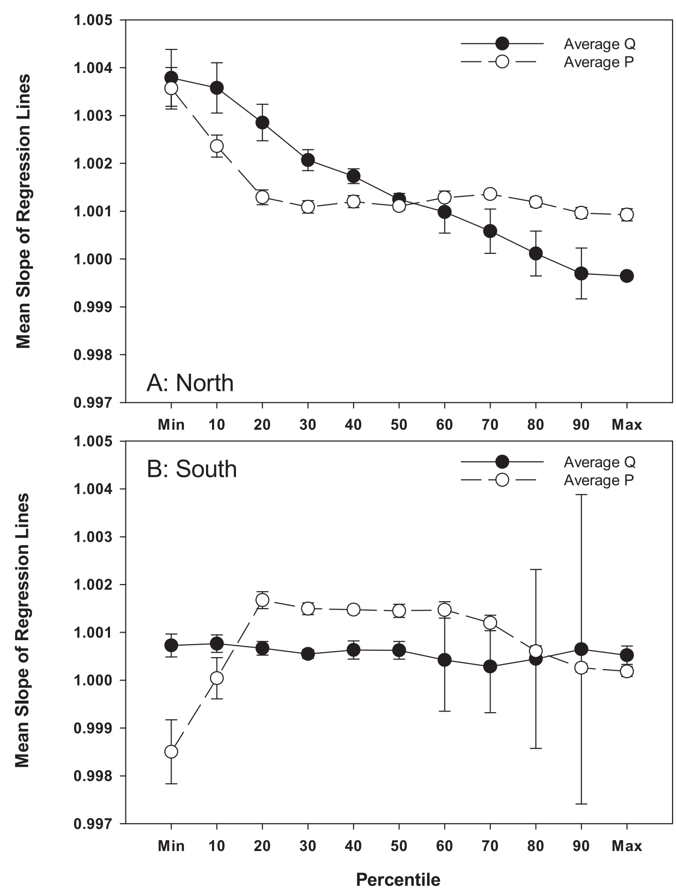

Fig. 4. Comparison of changes in the distribution of precipitation and discharge in (A) northern and (B) southern watersheds of the Chesapeake Bay basin from 1927 through 2014 by percentile, including the minimum (Min.), and maximum (Max.). Error bars represent the Standard Error of the Mean for each percentile determined. The discrete values at each percentile are connected by lines to facilitate visualization of the patterns. Units of the slopes for precipitation are in logarithm$_{(10)}$ of millimeters per month per year and for discharge are in logarithm$_{(10)}$ of cubic meters per second per month per year.

percentiles greater than P^{20th} were relatively constant to the maximum. Because the results are expressed as slopes, the actual magnitude of the change is related to the initial value and not to the absolute change in precipitation. Small changes in a large value can be much greater than large changes in a small value. The slopes representing changes in discharge from 1927 to 2014 followed a pattern different than that of precipitation, except that the largest slope for both precipitation and discharge was at the minimum value. The slopes for discharge at each higher percentile declined in sequence monotonically as the percentile increased to the maximum.

Patterns of precipitation and discharge percentiles in the south (Fig. 4B) were very different from those in the north. For precipitation in the south, the lowest value was 0.9985 at the minimum, and at P^{10th}, the value was 1.000. From P^{10th} to P^{60th}, the slopes were nearly identical. From P^{70th} to the maximum, the slopes declined. For discharge in the south, the values of the slopes were quite similar at all percentiles, although the variability among the values increased substantially for Q^{60th} to Q^{90th}, the part of the graph that corresponded to the decrease in mean slope for precipitation.

The regressions relating discharge with time that were developed for each of the watersheds for the first objective were extended from 2014 to 2025 to project discharge to the target date for implementation of the TMDL. All of the watersheds, from north to south, with the exception of site 25 (station ID 02035000) in the south that had a slight negative slope, were projected to have a higher annual mean discharge in 2025 than was modeled for 2014 (Table 3). In the north, discharge is projected to increase by an average of 4.01% ± 0.80, based on 18 positive slopes, 17 of which were significant. In the south, the average increase was smaller, *viz*, 1.53% ± 0.87. Because none of the regressions for the southern watersheds yielded a significant slope, the values given in Table 3 for the southern watersheds should be considered as upper limits, with the actual estimate falling between 0 and the listed value.

4. Discussion

The precipitation trend analyses using the PRISM data are in agreement with the results of three types of precipitation data used by Karl and Knight (1998), whose analyses over a shorter period show greater increases in precipitation in the northeast than in the southeast. Our analyses were specific to the CB basin, the total of which does not fit neatly into either the northeast or southeast divisions used by Karl and Knight (1998), Karl et al. (2009), and Melillo et al. (2014) (Fig. 1). Our analysis, based on watersheds rather than regions, provided finer spatial resolution such that we observed that the precipitation trend slopes decrease from north to south within the CB basin. This analysis provides a sharper demarcation in both precipitation and discharge, thus supporting and refining the earlier observations of the difference in precipitation between the northeast and southeast U.S.

When we examined the distribution of precipitation in comparison with the distribution of discharge, correlations (Pearson's r) between precipitation and discharge at all of the percentile values were weak in both the northern and the southern watersheds. These results underscore the problems associated with assuming that, for example, a P^{90th} event routinely and directly results in a Q^{90th} event. Similarly, Berghuijs et al. (2016) indicated that there is a disparity between the time of maximum precipitation and the time of maximum flooding in watersheds across the U.S. Thus, attempting to predict monthly mean discharge directly from monthly mean precipitation is scientifically unsupportable both in the timing and magnitude of the discharge events.

Table 3
Modeled annual mean discharge in 1927 and 2014, projected annual mean discharge in 2025, percent change in modeled annual mean discharge between 1927 and 2014, and projected percent change in modeled annual mean discharge between 2014 and 2025. Sites are listed in order from north to south. [ID, identification number; Q, discharge; m^3s^{-1}, cubic meters per second; %, percent; yr, year].

Site number	USGS station ID	Modeled annual mean Q in 1927, m^3s^{-1}	Modeled annual mean Q in 2014, m^3s^{-1}	Projected annual mean Q in 2025, m^3s^{-1}	Change from 1927 to 2014, %	Change from 2014 to 2025, %
1	04252500	533	812	856	52.3	5.2
2	01512500	1475	2032	2116	37.8	4.1
3	01503000	2310	2997	3097	29.7	3.3
4	01531000	35	50	53	43.4	4.7
5	01531500	5324	7334	7637	37.8	4.1
6	01532000	119	161	167	37.8	4.1
7	01534000	370	500	519	35.0	3.9
8	01550000	157	231	243	46.3	4.9
9	01543000	210	303	316	43.9	4.5
10	01545500	2606	3663	3824	40.5	4.4
11	01536500	8712	12,001	12,498	37.8	4.1
12	01551500	5651	7942	8292	40.5	4.4
13	01439500	131	150	153	15.0	1.8
14	01541500	376	528	551	40.5	4.4
15	01540500	11,020	15,183	15,810	37.8	4.1
16	01541000	312	430	448	37.8	4.1
17	01567000	2867	3574	3675	24.6	2.8
18	01570500	23,732	30,789	31,820	29.7	3.3
North-South split						
19	01562000	545	627	638	15.0	1.8
20	01638500	7019	8239	8407	17.3	2.0
21	01608500	765	934	958	22.2	2.6
22	01636500	1592	1869	1907	17.4	2.0
23	01606500	503	602	617	19.8	2.3
24	01668000	1187	1286	1300	8.30	1.0
25	02035000	5084	4985	4973	−2.00	−0.2
26	02019500	1437	1526	1537	6.19	0.8
27	03488000	216	244	247	12.7	1.5

Examination of changes in the distribution of precipitation and discharge by looking at trends in the flux of water at specific percentile values gave mixed results. While analysis of the monthly mean discharge records indicated positive slopes throughout, when the discharge was examined by percentiles, the trend patterns provided additional information. In the south, the slopes of the trend lines were relatively constant throughout all of the percentiles. The variability increased substantially for percentiles greater than Q^{60th}, however, so the small differences in slopes among the percentiles is not thought to be meaningful. It is interesting to note, although no reason can be put forth, that the increase in variability in the slopes of the discharge values corresponded exactly with the decrease in the slopes of the precipitation observed for those same percentiles. In the north, the slopes of the percentiles for discharge decreased rather uniformly across the percentiles from the minimum to the maximum. The variability in the discharge slopes was greater at the low and high percentile values, although the increased variability in the north in the Q^{60th} to maximum percentiles was substantially less than observed in the south. The shape of the discharge distribution pattern (*i.e.*, slope values at each percentile) was very different from the pattern for precipitation. Whereas discharge slopes declined monotonically with increasing percentiles, the precipitation slopes declined between the minimum value and the P^{20th} and were nearly constant at all higher percentiles. In both the northern and southern watersheds, the weak linkage between precipitation and discharge is evident, but in the north, the link is weaker. It can be inferred that the different space-time patterns between north and south identify a difference in human-nature system coupling.

At first glance, it may seem that the precipitation data (Fig. 4) contradict the findings of others who observed that increases in overall precipitation are most often associated with increases in high-precipitation events (Karl and Knight, 1998; Karl et al., 2009; Melillo et al., 2014). Fig. 4 shows that the relative amount of precipitation at all of the percentile values increased from 1927 to 2014, but that relative precipitation in the lower percentiles increased faster (at least in the northern watersheds). Given the small range of slopes of the regression lines, it is apparent that the changes were not widely different on a relative basis. Relative changes of similar magnitude represent much more absolute precipitation at the higher percentiles than the lower percentiles. Thus, while large events have increased in magnitude, the smaller events have increased as well, with an overall result of weather patterns in the CB basin becoming generally wetter.

These results have important implications for the mode of transport of pollutants to the CB, with the northern watersheds supplying pollutants at different discharges than the southern watersheds. More specifically, the northern watersheds tended toward a smaller increase in discharge in the higher percentiles, whereas the southern watersheds tended toward a larger increase in the highest percentiles. The lack of correspondence between high precipitation and high discharge calls into question models for the delivery of pollutants to water bodies such as the CB. If a model for discharge is based on precipitation input alone, the resulting discharge is likely to be incorrect, implying that the transport of pollutants would also be incorrect. For example, while the Universal Soil Loss Equation does a good job of modeling soil erosion from agricultural fields where precipitation intensity is an active driver, the model contains no terms for estimation of delivery of eroded material (*i.e.*, particulates and the pollutants sorbed to them) downstream to receiving bodies, including the CB.

The precipitation and discharge trends for the whole period (objective 1), the multivariate correlations (objective 2), and the trends in the percentiles (objective 3) all point to a lack of an intimate or direct connection between precipitation and discharge. For example, at the 70^{th} percentile in the northern group of watersheds, 13 watersheds had positive trends in precipitation, whereas only four had positive trends in discharge (Table S2). The observed lack of simultaneous precipitation and discharge response might be explained by the basic hydrology of watersheds. For example, lag times between the onset of precipitation and the response of streamflow; travel times of water through a watershed; seasonality of precipitation (*e.g.*, Berghuijs et al., 2014; Small et al., 2006); land use and land cover within the watershed; snow pack extent and timing of snowmelt (*e.g.*, Hodgkins and Dudley, 2006; Rice et al., 2015); and seasonality of evapotranspiration all influence the nature of the manifestation of precipitation on discharge. In particular, antecedent conditions—related to seasonality of precipitation and evapotranspiration—have been shown to have a profound influence on the magnitude of discharge caused by a precipitation event (Ivancic and Shaw, 2015). Berghuijs et al. (2016) concluded that variability in evaporation, snowmelt, and soil moisture control the timing of maximum flooding in watersheds across most of the U.S.

The fourth objective of the study was to project annual mean discharge in each of the watersheds for the year 2025. All of the watersheds had projected increased monthly mean discharge in 2025 over that modeled for 2014 (Table 3), with the exception of site 25 (station ID 02035000) for which the model generated a decrease in discharge of 2.0% for 1927–2014. Among the northern watersheds, the percent change in monthly mean discharge between 2014 and 2025 ranged from 1.8 to 5.2%. Among the southern watersheds, the percent change ranged from −0.2–2.6%. These results suggest that the northern watersheds are projected to experience greater increases in monthly mean discharge in 2025 than those in the south. The dominant watershed within the CB basin, the Susquehanna River, is projected to experience the greatest increase in absolute discharge, although the percentage increase is anticipated to be less than some of the other watersheds. From a management standpoint, these results indicate that discharge—thus, loads of nitrogen, phosphorus, and sediment—will continue to increase over the next eight years, barring a drastic change in precipitation or discharge, or a drastic reduction in land application. The largest increase in loads are anticipated to emanate from the northern part of the basin.

5. Conclusions

Through a rigorous examination of 88 years of precipitation and discharge data in the Chesapeake Bay basin, we found that: (1) annual trends in precipitation and discharge are positive; (2) the linkage between precipitation and discharge percentiles is low; (3) the distribution of annual precipitation and discharge percentiles has changed; and (4) annual mean discharge in 2025 is projected to increase.

Our results have implications for achievement of the TMDL and for maintenance of the improvements that have been achieved. As stated in the Introduction, *where*, *when*, and *how* discharge changes ultimately will determine the quantity of nitrogen, phosphorus, and suspended sediment that reach the bay. As shown in this analysis, location within the CB basin (*where*) is important, because total discharge in the northern watersheds is increasing more than that in the southern watersheds. On an annual time scale, *when* large discharge events occur is important because of the timing of fertilizer application within watersheds, changes in the timing of snowmelt, and variations in antecedent moisture conditions all factoring in to *when* the pollutant load is mobilized and transported. *How* discharge changes refers to the shift in the flow percentiles. Depending on stream bank slope and configuration, geology, land use, intensity of precipitation, *etc*., one watershed may begin transporting sediment at a different flow percentile than another watershed.

The type of analysis carried out in this study is useful for several applications: (1) evaluation of models that are designed to forecast future changes in streamflow; (2) design and planning models for water quality, water supply, flood hazard mitigation, and ecosystem protection; and (3) understanding natural variability and the persistence of changing hydrologic conditions. Analysis of trends in flow percentiles, as shown here, rather than simply trends in annual mean discharge, could be useful to apply to the management of large watersheds throughout the world, recognizing that the longer the data record, the more robust will be the results. A plethora of studies use modeling, scenarios, and projections—complete with bias corrections—to examine how river discharge might change in the future; their utility and accuracy can be strengthened by calibration and comparison with long-term empirical data. The use of long-term empirical data alone, however, remains a robust and trusted method on which to base environmental decisions. Finally, when such data are available, the empirical approach may be preferred over modeling studies.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2017.08.057.

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