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Precipitation thresholds for fecal bacterial indicators in the Chesapeake Bay

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ABSTRACT

Many coastal states of the United States restrict harvest of shellfish from select areas based on some environmental trigger. Such areas are classified as being conditionally approved. In Maryland, the trigger is an inch or more of rainfall that has fallen in the last 24 h. This study used 11 years of monitoring data to test the relationship between daily rainfall totals and densities of fecal indicators in Maryland shellfish harvest waters. Precipitation and fecal coliform (FC) water monitoring data from 2004 to 2014 were matched by date and watershed. The influence of antecedent rainfall conditions (i.e. rainfall in the preceding days or weeks) and the distance of each monitoring station to land were compared to the percent of samples exceeding the FDA criterion for managing shellfish harvest areas. Sample stations beyond 1000m from land had FC densities consistently below the FDA criterion and were excluded from further analysis. Rainfall events greater than an inch tended to result in significantly elevated FC for the following two days, followed by lower levels thereafter. The total amount of rain in the last three weeks was positively related to the proportion of samples with FC greater than the FDA criterion. Bay-wide, the percent of samples exceeding the FDA criterion rose from seven percent for rainfall less than an inch to 37% following one or more inches of rain. Watersheds were classified based on the percent of FC densities over the criterion when rainfall was an inch or more, with 41 of 81 watersheds showing FC responses indicative of potential conditionally approved areas, those shellfish growing areas where the one inch precipitation trigger may be applied. These areas largely overlapped the current conditionally approved areas defined by Maryland. The percent of open water, wetlands, and poorly drained soils explained a significant amount of the variability ($R^2 = 0.72$) in the difference in percent of samples exceeding the FDA criterion when rainfall was greater than an inch and when it was less than an inch. Logistic regression analysis showed that the current trigger of one inch of rain in 24 h is predictive of FC densities over the FDA criterion, though the appropriate threshold will most likely depend on how far the particular shellfish growing area is from land and antecedent rain conditions. In watersheds with relatively high percentages of open water to total watershed size, higher rainfall thresholds might be appropriate. The approach taken in this study could be applied to individual stations and sub-watersheds, potentially allowing the reclassification of some shellfish harvest areas.

1. Introduction

Fecal indicator bacteria in estuarine waters are used as indicators of fecal pollution and an increased risk of encountering human pathogens in nearby shellfish (Ashbolt et al., 2001; FDA, 2015). In areas where non-point sources are present or stormwater overflows occur, fecal pollution in estuaries is often related to rainfall (FDA, 2015; Kelsey et al., 2004). Thus, in the United States (US), under the Food and Drug Administration (FDA) guidance for management of shellfish harvest (FDA, 2015) and Environmental Protection Agency (EPA) guidance for recreational water use (EPA, 1986), access to these natural resources may be restricted after a specified level of precipitation. For shellfish, such areas are classified as 'conditionally approved' meaning that the area being open

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to harvest is conditional upon some set of environmental conditions. Shellfish harvest in many US coastal states is prohibited from conditionally approved beds whenever a specified amount of rain has fallen in the last 24 h.

In Maryland, the classification of conditionally approved shellfish beds is based on field studies that identified conditions generally meeting the FDA criteria except after large rainfall events. The bulk of these studies occurred in the 1980's. The threshold for closure, one inch of rain in the last 24 h, was established by quantifying fecal coliform (FC) densities in surface waters during and after rain events in select areas of the Bay in 1987. The level of FC in surface waters was measured at several times over several days following rain events (Kathy Brohawn, MDE, personal communication). The resulting management decision was to close conditionally approved areas for three days following a rain event over and inch in 24 h. Although this process provided evidence of the link between rainfall and FC densities in water and the extent of time that elevated FC densities occurred, it was limited in the number of samples, watersheds, and rain events tested. Therefore, the amount of rain necessary to produce significant runoff may not have been thoroughly investigated, nor were antecedent rainfall conditions (i.e. rainfall that occurred in the days or weeks preceding the current rain event) always taken into account. Additionally, field studies designed to assess the impact of rain events did not quantify related factors, such as land use or soil types, which may affect levels of fecal pollution.

Studies in other aquatic systems have assessed the relationship of fecal indicator bacteria, such as FC, in surface waters to a large number of environmental variables and, in some cases, have been able to develop models with moderate capability to predict fecal indicator bacteria densities (EPA, 2010a; Gonzalez et al., 2012; Kelsey et al., 2010; Maimone et al., 2007; Mallin et al., 2001). Predictive models for fecal indicator bacteria in recreational waters at beaches has been of particular focus (EPA, 2010a). Variables found to be predictive in previous studies included rainfall, wind velocity, turbidity, water temperature, and riverflow (Campos et al., 2013; EPA, 2010a; Kelsey et al., 2010; Maimone et al., 2007; Mallin et al., 2001). These studies primarily focused on using linear regression models (Ferguson et al., 1996; Kelsey et al., 2010; Maimone et al., 2007) and decision trees (Maimone et al., 2007) to provide guidance for risk of fecal bacterial densities exceeding established criteria, though some use of logistic regressions has attempted to predict probability of occurrence (Eleria and Vogel, 2005). The predictive power of rainfall and/or riverflow (typically a function of rainfall) for fecal indicator densities relates to the land-based source of most fecal bacteria (Kelsey et al., 2004). In general, the ability to predict concentrations of fecal indicator bacteria in natural water bodies with low uncertainty has proved challenging (EPA, 2010a; Novotny and Olem, 1994). For convenience, the use of a rainfall threshold that is predictive of excessive fecal bacteria may serve as a tool for shellfish managers to make decisions about shellfish bed closures based on the relative risk of having fecal pollution in the growing waters. An assessment of FC densities at California beaches following large storm events underscored the utility of precipitation thresholds (Ackerman and Weisberg, 2003).

In this study, empirical data was used to examine the relationship between FC densities and precipitation in Maryland's estuarine waters. The null hypotheses were that the level of precipitation necessary to result in FC densities in excess of the FDA criterion is at least an inch and is uniform between various small watersheds across Maryland's portion of the Chesapeake Bay. Supporting hypotheses were that the relationship between precipitation and FC levels was not influenced by the distance of the monitoring stations in each watershed to land, antecedent rain conditions, wind speed, and air temperature (as a proxy for seasonal patterns). The response of FC densities to rainfall was further compared to characteristics of the watershed, such as the percent of open water, impervious surface and soil types. Logistic regressions were used to assess the amount of rainfall resulting in a significant probability of fecal densities exceeding the FDA criterion for management of shellfish harvest areas.

2. Materials and methods

2.1. Meteorological data

Several sources of precipitation data were considered, including daily estimates from National Weather Service weather stations as well as estimated rainfall based on Doppler radar images. Ultimately, rainfall estimates produced by the Middle Atlantic River Forecast Center (MARFC) called Multi-Sensor Precipitation Estimates (MPE) (http://www.weather.gov/marfc/Multisensor_Precipitation) were chosen, primarily due to their use by the Maryland Department of the Environment (MDE) to regulate closures of their conditionally approved shellfish beds and the relatively fine spatial coverage (grid size is approximately 16 km^2). Some MPE data was excluded from our analysis on the advice of the MARFC (Jason Nolan, MARFC, personal communication). MPE data prior to 2004 was excluded based on a lower level of confidence in the estimates, and data for the months January through March were excluded because the radar precipitation estimates were not as accurate for frozen precipitation and suffer from 'bright banding' - where melting snow registers as large raindrops. The archived MPE data represents 24 h estimates of total precipitation in inches from 8:00pm to 8:00pm (UTC-5), the same time span used by MDE for conditionally approved shellfish area closures. Antecedent rainfall amounts were calculated by summing previous rainfall amounts for each day up to a week and then by week up to a month prior to the target date.

Wind speed and air temperature data were gathered from the Global Historical Climatology Network-Daily (GHCN-D) database through the National Centers for Environmental Information (NCEI) (www.ncei.noaa.gov/, accessed 4/7/2016). Mean daily air temperature and wind speed data were chosen from NOAA weather stations based on their completeness of record and geographic locations. Air temperature data came from weather stations at the Conowingo Dam (USC00182060) and Royal Oak (USC00187806) while wind data came from Baltimore/Washington National Airport (USW00093721) and Salisbury/Wicomico Regional Airport (USW00093720). Temperature and wind data were averaged between stations. To account for sharp changes in air temperature between consecutive days, an average of the air temperature for the day of sampling and the previous day was used. Averaging of weather station spatially and temporally has been conducted routinely by NCEI, such as the monthly mean air temperatures calculated for the climate divisions of the U.S. (www.ncdc.noaa.gov/monitoring-references/maps/us-climate-divisions.php).

2.2. Station and watershed data

Water quality stations monitored by the Maryland Department of Environment (MDE) were selected for this study based on the frequency and duration of sampling. All monitoring stations in Maryland's portion of the Chesapeake Bay sampled consistently from 2004 to 2014 were considered, in order to match the time period of the precipitation data. This provided data from 509 stations, with an average sample count of 107 per station and a total of 54,580 observations. MDE typically collects data from these stations twice a month, though data gaps exist, due primarily to winter ice conditions and extreme weather events. Distance from