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Effect of Historic Milldam Density on Current Water Quality Indicators in a Portion of the Chesapeake Bay Watershed

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Abstract

Suspended sediment, nitrogen, and phosphorus are a significant source of pollution in the Chesapeake Bay, and levels of these pollutants in the watershed's streams and rivers are concerning. Traditional approaches to reducing sediment and nutrient loads have focused primarily on upland soil erosion, but often fail to include in-stream processes like bank erosion. It has recently been shown that in the North American Piedmont geographical region, historic sediment that accumulated behind milldams in the 18th and 19th centuries, referred to as legacy sediment, is an underestimated source of sediments in the Chesapeake Bay. Breached dams result in altered stream structures that exacerbate bank erosion and erosion of legacy sediment. In this study, I aimed to examine the relationship between historic milldam density in a watershed and the current water quality leaving the watershed. I expected to find positive correlations with watersheds with higher milldam densities having higher current levels of suspended sediment, total nitrogen, and total phosphorus. Watersheds were constructed using ArcMap software based on USGS stream gauge stations in Pennsylvania and Maryland in the Chesapeake Bay watershed. Milldam density for each of these watersheds was calculated as number of dams per hectare, and linear regression analyses were run for each of the water quality variables. No statistically significant results were found for the 14 studied watersheds. More research is needed to determine whether there is a relationship between historic milldam density and current water quality indicators.

Introduction

Suspended sediment, nitrogen, and phosphorus are important water quality concerns in the United States (Lutgen et al., 2020). Just under 53 percent of assessed rivers and streams in the U.S. were classified as impaired in 2016, with approximately 80 percent of assessed bays and estuaries being impaired (USEPA, 2016). An area of particular interest is the Chesapeake Bay watershed. The Chesapeake Bay is the continent's largest estuary, and its watershed spans six states in the Mid-Atlantic U.S. region (NRCS, n.d.). Despite its magnitude and importance, the health of the bay suffers greatly from sediment and nutrient pollution (NRCS, n.d.). The traditional approaches to improving the health of the Chesapeake Bay and its tributaries have focused on upland soil erosion, particularly agricultural erosion (Lutgen et al., 2020). Many of these approaches are based on models relying on the Universal Soil Loss Equation (USLE) and its derivatives (Boomer et al., 2008). However, research suggests that the USLE, which is based on estimated values for rainfall and runoff, slope length and steepness, soil erodibility, and land cover and management practices, is insufficient to predict sediment loads in the Chesapeake Bay watershed (Boomer et al., 2008). This inconsistency suggests that there exists a sediment source other than those accounted for in the USLE that is currently being underestimated as a driver of sediment loads.

Limitations of the USLE include its failure to acknowledge gully erosion, bank erosion, and sediment resuspension as conditions that could lead to high sediment loads (Boomer et al., 2008). Of these, it has more recently been shown that streambank erosion from sediment-filled valley-bottoms can be an important factor in sediment and nutrient pollution in waterways (Lutgen et al., 2020). In fact, it has been estimated that bank erosion contributes 50 percent to 100 percent of the total measured suspended sediment loads for streams in the northern Piedmont geographical region (Lutgen et al., 2020).

During a period of intensive land clearing in the 18^{th} and 19^{th} centuries, settlers in the Piedmont region converted wetlands into cropland and pasture, building water-powered mills and milldams. The millponds filled with sediment and as dams breached throughout the 20^{th} century, the newly formed rivers cut through the reservoirs of sediment, altering the pre-settlement landscape (Voli et al., 2009). This change in stream structure is evident in the steep banks and high sediment loads of modern rivers (Walter & Merritts, 2008).

Pre-settlement streams in the northern Piedmont region wound through vegetated wetlands and were smaller and more branching than modern streams. The single meandering stream cutting through high floodplain deposits that we see today is a result of breaching in the aforementioned milldams. These dams were constructed at such high densities that it is estimated that in Pennsylvania alone, up to 18,000 milldams existed at one point (Walter & Merritts, 2008). The sediment found in today's floodplains built up behind milldams, filling millponds, and is referred to as legacy sediment. The early years of European settlement in the region had a dramatic impact on the land—land clearing, farming, and mining caused widespread erosion and increased sediment flow in rivers, resulting in an excessive amount of sediment being trapped in the millponds and covering previously existing wetlands. For instance, at Big Spring Run in Lancaster County, Pennsylvania, geologic and paleoecologic records show the existence of pre-settlement wetlands that were buried under the sediment (Voli et al., 2009). These relatively recent discoveries have led to a new method of stream restoration in areas affected by milldams, which centers around restoring natural riparian wetlands by removal of legacy sediment (Voli et al., 2009).

Despite the success of removing legacy sediment to improve water quality, much of the current focus on reducing sediment and nutrient pollution in waterways remains on construction and agricultural practices. However, bank erosion is another key factor that must be considered, especially in the Chesapeake Bay watershed. A study of a suburban Chesapeake Bay watershed in Virginia found that bank-derived sediment was the main source of fine sediment in the stream of interest, both for bed sediment and suspended sediments, with minor (less than 10 percent) contributions from forests or roads (Cashman et al., 2018). Other studies have produced similar results, such as a study done by Voli et al. (2013), which showed that stream bank erosion of legacy sediment is the primary cause of high sediment loads in catchments of the Falls Lake basin in North Carolina.

Bank erosion occurs in three main ways, including freezing and thawing of surface soil, mass wasting of bank material, and fluvial detachment of particles (Merritts et al., 2010). These erosion patterns cause stream banks to recede laterally, altering the flow of the stream while also contributing to the suspended sediment load. A key difference between this type of sediment pollution and sediment pollution from cropland or construction sites is that bank erosion is more direct, and thus more likely to result in transport of the sediment further downstream and throughout the river system (Merritts et al., 2010).

Phosphorus levels are also a major issue with bank erosion, and many stream banks have consistent levels of phosphorus trapped in the legacy sediment (Merritts et al., 2010). Conversely, nitrogen abundance in legacy sediment varies, possibly due to historical land use practices or the difference in chemical and physical properties of nitrogen and phosphorus. Nitrogen levels in waterways increase substantially because of bank erosion, but nitrogen loads are not released via bank erosion to the same extent as sediment and phosphorus (Merritts et al., 2010).

While it is known that historic milldams altered the wetlands they were built on, it remains unknown whether there is a direct relationship between the presence of historic milldams and the current water quality leaving watersheds that contained high numbers of dams. Current stream restoration practices focus primarily on current land use as the primary driver of high sediment and nutrient loads, but studies like the one by Merritts, et al. (2010) show that stream corridor erosion is also a major contributor. This research suggests that rather than focusing solely on controlling point source pollution or implementing riparian buffers, a more effective approach to stream restoration may be legacy sediment removal (Voli et al., 2009).

While current research clearly suggests the modern structure of streams in the Piedmont region is very susceptible to bank erosion that harms water quality, it is not yet known whether the presence of milldams affects water quality at a catchment-level scale. This study seeks to determine whether a milldam signature exists at the watershed scale. The research attempts to address this question by investigating a potential correlation between historic milldam density in a watershed and the current water quality leaving the watershed. Because of the impact of historic milldams at the scale of an individual stream, it was hypothesized that the presence of milldams would also have an impact on water quality at a watershed scale. Thus, it was hypothesized that this study would find a negative correlation between the density of historic milldams in a watershed and the water quality of streams in those watersheds.

Methods

I chose current water quality indicators to be concentrations of suspended sediment, total nitrogen, and total phosphorus, as these are pollutants of concern in the Chesapeake Bay watershed (Lutgen et al., 2020). These data were downloaded as the annual loads table from the United States Geological Survey (USGS) website for nontidal monitoring stations in the Chesapeake Bay watershed for stream gauges in Pennsylvania and Maryland. The data are for the water year (October-September) 2018, with units being the flow normalized mean annual concentration for all the days in mg/L.

Calculating dam density within the watersheds required data showing the locations of historic milldams for the region. These data are from Dr. Dorothy Merritts and Michael Rahnis at

Franklin & Marshall College, as well as from a layer by WSI1234 (Water Science Institute) from the ArcGIS Online Living Atlas. The next step in calculating dam density was creating watershed boundaries using geographic information systems (GIS), which required elevation data. This elevation data came from digital elevation models (DEMs) from the USGS website for the selected locations.

To determine the upland area draining into the selected stream gauges, watersheds were created using ArcMap software (Version 10.8.1). To create the watersheds, DEMs were added to an empty map on ArcMap. The 'fill' feature was used to remove erroneous spots of low elevation in the DEMs. The 'flow direction' tool was used to determine which way water flows, based on the elevation data in the DEMs. To determine where water accumulates based on the flow direction, the 'accumulation' analysis was run. Then, because the latitude and longitude measurements for the stream gauge layer did not necessarily match up with the accumulation layer, the 'snap pour point' tool was used to snap each stream gauge point to an area of accumulation to ensure the pour point was actually located on the stream. To establish the watershed boundary for a given stream gauge point, a 'watershed' analysis was run using the flow direction and pour point data. The created watershed layers were then converted from raster form, which contains data in a matrix of individual cells, to polygon form, which allows the area of the shape to be calculated. Watershed polygons were then projected into NAD 1983 UTM Zone 17N or 18N and added to a new map. The dam data was projected into NAD 1983 UTM Zone 18N and added to the new map, as well. Then, the area of each watershed was calculated (in hectares), and the number of dams within each watershed was recorded.

The relationships between milldam density in the watersheds and the water quality indicators at the corresponding stream gauges were analyzed with linear regression analyses using IBM SPSS Statistics software (Version 27) at a significance level of 0.05. The milldam density per watershed (calculated in Excel as number of dams per hectare) was used as the independent variable. The dependent variables were the water quality indicators: suspended sediment (mg/L), total nitrogen (mg N/L), and total phosphorus (mg P/L). Because dam data were limited to certain counties and watersheds often include several counties, not all the constructed watersheds had dam data throughout the whole watershed. To control for this, separate analyses were run. Three analyses were run using the set of ten watersheds that had complete dam data, and three analyses were run using the ten complete watersheds as well as the four watersheds having incomplete dam data.

Results

The area varied for the 14 analyzed watersheds from 8458 ha to 132709 ha, with watersheds in Pennsylvania and Maryland (Table 1). Dam density ranged from 0.000550 dams/ha to 0.0029085 dams/ha (Table 1). Map outputs produced visual representations of the high dam density in the studied watersheds (Figures 1-3).

For the ten watersheds with complete dam data, the simple linear regression analysis for dam density and suspended sediment did not produce statistically significant results ($t= 1.779$, $F_{1,8}=3.163$, $p=0.113$, $R^2=0.283$; Figure 4), nor did the linear regressions for nitrogen ($t= 0.146$, $F_{1,8}=0.021$, $p=0.888$, $R^2=0.003$; Figure 5) or phosphorus ($t= -0.202$, $F_{1,8}=0.041$, $p=0.845$, $R^2=0.005$; Figure 6). Three linear regression analyses were also run using all 14 watersheds, including the four for which dam data were incomplete. These output analyses for suspended sediment ($t=1.375$, $F_{1,12}=1.890$, $p=0.194$, $R^2=0.136$), nitrogen ($t= 0.597$, $F_{1,12}=0.357$, $p=0.562$, $R^2=0.029$), and phosphorus ($t=0.185$, $F_{1,12}=0.034$, $p=0.856$, $R^2=0.003$) were also insignificant. While the graph of suspended sediment concentrations as a function of milldam density shows a positive trendline, the graphs for nitrogen and phosphorus do not visually suggest any potential relationship between the dependent variables and milldam density.

Table 1. Names of selected stream gauges and area, number of dams, and dam density for corresponding watersheds in Pennsylvania and Maryland.

Stream Gauge	**Watershed Area (ha)**	**Number of Dams**	**Dam Density (number of dams/ha)**
Conodoguinet Creek near Hogestown, PA	120513.80	105	0.0008713
Yellow Breeches Creek near Camp Hill, PA	55770.56	90	0.0016138
Quittapahilla Creek near Bellegrove, PA	19034.80	21	0.0011032
Conewago Creek near Falmouth, PA	12193.38	11	0.0009021
West Conewago Creek near Manchester, PA	132709.08	140	0.0010549
Codorus Creek at Pleasureville, PA	68890.97	115	0.0016693
Pequea Creek near Ronks, PA	18031.25	50	0.0027730
Conococheague Creek at Fairview, MD	129948.14	105	0.0008080
Octoraro Creek near Richardsmere, MD	45727.49	133	0.0029085
Gwynns Falls at Villa Nova, MD	8458.53	16	0.0018916
Patuxent River near Unity, MD*	9008.90	5	0.0005550
Monocacy River at Bridgeport, MD*	44799.83	40	0.0008929
Antietam Creek near Waynesboro, PA*	24287.30	39	0.0016058
Gunpowder Falls at Glencoe, MD*	41379.93	55	0.0013291

**Indicates a watershed with incomplete dam data*

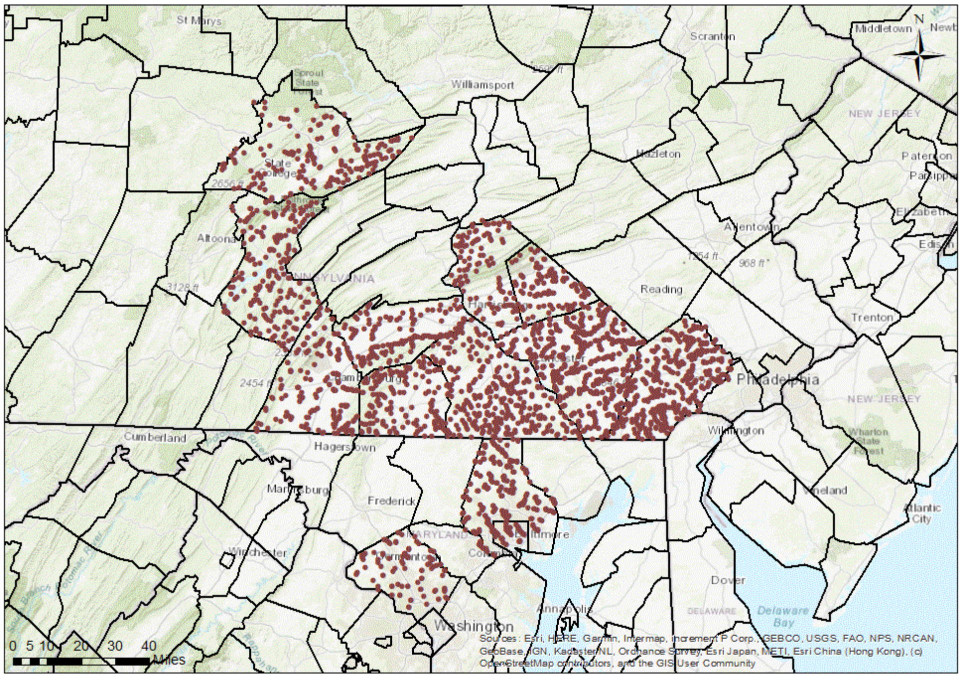

Figure 1. Dam data and county boundaries for parts of Pennsylvania and Maryland. Counties are outlined in black and each brown dot indicates the presence of a dam.

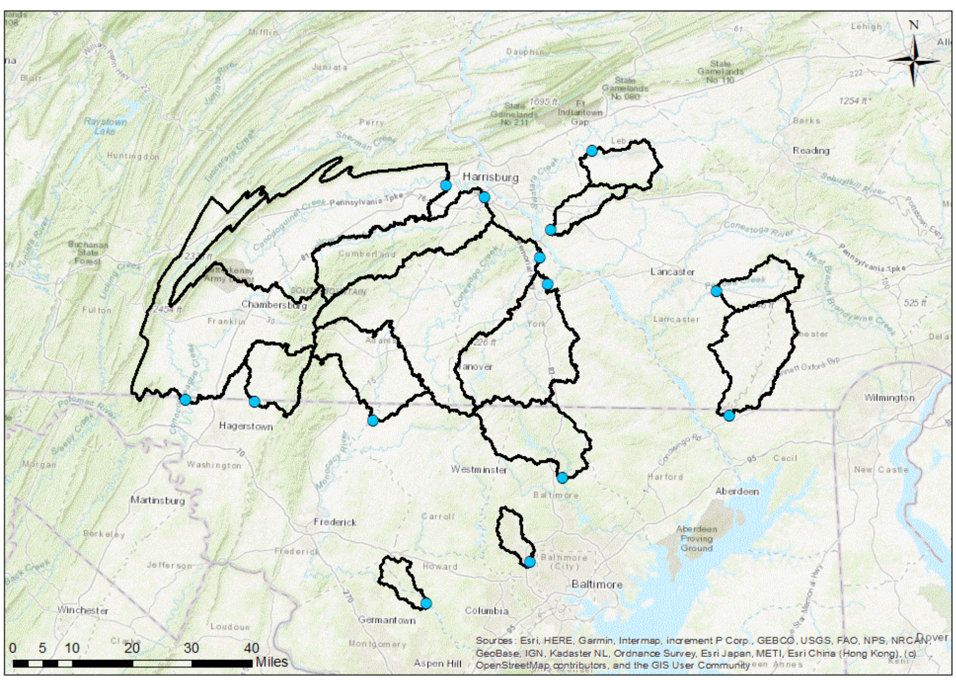

Figure 2. Stream gauges (blue dots) and their corresponding watershed boundaries for the 14 watersheds used in this analysis.

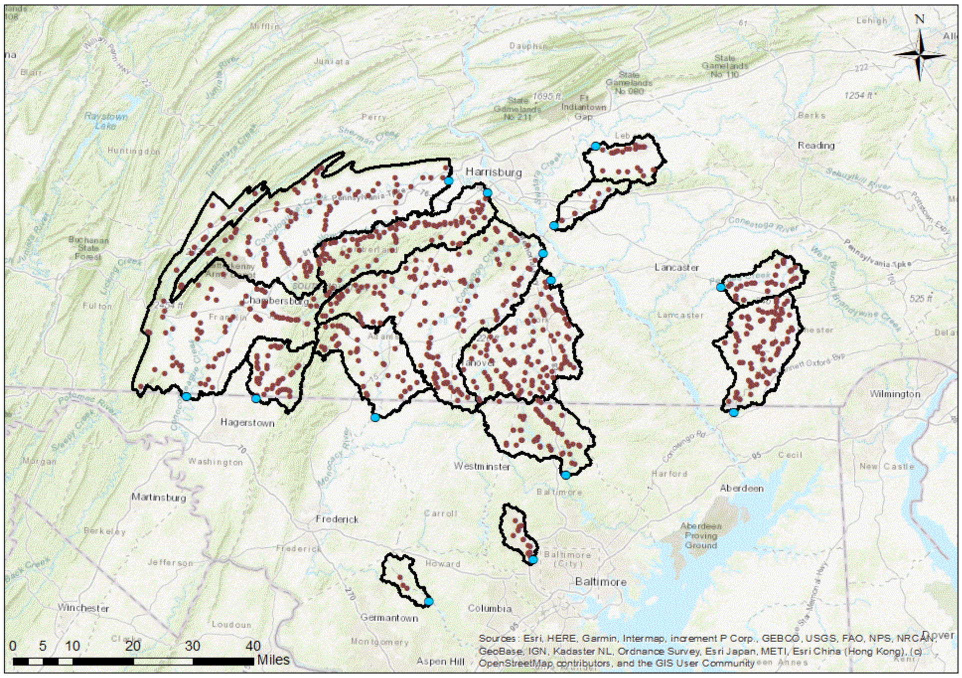

Figure 3. Stream gauges (blue dots), watershed boundaries, and dam data (brown dots) for the 14 watersheds used in this analysis.

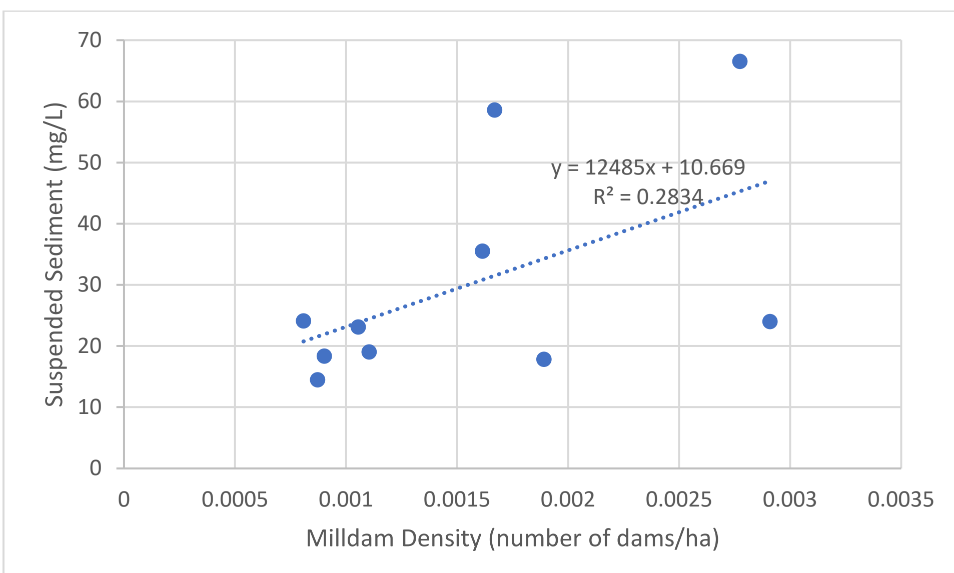

Figure 4. The relationship between milldam density (in number of dams/ha) for each watershed and the suspended sediment concentration (in mg/L) recorded at its corresponding stream gauge.

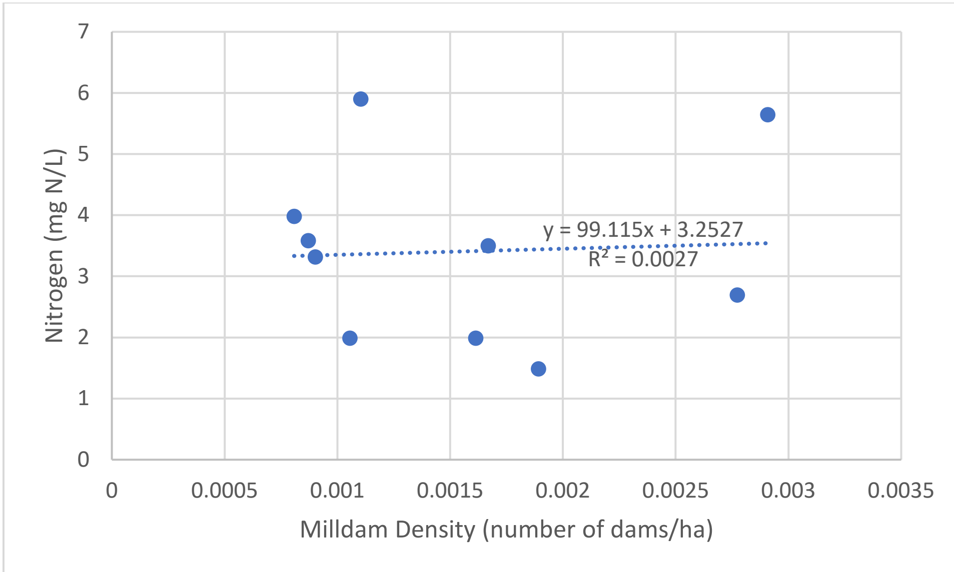

Figure 5. The relationship between milldam density (in number of dams/ha) for each watershed and the nitrogen concentration (in mg N/L) recorded at its corresponding stream gauge.

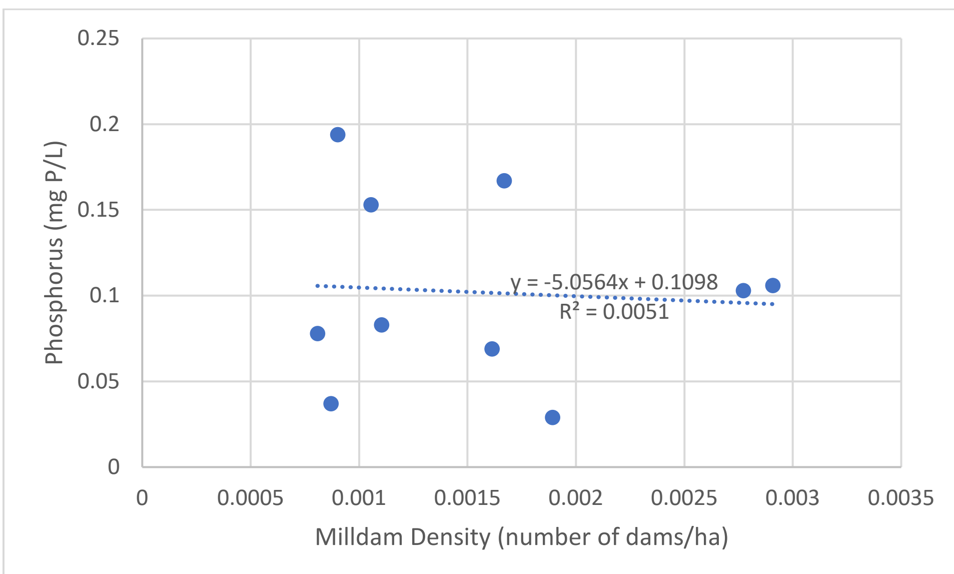

Figure 6. The relationship between milldam density (in number of dams/ha) for each watershed and the phosphorus concentration (in mg P/L) recorded at its corresponding stream gauge.

Discussion

The results of this study fail to support the hypothesis that there is a positive correlation between historic milldam density in a watershed and the current suspended sediment, nitrogen, and phosphorus concentrations of water leaving those watersheds. At a significance level of 0.05, none of the regression analyses produced statistically significant results. Therefore, this study does not show evidence of a statistically significant relationship in the study area between historic milldam density in a watershed and current water quality indicators for water leaving a watershed.

While this result does suggest historic milldam density is not the sole factor explaining current water quality at the watershed scale, it does not eliminate the possibility that milldam density is a contributing factor to poor water quality in the Piedmont region. Given the complexity of watershed dynamics, it is likely that there are several factors affecting current water quality in the region of this study. Only exploring one independent variable (historic dam density) is a limitation of this study, as there are many other factors that affect water quality. For instance, it is known that changes in land use affect sediment and nutrient yields in watersheds, with pollutants being higher in catchments with predominantly residential or agricultural land cover, and lower in catchments with predominantly forest land cover (Delia et al., 2021). To improve upon this analysis, land use data for the selected watersheds could be used in addition to dam density, or a subset of watersheds that share similar land use patterns could be analyzed to control for those variables. Factors such as slope length and steepness also impact sediment yields and are typically included in soil loss models (Boomer et al., 2008). Future research could and should incorporate these factors, as well as dam density, into analysis.

Results of these analyses may also be limited by the small sample size. In this study, the small sample size was due to a lack of easily accessible data showing historic milldam locations. More dam data would allow a larger area in the northern Piedmont region to be investigated and more watersheds to be analyzed, thus expanding the sample size. Another potential limitation of the study is that each milldam is treated the same way in the analysis, even though some dams may have breached a long time ago, some may have breached recently, and some may still exist today. The status of the dam could impact current water quality. For instance, if a dam still exists, legacy sediments are less likely to influence water quality. If a dam breached in the 18th century after only existing for a short time, legacy sediment may not have accumulated to an extent that it is still impacting water quality today. Other possible areas of future research could look at potential correlations for different response variables, or could investigate more specific types of these variables, such as dissolved nutrients, organic nutrients, inorganic nutrients, or nitrate.

Despite the limitations of this study, results suggest a relationship may exist between milldam density and current suspended sediment levels. The p-value for this analysis (using only the ten watersheds with complete dam data) was 0.113, with an R^2-value of 0.283. Although the results were not significant by this statistical analysis, it is possible that a relationship exists between these two variables that could be worth further study. Streambank legacy sediments have been shown to be an important contributor to sediment loads for watersheds in the Piedmont region (Jiang et al., 2020). Since milldams are the primary cause of legacy sediment accumulation in the Piedmont region, their presence could be used to better predict sediment loads at a catchment level. While the ideas in this study have implications for predicting sediment and nutrient loads and establishing best management practices to improve water quality, more research must be done to determine the effects of historic milldam density on current water quality at a watershed scale.

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