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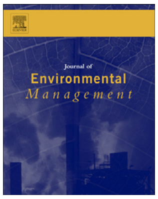

Research article

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