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THE EFFECTS OF MILL DAMS ON INSTANTANEOUS SUSPENDED SEDIMENT YIELD: BALTIMORE COUNTY, MARYLAND

by

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This is to certify that the thesis prepared by Benjamin J. Allen, entitled The Effects of Mill Dams on Instantaneous Suspended Sediment Yield: Baltimore County, Maryland, has been approved by the thesis committee as satisfactorily completing the thesis requirements for the degree Master of Science.

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ABSTRACT

THE EFFECTS OF MILL DAMS ON INSTANTANEOUS SUSPENDED SEDIMENT YIELD: BALTIMORE COUNTY MARYLAND

Benjamin J. Allen

The construction and demise of historic mill dams has recently been viewed as an important cause of stream channel degradation and increased sediment loads. When intact, mill dams trapped agricultural sediments, which were subsequently released after the dams breached or were removed. In this project, I documented the locations of 164 former mill sites in Baltimore County using historic maps, LiDAR data, and field visits. Additionally, I compared instantaneous suspended sediment yields between a group of previously dammed watersheds and a similar group of undammed watersheds. It was determined that both groups transported similar, relatively high amounts of sediment, which may be attributable to the small range of discharges sampled during this one-year study, or that factors other than the presence of mill sediments, such as upland soil erosion, may be responsible. Future work is needed to investigate this comparison over a longer time period, and to identify sources of sediment.

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Introduction

Sediment has been long recognized as a major stressor to the Chesapeake Bay (Phillips, 2002). Suspended sediments increase the turbidity of water and limit the growth of submerged aquatic vegetation, which acts as a food source, shelter and nursery for many aquatic organisms, and helps improve water quality by producing oxygen, retaining excess nutrients, and slowing down water currents that cause shore line erosion and sediment re-suspension (Hurley, 1991). Excessive sedimentation can lead to the smothering and subsequent mortality of oysters (Heral et al., 1990), which would have otherwise helped improve water quality through filter feeding (Pietros and Rice, 2003).

Sediments carrying nutrients are associated with eutrophication, which causes excessive algal growth and a subsequent depletion of oxygen necessary to sustain aquatic life (Boesch et al., 2001). Sediments can also carry trace metals and organic contaminants; benthic organisms may become exposed to them during sedimentation, and can subsequently pass them onto other organisms through food web interactions (Forstner, 1987). Changes in sediment chemistry and sediment re-suspension can lead to the mobilization of trace metals and organic contaminants, which can in turn make them available for uptake by aquatic organisms in the open water (Forstner, 1987).

Influence of land cover on sediment production

In the mid seventeenth century, prior to European settlement, the Maryland Piedmont region was dominated by oak, hickory, and pine forests (Brush, 2001). Despite extensive Native American agriculture during this time, sedimentation rates into nearby estuaries were less than 1mm per year (Paskernack et al., 2001). With European settlement came widespread land clearing, agricultural development, and soil erosion. Agriculture peaked in the Maryland Piedmont region during the nineteenth and early twentieth century, producing sedimentation rates into nearby estuaries as high as 34.6mm per year (Paskernack et al., 2001). Studies of early agriculture in the eastern piedmont blame high erosion rates on the use of steeply sloping fields, neglect by tenant farmers, and poor land management practices (Earle and Hoffman, 2001). Starting in the 1930's, upland soil erosion and lowland sedimentation declined in the Maryland Piedmont region due to improvements in soil conservation, reforestation from farm abandonment (Brush, 1989), and sediment storage behind large water-supply reservoirs (Paskernack et al., 2001). These long term changes in land use, soil erosion, and sedimentation were similar to that documented in the southern piedmont of Georgia and South Carolina (Trimble, 1974).

Changes in settlement patterns since the mid twentieth century have resulted in increased rates of land conversion from rural to urban landscapes. Wolman (1967) suggested that urbanization affects stream channels by first contributing massive amounts of sediment during construction, causing newly urbanized streams to shrink as the sediment is stored in the channel. Subsequently, the many impervious surfaces of the urban environment prevent the loss of sediment from hill slopes, while increasing storm water runoff. This increase in runoff promotes more frequent flooding, which causes older urban stream channels to enlarge, as channel incision and bank erosion occur (Wolman, 1967). Wolman's model for urban induced stream channel aggradation and degradation was observed over a forty-one year time period by Leopold (1973) and Leopold et al. (2005), confirmed empirically at various sites worldwide (Chin, 2006), and has been elaborated into a model of visual cues for identifying these changes in contemporary streams (Colosimo and Wilcock, 2007).

Conflicting view points on the production, storage, and transport of sediment

Our current understanding of the production, storage, and transport of sediment is shaped by several opposing ideas. Soil loss models predict that more than 60% of the estimated 10t/ha/yr of soil that currently erodes from U.S cropland gets transported to waterways (Piementel, 2006), making it an important source of sediment, which will require an estimated 8.4 billion dollars per year to prevent (Piementel et al., 1995). However, it is argued that soil loss models commonly produce unreliable estimates of the production, movement and storage of sediment, and do not account for in-channel erosion processes, which should be determined using more field based observations (Trimble and Crossin, 2000; Boardman, 2006; Boomer et al., 2008).

Using field mapping techniques and a sediment budget approach, Costa (1975) found that 52% of the sediment eroded from Piedmont agricultural land was stored as colluvium at the base of hill slopes, and 14% as alluvium on floodplains. Starting in the 1930’s, improvements in soil conservation and the decline in agricultural land use led to a decrease in stream sediment loads. This caused streams to cut into and release many of the previously deposited legacy sediments, leading to widespread channel enlargement and accelerated bank erosion (Costa 1975; Jacobson and Coleman, 1986).

More recently, Walter and Merritts (2008) discovered that previous upland soil erosion coincided with the construction of tens of thousands of low-head mill dams, which trapped many of these legacy sediments. When these dams breach or are removed, channel incision and widening occur into the accumulated legacy sediments (Pizzuto, 2002; Doyle et al., 2003), which can lead to accelerated bank erosion rates as high as one meter per year (Walter et al., 2007). Pizzuto and O'Neal (2009) found that accelerated bank erosion rates along a 30 km portion of Virginia's South River were best explained by the channel adjustments that followed the breaching of several mill dams and were not likely due to changes in riparian land use, stream flow, or freeze-thaw intensity. Along a 28 km portion of Little Conestoga Creek in Pennsylvania, Schenk and Hupp (2009) used a sediment budget to report 10,437 Mg/year of bank erosion and 4,802 Mg/year of floodplain deposition, suggesting that more than half of the sediments derived from bank erosion were being transported out of the system.

The nearly ubiquitous presence of mill dams suggests that many modern stream channels in the eastern U.S are either currently incised and actively eroding, or have the potential to do so upon mill dam breaching (Walter and Merritts, 2008). Consequently, between 30 and 100% of the suspended sediments transported out of many eastern U.S waterways could be derived from bank erosion, as exemplified in Walter and Merritts (2008), Mukundan et al. (2010), and Banks et al. (2010).

Although several studies suggest that legacy sediments are an important source of sediment, there is contradictory evidence that suggests otherwise. Using sediment budgets, Trimble (1999) and Allmendinger et al. (2007) argue that legacy sediments contribute little to suspended sediment yield due to their deposition onto downstream floodplains. Allmendinger et al. (2007) predicted that even if legacy sediments were transported out of the system, they would only contribute to 20% of the total suspended sediment yield. Additionally, despite the use of a sediment budget in Schenk and Hupp (2009) to find that more than half of the sediments derived from bank erosion are being transported out of Little Conestoga Creek, Gellis et al. (2009) used sediment fingerprinting to find that 77% of the total suspended sediment load of the same stream came from upland soil erosion.

This issue is further confused by the addition of urbanization. Harbor (1999) indicates that despite the improved regulations of construction activity, it can still be an important source of sediment due to the improper installation and maintenance of erosion prevention and sediment control practices. Furthermore, as streams affected by mill damming urbanize, the added stress of urban runoff combined with the presence of legacy sediments could lead to further channel degradation.

Merritts et al. (2011) state that stream channel degradation is largely decoupled from modern land use change and argue that the breaching of mill dams better explains why channel enlargement and increased sediment loads are widespread amongst forested, agricultural, and urban streams. In the past, upland soil erosion has been linked to high sediment loads, and therefore has been targeted for reduction. Despite efforts to control upland soil erosion, sediment loads in many streams remain high (Gellis et al., 2004), which suggests that in-channel sediment sources, specifically legacy sediments behind former mill dams, are also important targets of management (Merritts et al., 2011).

This thesis will explore the idea that mill dam trapped legacy sediments are an important source of suspended sediment. In chapter two, historic maps, two-foot contoured LiDAR data, and field surveys were used to assess the local prevalence and current status of mill sites in Baltimore County. In chapter three, the effects of mill dams on sediment transport were investigated by comparing instantaneous suspended sediment yields between a group of previously dammed watersheds and a similar group of apparently undammed watersheds.

Chapter Two:

Techniques for Identifying Mill Sites and Their Associated Legacy Sediments: Baltimore County, Maryland

Introduction

The widespread deforestation and agricultural development of the eastern United States (U.S.) by European settlers has led to considerable upland soil erosion (Earle and Hoffman, 2001). These eroded sediments were transported downstream and deposited on floodplains (Jacobson and Coleman, 1986). Today, this material is frequently referred to as legacy sediment (Walter et al., 2007). Starting in the 1930's, streams started to receive less sediment due to improvements in soil conservation, reforestation from farm abandonment (Brush, 1989), and sediment storage behind large water-supply reservoirs (Pasternack et al., 2001). This caused streams to cut into and release many of the previously deposited legacy sediments, which led to widespread channel enlargement (Costa, 1975; Jacobson and Coleman, 1986). This historical sedimentation process, coupled with more recent channel aggradation and degradation caused by urbanization were thought to be the reasons for recent stream channel widening and bank erosion (Wolman, 1967; Leopold, 1973; Costa, 1975; Jacobson and Coleman, 1986; Leopold et al., 2005).

More recently, Walter and Merritts (2008) discovered that many of these legacy sediments accumulated behind tens of thousands of historic low-head mill dams. Once these dams breach or are removed, they release sediment as upstream channel incision and widening occur (Pizzuto, 2002; Doyle et al., 2003), leading to accelerated rates of bank erosion (Walter et al., 2007; Pizzuto and O'Neal, 2009; Schenk and Hupp, 2009; Merritts et al., 2011). Due to the nearly ubiquitous presence of mill dams, it is likely that their construction and demise has caused widespread degradation to many eastern U.S. waterways (Walter and Merritts, 2008).

The purpose of this paper is to improve water quality and stream restoration efforts by providing watershed decision-makers with ways to identify former mill sites and their associated legacy sediments, as these legacy sediments could be an important source of suspended sediment in many modern streams. This was accomplished through a case study of Baltimore County, Maryland in which historic maps, two-foot contoured Light Detection and Ranging data (herein referred to as contoured LiDAR data) and field surveys were used to locate and assess the current condition of mill sites and their associated legacy sediments. This study will attempt to answer the following questions:

1). How effective are historic maps, contoured LiDAR data, and field surveys in identifying former mill sites?

2).What is the current condition of former mill sites and their associated legacy sediments?

The milling industry

Water-powered milling became widespread in the American colonies after the enactment of several mill acts, which encouraged the rapid construction of dams, races, and mill buildings to promote economic development (Staples, 1903). For example, the Maryland Mill Act (effective from 1669-1766) transferred over ten acres of riparian property rights to those who were willing to build a water-powered mill (Hart, 1995). Compensation was given to the previous property owner, who could only resist the taking of their land by building their own water-powered mill on the disputed site (Hart, 1995).

Starting in the late eighteenth century, grain production for overseas trade increased the need for more water-powered mills (Hunter, 2005). By 1840, there were more than 65,000 milling operations in the eastern U.S. (Walter and Merritts, 2008). The highest concentration of mills were in the piedmont physiographic province, which has high stream gradients that are conducive to mill dam construction, and which is close to major cities and their shipping ports (Walter and Merritts, 2008). This was evident in the Baltimore region (Hunter, 2005; Blood, 1937), which had as many as 365 milling operations by 1820 (McGrain, 1968).

Methodology

Mill site documentation

Baltimore County historic maps from 1850, 1857, 1877 and 1898 were examined to document the existence and general location of mill sites. These maps were obtained from the Baltimore County historical society and some were even found on-line. After completing the digitization of historically documented mill sites, their exact locations were identified using contoured LiDAR data, which were collected between April 18 and March 15, 2005 by the Sanborn Map Company and have an average point spacing of 1.4 m for bare-earth returns, a gridded digital elevation model of 1.83 x 1.83-m raster cells, and an average vertical root mean squared error of 5 cm. Using these contoured LiDAR data, the stream valleys near the historically documented mill sites were searched for mill features such as intact dams, remnants of breached dams, mill races, and tail races (Figures 1 and 2).

Field verification:

The possibility of false positive mill sites (i.e. features that were mistakenly identified as mill sites) was assessed by field verifying thirty-eight mill sites identified using the contoured LiDAR data. These field surveys were confined to rural areas outside of the urban rural demarcation line (URDL), where mill features are less likely to be mistaken for features such as roadways or bridge crossings, and so that anthropogenic stream channel alterations would not be confused with previous dam construction. Mill sites were generally chosen for field verification in small watersheds (<11km^2); however, a few sites were chosen for convenience if they were close to a roadway.

The possibility of false negative mill sites (i.e. mill sites missed by the contoured LiDAR data) was assessed by randomly selecting ten watersheds from 123 candidate watersheds with no historically documented mill sites. These watersheds were less than $11 km^2$ in area and met the following requirements: were outside of the URDL, did not have any large ponds or active dams, and their pour point was at least one mile upstream from a mill site, was easily accessible, and was given permission for access by the landowner. Each watershed was searched for evidence of previous milling using the contoured LiDAR data and through field surveys, where the length of the main channel was walked.

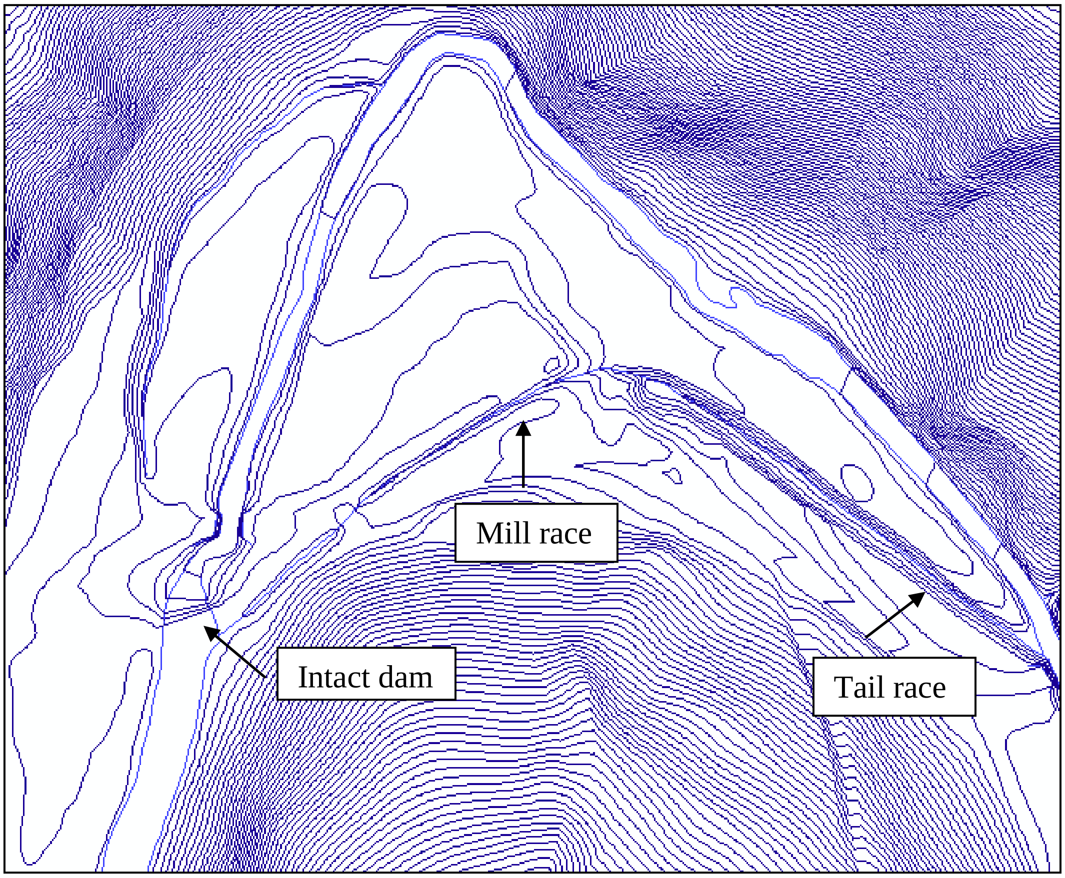

Figure 1: An example of an intact mill dam, mill race, and tail race on Little Falls, as seen in contoured LiDAR data. Note that channel incision has not yet occurred upstream from the dam.

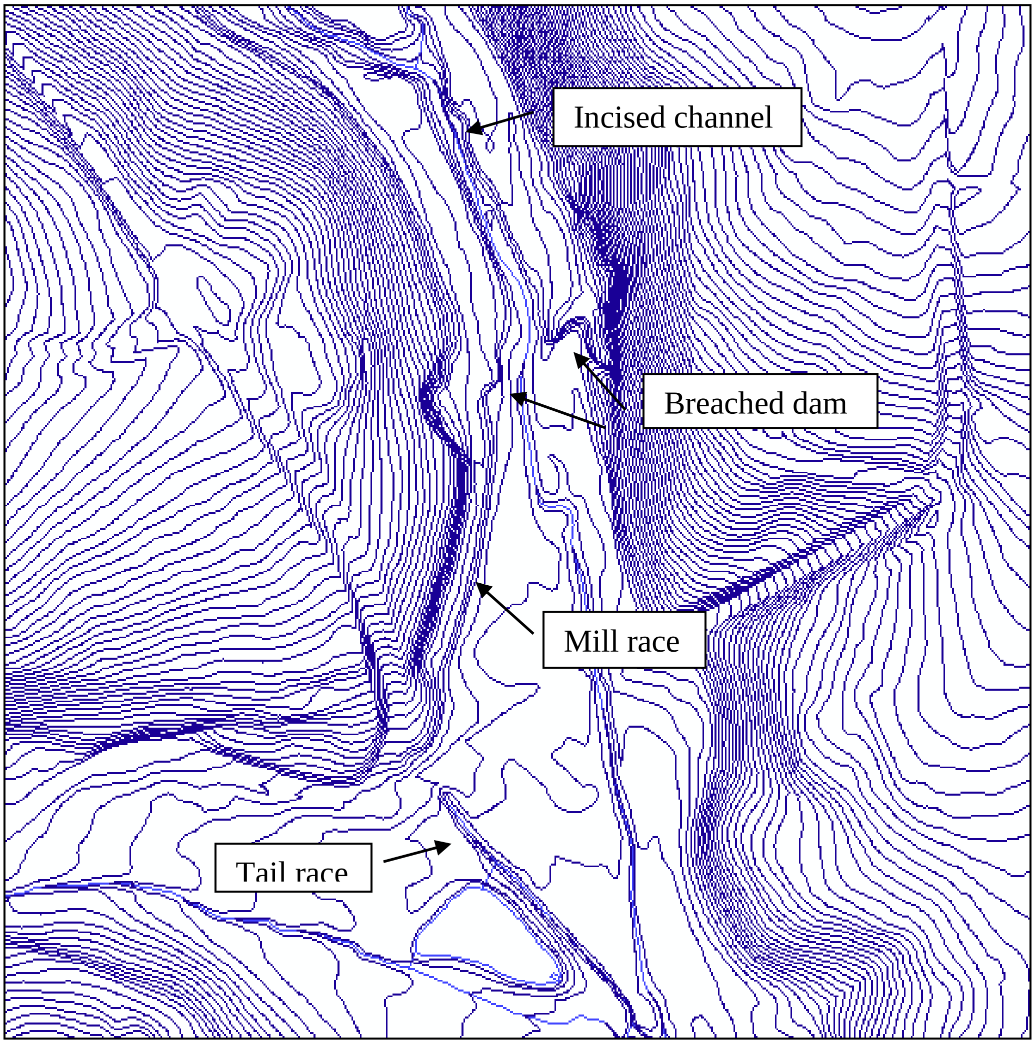

Figure 2: An example of a breached mill dam, mill race, and tail race on Little Falls, as seen in contoured LiDAR data. Note the incised channel upstream from the breached dam.

Results and discussion

Effectiveness of historic maps in identifying mill sites

A total of 164 mill sites were documented in Baltimore County, excluding twenty-five sites currently inundated by modern reservoirs (Figure 3). Of these 164 mill sites, 152 sites (93%) were initially identified using historic maps. The historic maps provided fairly accurate site locations for most mill sites; 107 of the sites (70%) were quickly identified using the contoured LiDAR data, while forty-five of the sites (30%) could not be identified using the contoured LiDAR data. Thus, using historic maps appears to be a quick and effective way to determine the existence and general location of mill sites.

The limitations of using historic maps are they cannot pinpoint the exact location of mill sites and cannot indicate their current condition, and that of the surrounding stream channel. Additionally, the lack of stream detail on some historic maps made it difficult to determine the location of some mill sites. For example, the 1850 and 1857 historic maps showed a mill site in the headwaters of Gwynns Falls, but did not indicate whether it was located on the upper or lower tributary, which was later determined using the contoured LiDAR data. Finally, some mill sites were either too small for historic map documentation or were built after the maps were published. As a result, nine mill sites (5%) were found only using the contoured LiDAR data and three sites (2%) were found solely through field surveys; however, it is likely that more mill sites would have been found had a more extensive field search occurred.

Effectiveness of contoured LiDAR data in identifying mill sites

Of the 164 mill sites documented in Baltimore County, mill features were identified for 116 of the sites (71%) using the contoured LiDAR data. From this, thirty-eight mill sites were selected for field verification; it was possible to confirm the existence of all thirty-eight mill sites (100%) in the field. Many of these mill sites would have been difficult to find in the field, had the contoured LiDAR data not been used first, because they have been abandoned for decades or even centuries, and have since been covered in thick vegetation. This study suggests that contoured LiDAR data are an effective tool for identifying mill sites in rural areas before they are visited and assessed in the field. Future studies should also concentrate on field verifying mill sites in urban and suburban areas to further assess the usefulness of contoured LiDAR data as a tool for identifying mill sites.

During the search for false negative mill sites in watersheds with no historically documented mill sites, the contoured LiDAR data showed that a mill site was present in three of the ten watersheds. These three mill sites were later field verified as a part of the false positive mill site assessment. No new mill sites were found in the field for the remaining seven watersheds. However, three false negative mill sites were found elsewhere, while searching for other mill sites in the field.

Of the 164 mill sites documented in Baltimore County, mill features could not be identified for forty-eight sites (29%) using the contoured LiDAR data. This was most likely due to alterations of the ground surface by agriculture, road building, and urban development. Furthermore, it was apparent that mill features at some sites can only be found in the field. For example, at some mill sites, contoured LiDAR data could only identify remnants of the dam, but features such as the mill race were easily recognized in the field. James et al. (2007) found that abrupt, small changes in terrain are sometimes not detectable in LiDAR data because the average spacing of bare-earth point returns are sometimes not close enough to get an accurate representation of a narrow section of terrain, or that the angle to which the bare-earth point returns were collected from was insufficient to capture the profile of the feature. Additionally, when filtering initial point return data, abrupt changes in terrain may be mistaken for features other than the ground surface, and may be purposefully removed from the dataset (James et al., 2007).

Effectiveness of field surveys in identifying mill sites

Using field surveys, an additional three mill sites were found that would have otherwise been missed, had only the historical maps and contoured LiDAR data been used. This number would have been higher had a more extensive search of mill sites occurred. However, searching for undocumented mill sites can be an arduous and time consuming task because they are found without any prior knowledge of their existence.

Once mill sites are identified using historic maps and contoured LiDAR data, they can be more quickly and effectively identified in the field. In doing so, additional mill features were found at some mill sites, such as the mill race, which was sometimes not identified using the contoured LiDAR data.

Current condition of mill sites and their associated legacy sediments

Using the contoured LiDAR data and field surveys helped to determine the current condition of 119 mill sites. A total of fifty-seven mill sites (48%) had evidence of a breached dam remaining and forty-four sites (37%) had evidence of only the mill race remaining, with no trace of the breached dam. Thus, at least 101 mill sites had dams that are now breached. Pinpointing the exact location of mill features, especially the breached dam, is important because bank erosion is often most severe directly upstream from the breached dam, where legacy sediment accumulation is greatest (Merritts et al., 2011).

Another advantage of using the contoured LiDAR data and field surveys is that an assessment of potential stream channel degradation can be made. Of the 101 breached mill sites, 96 sites (95%) showed signs of channel incision (i.e. $\geq$ 1.2 m in contoured LiDAR data) either upstream from the breached dam or within the surrounding area of where the dam likely was located (i.e. the sites with only a mill race remaining). Field surveys were able to further assess the potential for stream channel degradation; at thirty-two of thirty-six breached mill sites, actively eroding stream banks were observed upstream from the mill dam (Figures 4 and 5).

A total of eighteen mill sites (15%) had dams that were intact; at least two of these dams have been removed since 2005, when the LiDAR data were collected. Approximately 75,000 large intact dams are included in the National Inventory of Dams; however, millions of smaller low-head mill dams are excluded (Smith et al., 2002), which can be effectively located, in individual watersheds of interest, using the techniques described in this paper.

Intact dams represent a potential water quality hazard because sediment transport is most significant when dams first breach (Merritts et al., 2011). Thus, the proper management of intact dams is important to help minimize sediment transport and stream channel degradation once they breach, or are removed (Downward and Skinner, 2005). These management strategies may include removing the dam in a controlled manner, maintaining the dam’s structure so it does not breach, or to allow the dam to breach naturally; the latter of which is only effective if sedimentation behind the dam was not significant or if previous dredging was routinely performed (Downward and Skinner, 2005).

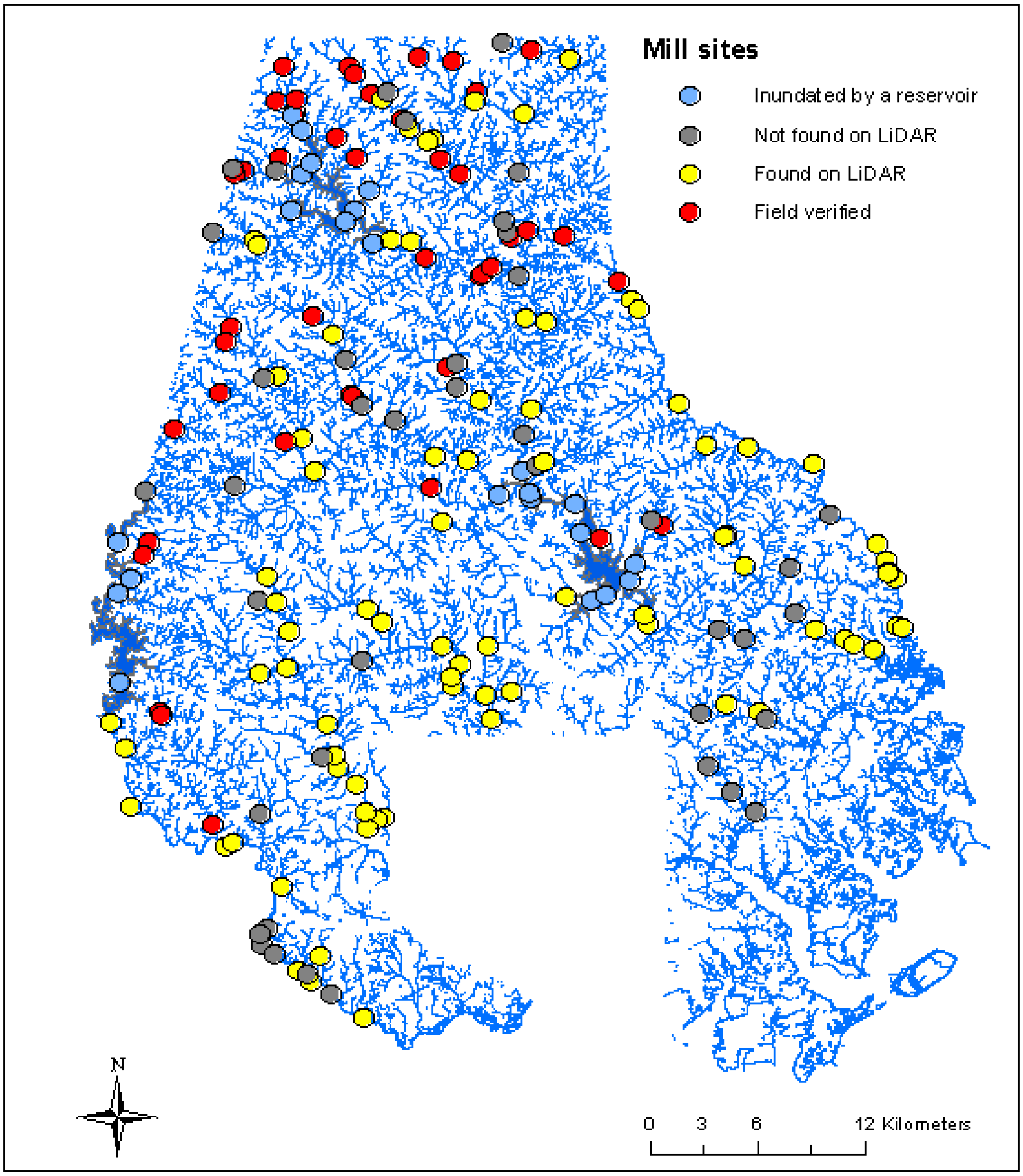

Figure 3: A map of the 164 mill sites documented in Baltimore County. The twenty-five mill sites currently inundated by modern reservoirs (blue circles) were excluded from further analysis.

Figure 4: An actively eroding stream bank directly upstream from a breached mill dam on Gunpowder Falls.

Figure 5: An actively eroding stream bank directly upstream from a breached mill dam on Little Piney Run.

Conclusions

This paper has discussed ways to identify mill sites and their associated legacy sediments. Because so many mill sites may be contributing sediment to downstream waterways, stream restoration and water quality practitioners should make some attempt to quantify the impact of them on watersheds of interest.

Here, mill sites were identified using historic maps, contoured LiDAR data, and field surveys. The historic maps were a simple, fast, and effective way to assess the local prevalence of mill sites, which are readily available for use at local historical societies, and in some cases can be found on-line. The contoured LiDAR data were effective at pinpointing the exact location of mill sites by identifying mill features, which was confirmed in rural areas through field surveys. Additional field surveys should be conducted to determine how well the contoured LiDAR data identify mill features in urban and suburban areas, where mill features are more likely to get mistaken for features such as roadways or bridge crossings. The contoured LiDAR data were capable of determining if a dam was intact or breached, and if upstream channel incision was evident, which can be important for future management strategies, such as planning for a dam removal, or stream restoration project. Finally, using field surveys, additional mill sites were found that were not documented on the historic maps, or that could not be identified using the contoured LiDAR data. However, because of the great difficulty in walking the length of entire streams, field surveys were found to be most effective at verifying work completed using the historic maps and contoured LiDAR data.

Chapter Three:

The Effects of Mill Dams on Instantaneous Suspended Sediment Yield: Baltimore County, Maryland

Introduction

Suspended sediments can come from a variety of sources within river systems. Recent attention has been brought to stream bank erosion as an important source of sediment by Walter and Merritts (2008), who found that the construction and demise of tens of thousands of historic low-head mill dams has led to widespread channel degradation in many eastern United States (U.S.) waterways. When intact, mill dams trap sediments eroded from the uplands, which are commonly referred to as legacy sediments (Walter et al., 2007). These legacy sediments are released when the dams breach or are removed, as channel incision and widening occur into the accumulated sediments (Doyle et al., 2003; Pizzuto, 2002). The subsequent channel enlargement caused by mill dam breaching has led to accelerated rates of bank erosion (Walter et al., 2007; Pizzuto and O'Neal, 2009; Schenk and Hupp, 2009; Merritts et al., 2011), which could make up between 30 and 100% of suspended sediment loads in many eastern U.S. waterways, as exemplified in Walter and Merritts (2008), Mukundan et al. (2010), and Banks et al. (2010). Despite this widespread stream channel degradation caused by mill dam breaching, soil erosion from agricultural land can still be an important source of sediment, as predicted by soil loss models (Piementel et al., 1995; Piementel, 2006), and shown using more empirical evidence (Gellis et al., 2009).

Previous studies have focused intensively on stream reaches or single watersheds impacted by mill dams to investigate their impacts on sediment production and transport (Walter and Merritts, 2008; Schenk and Hupp, 2009; Pizzuto and O'Neal, 2009; Gellis et al., 2009; Banks et al., 2010; Merritts et al., 2011). However, it still remains unclear how sediment transport in previously dammed watersheds, where watersheds have at least one breached mill dam, compares to that in similar apparently undammed watersheds, where watersheds do not show evidence of previous damming.

The purpose of this paper is to investigate the relative impact that mill dams have on sediment transport in small watersheds (<11 km^2) by comparing instantaneous suspended sediment yield, over a variety of storm flow magnitudes, between a group of previously dammed watersheds and a similar group of apparently undammed watersheds in Baltimore County, Maryland. Additionally, it will be determined if the suspended sediments collected from the group of previously dammed watersheds differ in trace element composition from those collected from the group of apparently undammed watersheds. Sediments formerly subject to inundation by mill dams may differ in chemical composition from background sediments, due to their different weathering history within a redox environment. Collectively, these instantaneous suspended sediment yield and trace element composition data will attempt to answer the question: do previously dammed watersheds have higher instantaneous suspended sediment yields, and do their suspended sediments differ in trace element composition from that of similar apparently undammed watersheds?

Methodology

Site Selection

A total of ten watersheds were randomly selected from 123 candidate watersheds with no historically documented mill sites. These watersheds were less than 11km^2 in area and were outside of the urban rural demarcation line (URDL). The URDL is a political unit used for planning purposes in Maryland and consists of developed areas within the county that are contiguous with Baltimore City.

The ten watersheds did not have any large ponds or active dams; their pour point was at least one mile upstream from a mill site; were easily accessible; and were given permission for access by the landowner. Contoured LiDAR data were used to search for mill features in these watersheds, such as intact dams, remnants of breached dams, mill races, and tail races. Three of the ten watersheds showed evidence of mill features; however, one had a small dam that appeared not to be intact very long, as it had little to no impact on upstream channel morphology. For the purpose of this study, this watershed was considered to be apparently undammed. Upon field verification, there were no mill sites in the remaining seven watersheds. These eight apparently undammed watersheds were grouped together and a total of eight watersheds with similar site characteristics and at least one breached mill dam were selected and grouped together for comparison. A map of the previously dammed and apparently undammed watersheds and their corresponding site characteristics are found in Figure 6 and Table 1, respectively.

The stream banks in the previously dammed watersheds were steep and actively eroding, especially directly upstream from the dam, because this is typically where legacy sediment accumulation is greatest (Merritts et al., 2011). Actively eroding stream banks were also observed in the apparently undammed watersheds. These watersheds were at least one mile upstream from a mill site, and therefore were expected not to be influenced by any effects of a downstream mill dam. The actively eroding stream banks in these apparently undammed watersheds were likely the result of local overbank legacy sediment deposits; however, the backwater effects of a downstream dam could have extended further upstream than anticipated, which could have been the cause of this observed channel degradation. In either case, the stream banks were less steep in apparently undammed watersheds, compared with that observed in the previously dammed watersheds.

Figure 6: A map of the previously dammed and apparently undammed watersheds used in this study.

Table 1: A list of the group of eight previously dammed watersheds and the group of eight similar apparently undammed watersheds, and their corresponding site characteristics. Note that "d" corresponds with the group of previously dammed watersheds "u" corresponds with the group of apparently undammed watersheds. National Land Cover Data (2001) were used to determine land cover percentages.

Site name		**Drainage area (km^2)**		**% Forest**		**% Agriculture**		**% Developed**	
d	u	d	u	d	u	d	u	d	u
Panther Branch near Big Falls Road	Mingo Branch near Bunker Hill Road	3.03	2.00	68.50	73.79	26.64	23.95	4.85	2.26
Keysers Run at Ivy Mill Road	Trib. of Mardella Branch at Offutt Road	3.32	4.78	33.51	38.88	60.96	58.52	5.34	2.49
Trib. of 1st Mine Branch at Hunters Mill Road	Buffalo Creek at Cold Bottom Road	3.63	3.82	43.81	40.47	56.01	59.32	0.07	0.00
Little Piney Run at Dark Hallow Road	Trib. of Blackrock Run at Benson Mill Road	3.64	3.75	24.23	21.91	74.78	77.56	0.32	0.38
Falls Run near Powells Run Road	Locust Run at Wards Chapel Road	5.27	5.04	49.42	76.13	46.57	23.72	3.86	0.14
Norris Run at Ivy Mill Road	Cooks Branch at Ivy Mil Road	6.58	6.06	47.67	74.38	45.75	25.09	6.54	0.49
Oregon Branch at Beaver Dam Road	Indian Run at Blackrock Road	6.18	6.86	51.90	32.26	47.53	67.51	0.01	0.00
Little Falls at Keeney Mill Road	McGill Run at Osborn Road	10.35	9.44	24.80	35.02	74.92	64.75	0.03	0.09

Field methods

From September 2010 to September 2011, stream discharge was measured and suspended sediment samples were collected during base, intermediate, and high flow events. Base flow data were collected seasonally, approximately every three months.

Stream discharge was measured using the velocity-area method described in Rantz et al. (1982). At each watershed pour point, the channel cross section of flow was divided into ten subsections of equal width using a measuring tape. At each subsection, the location along the measuring tape and stream depth were recorded, and a velocity reading was obtained at six-tenths depth using an Acoustic Doppler Velocimeter. Stream discharge (m^3/s) was determined by the sum of velocity multiplied by area at each subsection.

Level loggers were deployed at the four largest watersheds to collect continuous stage height data. Manual stage height measurements were made at eight site visits, which were compared against the level logger stage height data to develop a correction factor. When storm flow was too dangerous for wading, these stage height data were used to estimate stream discharge using a stage height-stream discharge empirical model. When storm flow was too dangerous for wading at the twelve watersheds without level loggers, the edge of the water at the time of the site visit was marked and later surveyed into the channel cross section to determine stage height, which was used to estimate stream discharge using a stage height-stream discharge empirical model.

Immediately after stream discharge was measured, a suspended sediment sample was collected using the equal width increment method described in Edwards and Glysson

(1999). At ten subsections of equal width in the channel cross section of flow, a one liter bottle was used to collect approximately 1000mL of stream water at the surface of the water. These samples were not depth integrated and therefore were biased towards smaller particle sizes that get transported at the surface of the water. This method was consistently used throughout the data collection period. However, when storm flow was too dangerous for wading, a 1000mL grab sample of stream water was obtained from the side of the stream channel. Duplicate suspended sediment samples were collected at the tenth or last site visit (whichever came first) of nine sampling events to ensure consistent results.

Suspended sediment analysis

The suspended sediment samples were filtered using the methods described in Eaton et al. (1995). Each sample was filtered through pre-weighed 47mm glass fiber filter paper, using a vacuum pump. Once filtered, the filter paper with sediment was dried for one hour at 103-105^{o} C. Once cooled to room temperature, the initial weight of the filter paper was subtracted from the final weight of the filter paper with sediment. The total mass of sediment captured was multiplied by 1000 and divided by the sample volume used in mL to determine the suspended sediment concentration in mg/L (same as g/m^3). The suspended sediment concentration (g/m^3) was then multiplied by stream discharge (m^3/s) and divided by watershed area (km^2) to determine instantaneous suspended sediment yield (g/s/km^2). Instantaneous suspended sediment yield was plotted against stream discharge; these data were compared between the group of previously dammed watersheds and the group of apparently undammed watersheds.

The trace element composition of the suspended sediment samples was determined using an Inductively Coupled Plasma-Mass Spectrometer. The filter paper with sediment and 5mL of 7N HNO_3 were added to an acid cleaned Teflon vial, which was capped and placed on a hot plate at 120^oC overnight. The solution was then cooled to room temperature, decanted, and then diluted to 50mL with an internal standards solution (indium and bismuth). Once this solution sat overnight to allow any free floating sediment particles to settle out, 10mL were transferred to a 15mL centrifuge tube. Sets of twenty-five samples were run with a multi-element five point calibration curve, sample blank, sample duplicate and at least one digestion of National Institute of Standards and Technology Soil standard reference material (2709) to monitor for external reproducibility. The trace elements analyzed were: Vanadium (V), Chromium (Cr), Manganese (Mn), Nickel (Ni), Copper (Cu), Arsenic (As), Selenium (Se), Rubidium (Rb), Strontium (Sr), Cesium (Cs), Barium (Ba), Lead (Pb), Uranium (U). Zinc (Zn) and Cadmium (Cd) were also analyzed but were eliminated from further analysis because their concentrations appeared to be unreliable, due to contamination from the filter paper.

Trace element concentration was reported as an elemental enrichment ratio relative to the average concentration (ppm) in the upper continental crust, which were obtained from Taylor and McLennan (1985). The elemental enrichment ratio data were plotted against suspended sediment concentration for each suspended sediment sample collected; these data were compared between the group of previously dammed watersheds and the group of apparently undammed watersheds.

Statistical analysis

Different linear mixed effects Analysis of Covariate (ANCOVA) models were set up to determine which set of independent variables within the group of previously dammed watersheds and the group of apparently undammed watersheds have the most influence on instantaneous suspended sediment yield, such as the presence of mill dams, or stream discharge. The watersheds were not independent of instantaneous suspended sediment yield and were added to each model as a separate random nested effects variable.

A total of three models were considered in this analysis. Stream discharge was used in all three models because it is an important mechanism for sediment transport. The three models tested the following effects on instantaneous suspended sediment yield: 1) stream discharge, the presence of mill dams, and the interaction between them; 2) stream discharge and the presence of mill dams; and 3) stream discharge.

Results

Instantaneous suspended sediment yield data

During the one year of data collection, 268 flow events were sampled, ranging from base flow to near bank-full flow. The stream discharges ranged from 0.004 m^3/s to 3.49 m^3/s, with twenty-eight higher than 1 m^3/s, and six higher than 2 m^3/s. The suspended sediment concentrations ranged from 0.105 mg/L to 5154.352 mg/L, with twenty-two higher than 1000 mg/L, and twelve higher than 2000 mg/L. Finally, the instantaneous suspended sediment yields ranged from 0.0003 $g/s/km^2$ to 1905.812 $g/s/km^2$, with eleven higher than 500 $g/s/km^2$, and six higher than 1000 $g/s/km^2$.

The suspended sediment concentrations reported in this study were similar to that in Gellis et al. (2004), which found that Chesapeake Bay tributaries were transporting "anomalously high" amounts of sediment. Figure 7 compares the measured suspended sediment concentrations in this study against those at Killpeck Creek in Huntersville, Maryland (USGS gauging station 01594710), an 8.44 km^2 watershed that is typical of the smaller watersheds included in Gellis et al. (2004). In that study, watersheds under 9 km^2 produced up to 10,000 mg/L of suspended sediment for a storm discharge of 1 m^3/s, while the watersheds in this study produced up to 5,000 mg/L of suspended sediment for a similar sized storm. Thus, the amount of sediment being transported out of both watershed groups appears to be relatively high, for the in-channel flow conditions sampled.

A total of nine suspended sediment sample duplicates were collected, which are presented in Table 2. The average error of the base flow and storm flow suspended sediment sample duplicates together (n=9) was 14.93%. When separating the base flow and storm flow suspended sediment sample duplicates, the average error of the base flow duplicates (n= 4) was 29%, and that for the storm flow duplicates (n= 5) was 3.86%.

The relationship between stream discharge and instantaneous suspended sediment yield for the group of previously dammed watersheds and the group of apparently undammed watersheds is presented in Figure 8. There was variability in the relationship between stream discharge and instantaneous suspended sediment yield in which the regression coefficients for the group of previously dammed watersheds and the group of apparently undammed watersheds were 0.53 and 0.71, respectively.

Three linear mixed effects ANCOVA models were considered to explain the variation in instantaneous suspended sediment yield between the group of previously dammed watersheds and the group of apparently undammed watersheds (Table 3). The model including stream discharge, the presence of mill dams, and the interaction between them had the lowest AIC_c value (3383.32), suggesting that it has the best goodness of fit relative to the variability in instantaneous suspended sediment yield between the two watershed groups, and has the highest w_i (0.9961), suggesting that it is most consistent with this data variability. This model explained 64% of the variation in instantaneous suspended sediment yield between the two watershed groups and predicts that for every 1 m^3/s increase in stream discharge, the group of apparently undammed watersheds transports 65.11 $g/s/km^2$ more suspended sediment than the group of previously dammed watersheds. Thus, in a conservative sense, there is no difference in instantaneous suspended sediment yield between the group of previously dammed watersheds and the group of apparently undammed watersheds, during the in-channel flow conditions sampled (n= 268).

Trace element composition data

Overall, there was a consistent pattern in the trace element composition of the suspended sediments collected from the group of previously dammed watersheds and the group of apparently undammed watersheds. As the suspended sediment concentration increased, the elemental enrichment ratio relative to the upper continental crust decreased to a value near 1.0 (Figure 9a-m).

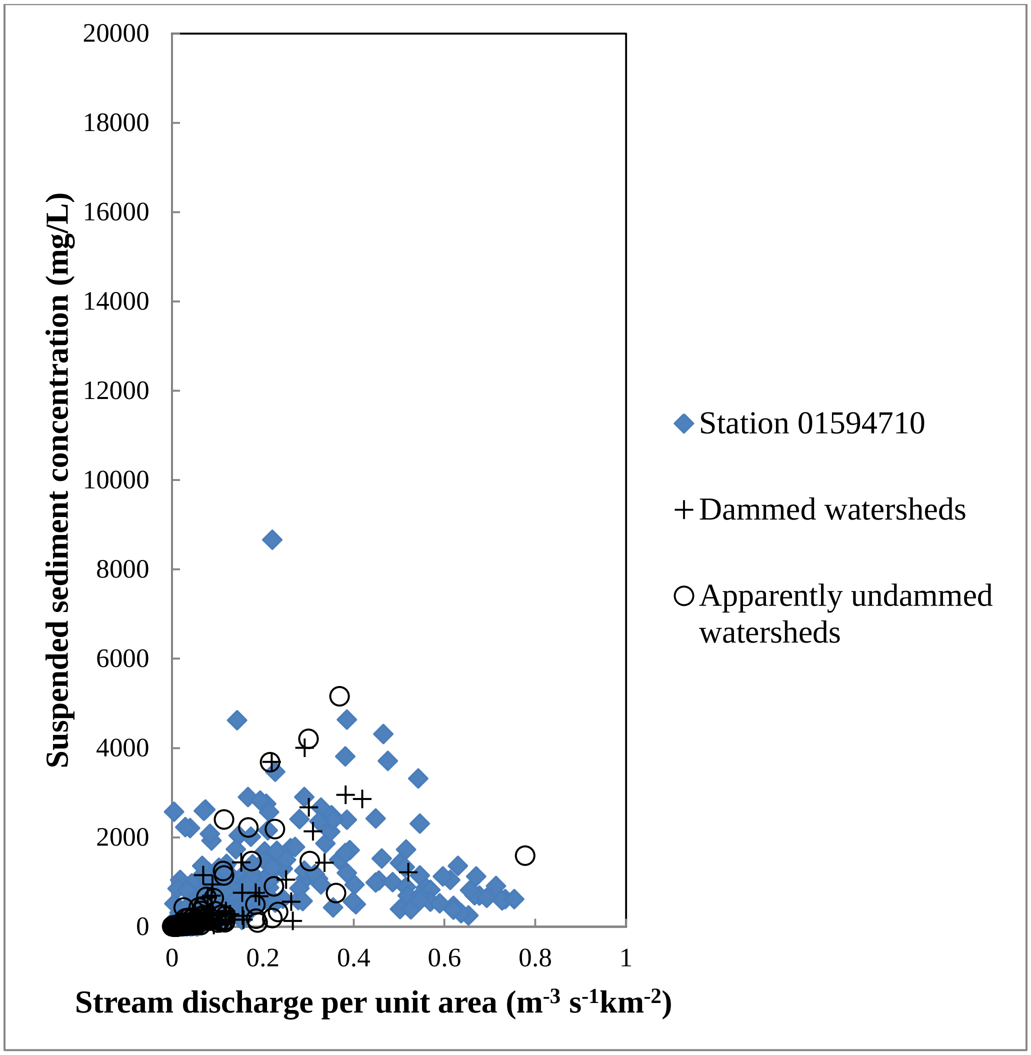

Figure 7: Comparison between the suspended sediment concentrations reported in the present study and that from USGS gaging station 01594710 (8.44 km^2), a similar sized watershed that drains to the Chesapeake Bay (Gellis et al., 2004). The suspended sediment concentrations are plotted against stream discharge, normalized to drainage area.

Table 2: The nine suspended sediment sample duplicates and their associated error.

Site	**Flow type**	**Sample 1 suspended sediment concentration, mg/L**	**Sample 2 suspended sediment concentration, mg/L**	**Absolute difference in concentration between sample 1 and 2**	**% error**
Panther Branch	Base	5.61	11.50	5.89	51.23
Falls Run	Base	0.57	0.71	0.15	20.39
Cooks Branch	Base	0.70	1.06	0.36	33.84
McGill Run	Base	3.00	2.68	0.32	10.52
Trib. of 1st Mine Branch	Storm	937.35	946.24	8.89	0.94
Trib. of 1st Mine Branch	Storm	263.43	249.57	13.86	5.26
Norris Run	Storm	17.14	16.41	0.73	4.26
Norris Run	Storm	81.94	85.40	3.46	4.05
Keysers Run	Storm	659.06	633.47	25.59	3.88
Average % error for all samples					14.93
Average % error for base flow samples only					29.00
Average % error for storm flow samples only					3.68

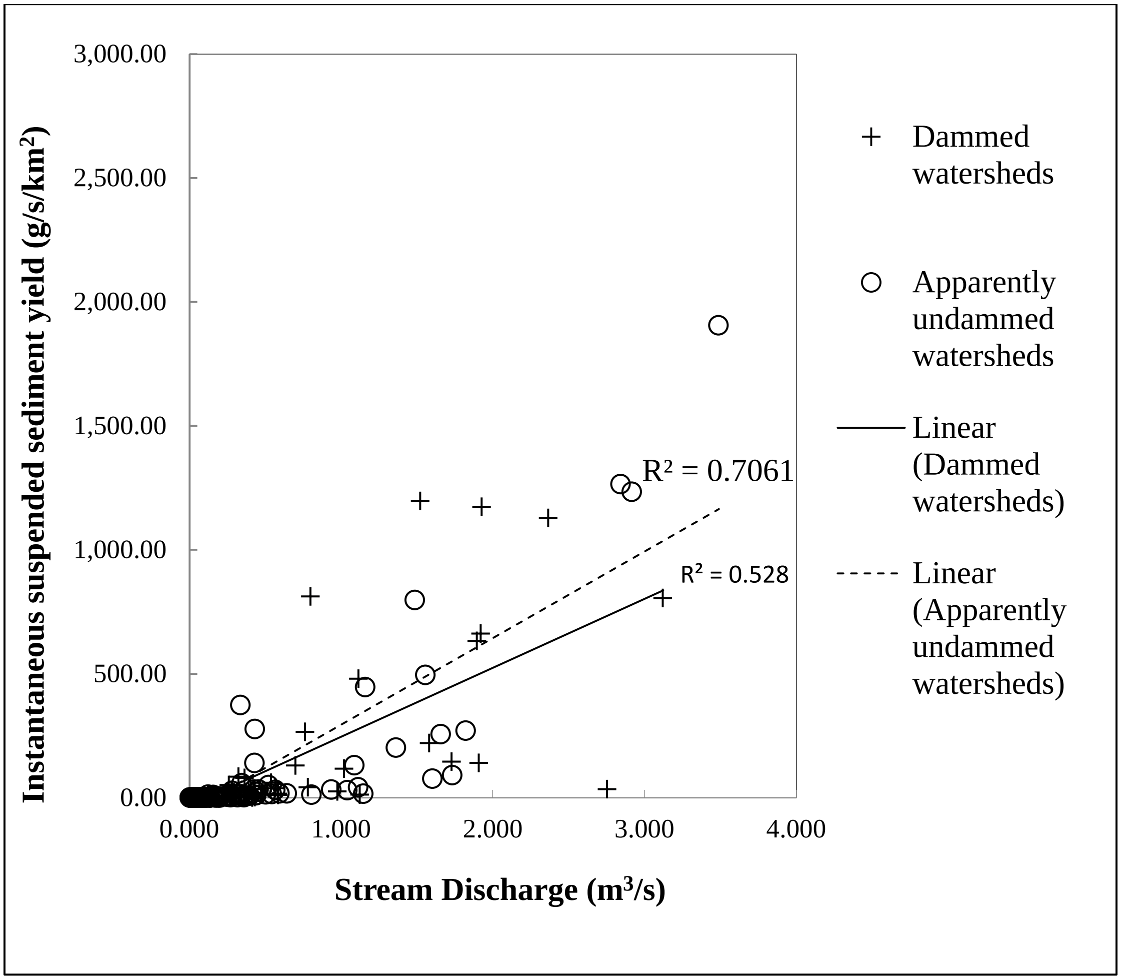

Figure 8: The relationship between stream discharge and instantaneous suspended sediment yield for the group of previously dammed watersheds and the group of apparently undammed watersheds.

Table 3: The results of the three linear mixed effects ANCOVA models used to explain the variation in instantaneous suspended sediment yield between the group of previously dammed watersheds and the group of apparently undammed watersheds. Note that k refers to the number of independent variables used in each model; AIC_c refers to the Akaike Information Criterion corrected for small sample size, Delta AIC_c refers to the difference between AIC_c and the smallest AIC_c; and w_i refers to the relative consistency of each model to the data variation.

Model	**k**	**AIC_c**	**Delta AIC_c**	**w_i**
Presence of mill dams, stream discharge, and the interaction between them	4	3383.3191	0	0.9961
Presence of mill dams and stream discharge	3	3394.4999	11.1808	0.0037
Stream discharge	2	3400.6583	17.3392	0.0002

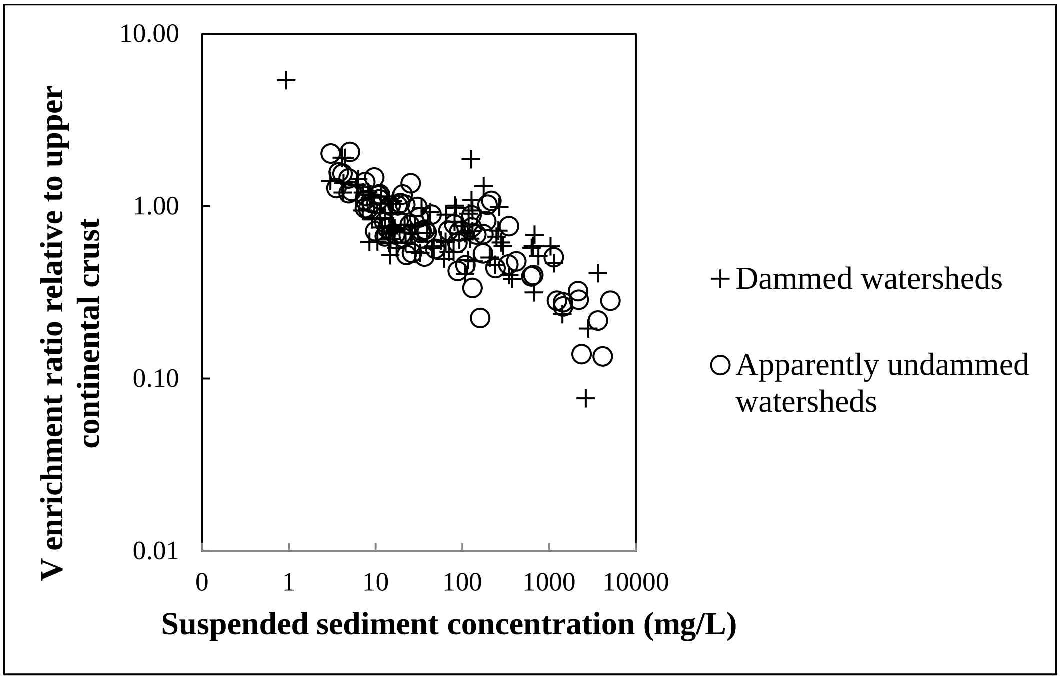

Figure 9(a): Represents the trace element V.

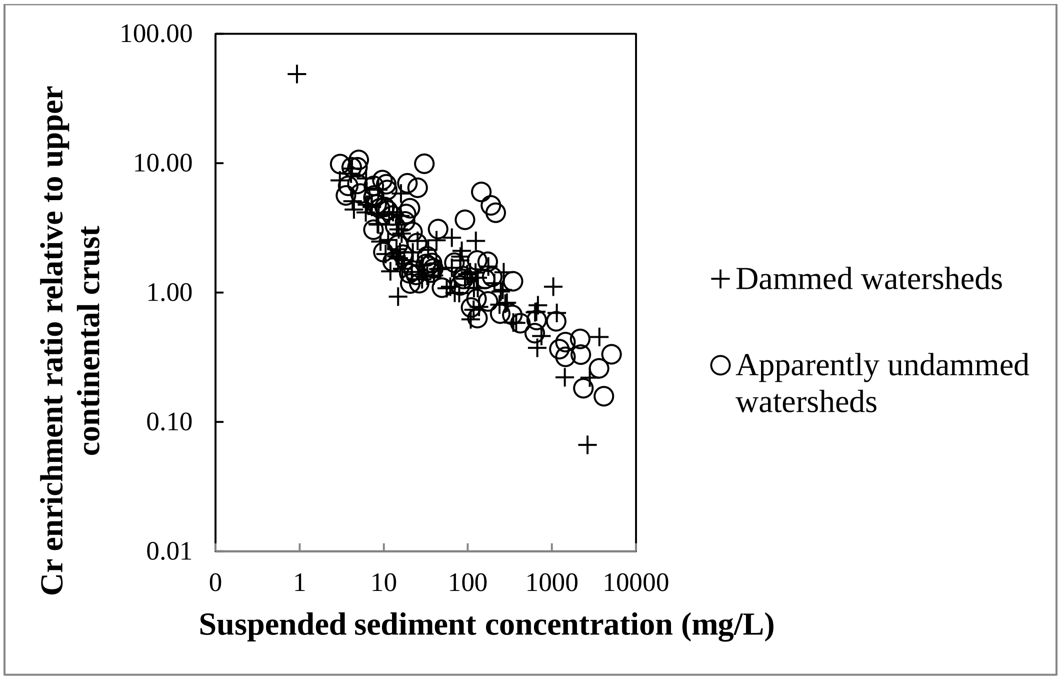

Figure 9(b): Represents the trace element Cr.

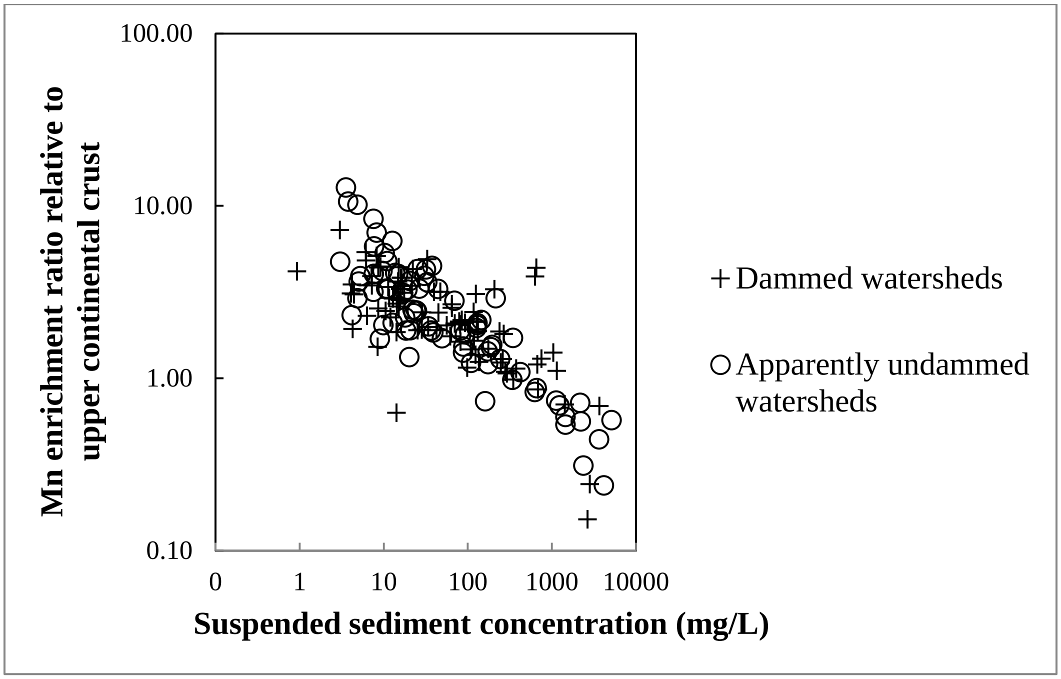

Figure 9(c): Represents the trace element Mn.

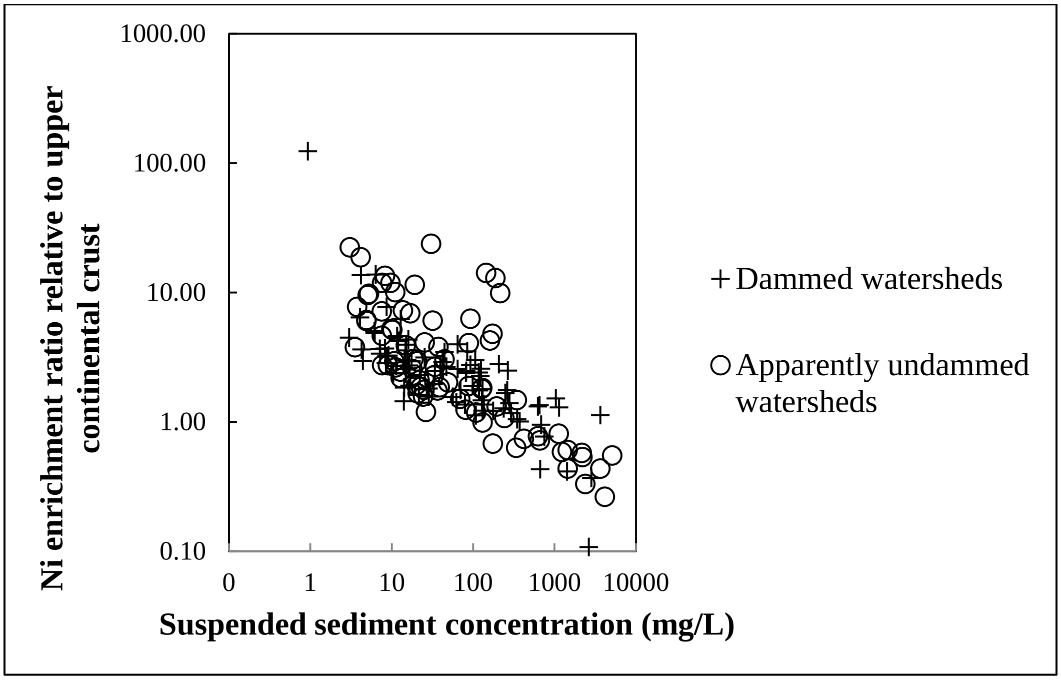

Figure 9(d): Represents the trace element Ni.

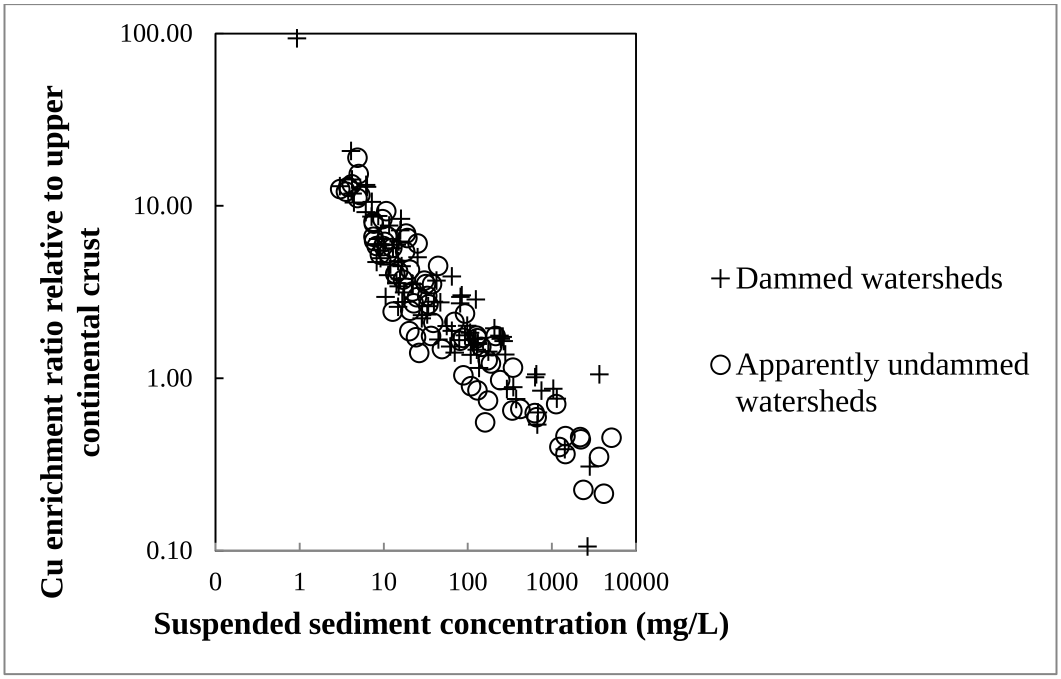

Figure 9(e): Represents the trace element Cu.

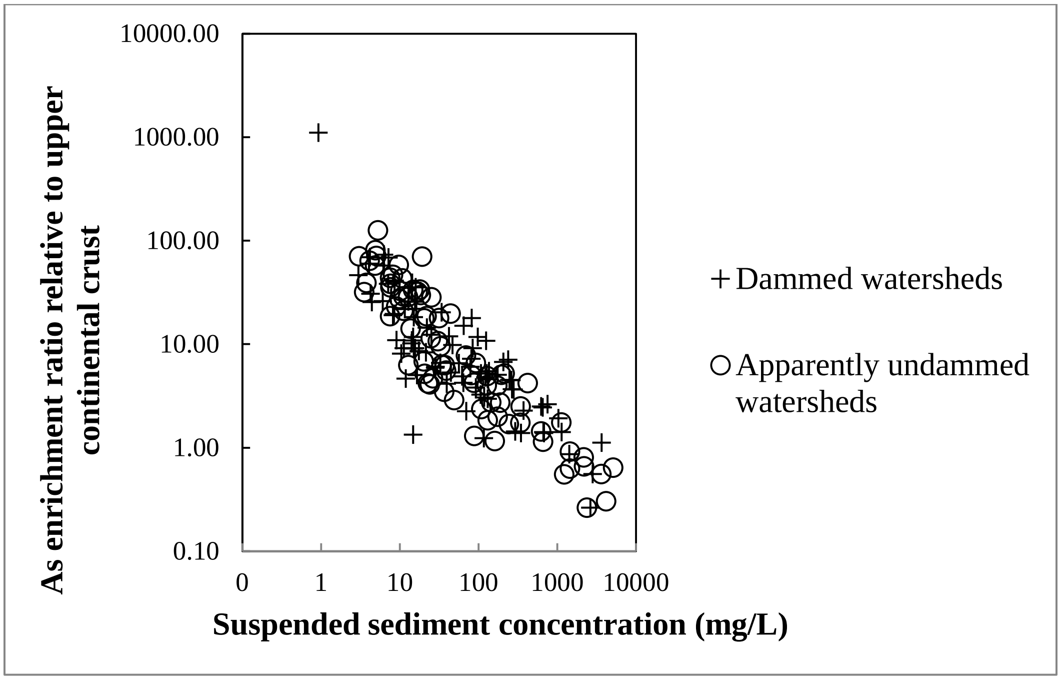

Figure 9(f): Represents the trace element As.

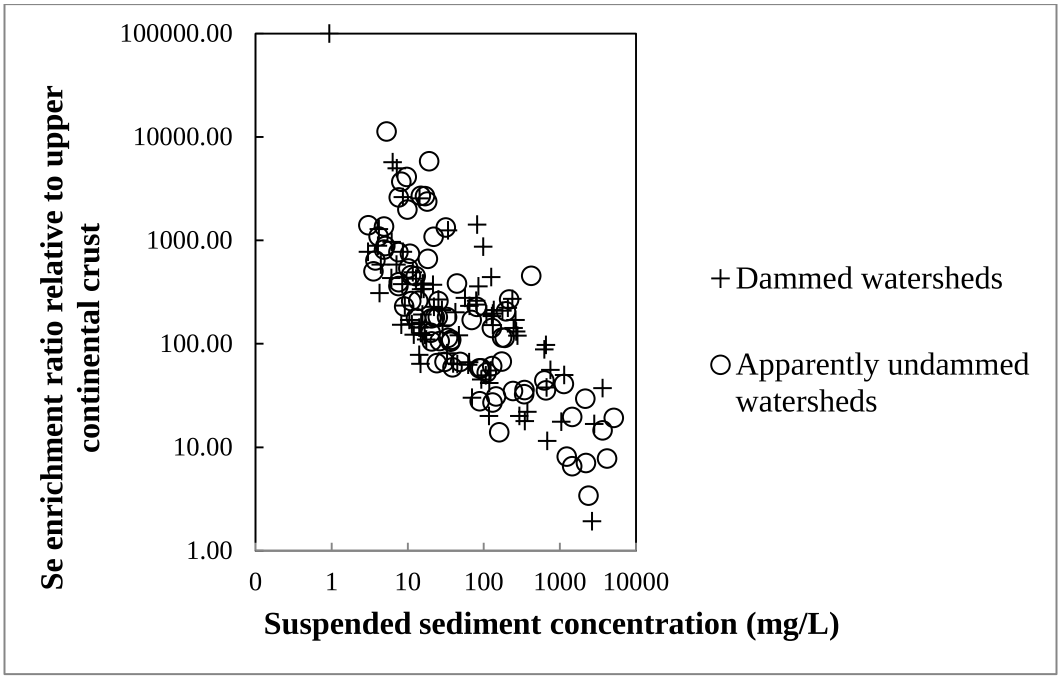

Figure 9(g): Represents the trace element Se.

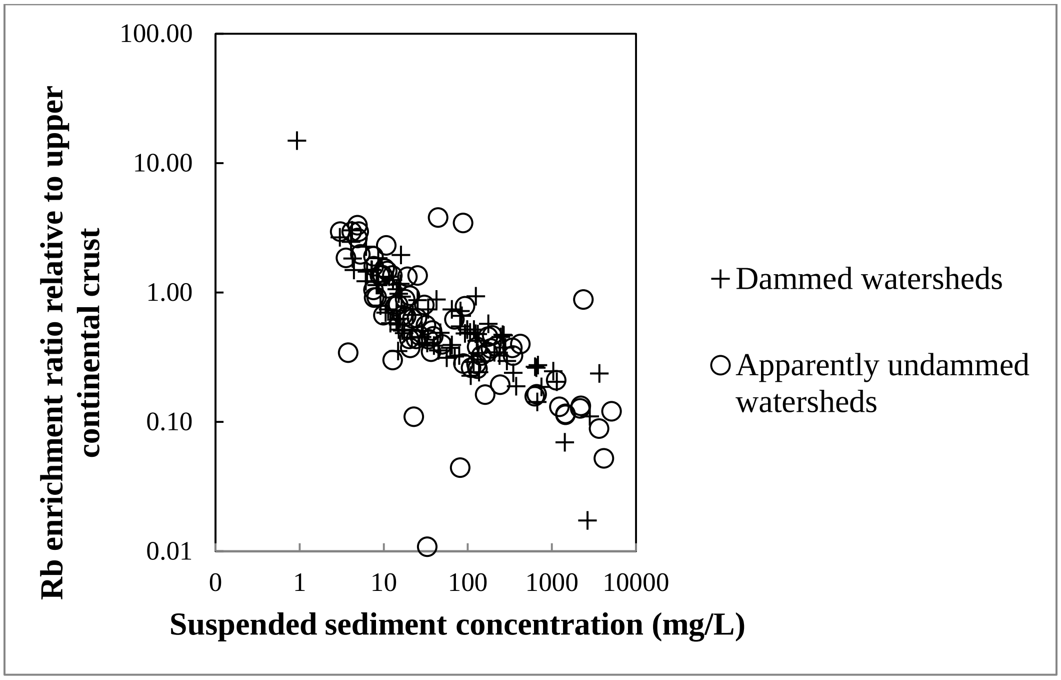

Figure 9(h): Represents the trace element Rb.

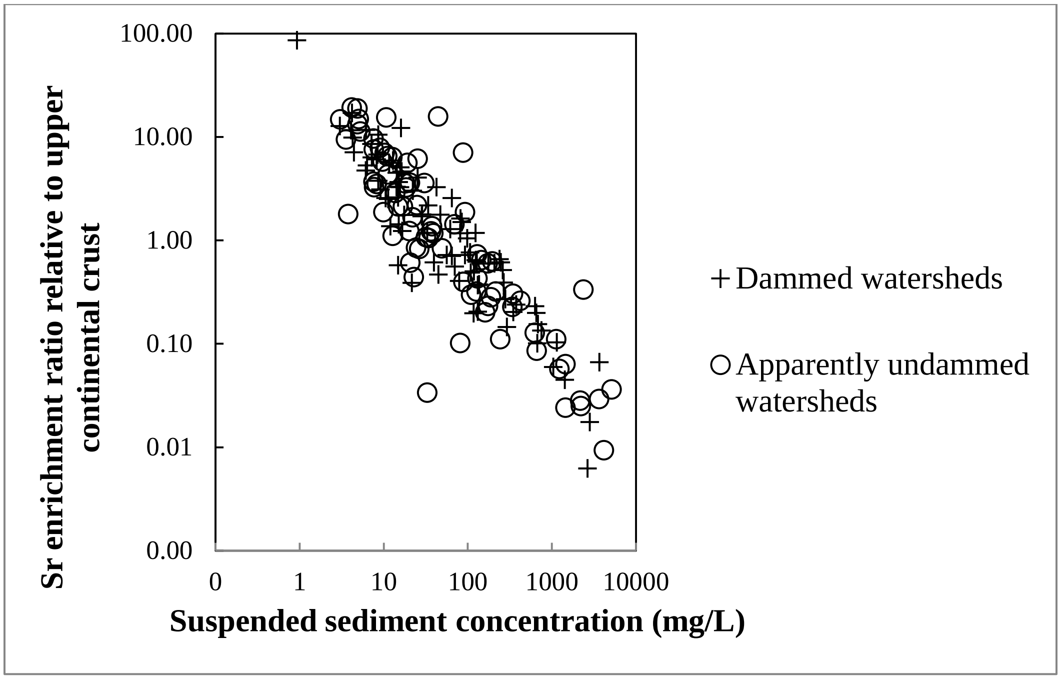

Figure 9(i): Represents the trace element Sr.

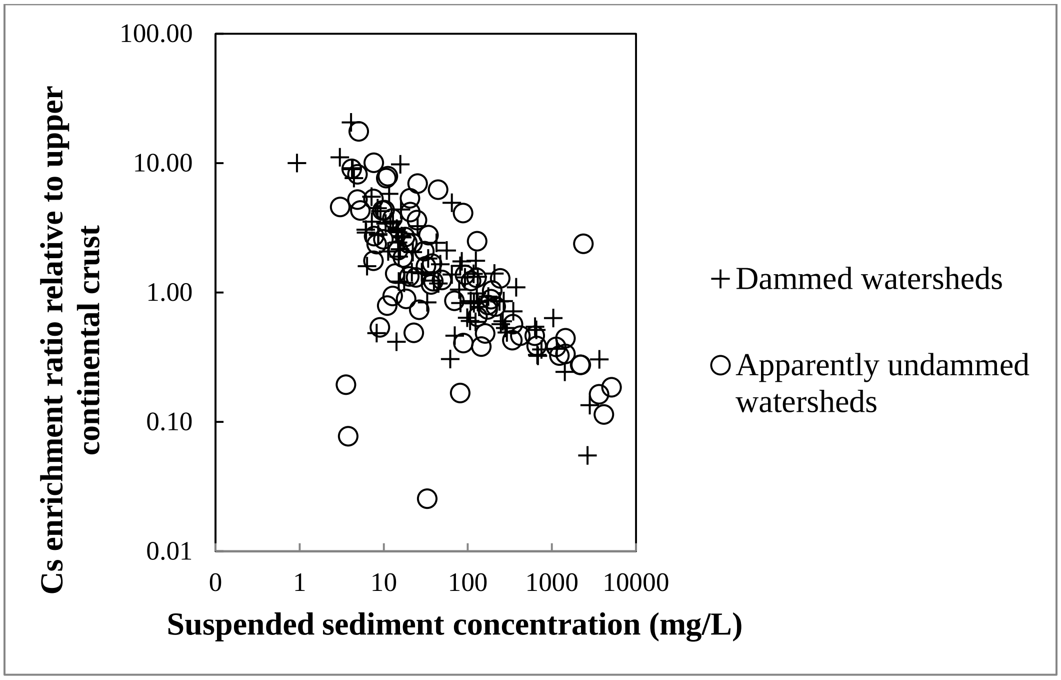

Figure 9(j): Represents the trace element Cs.

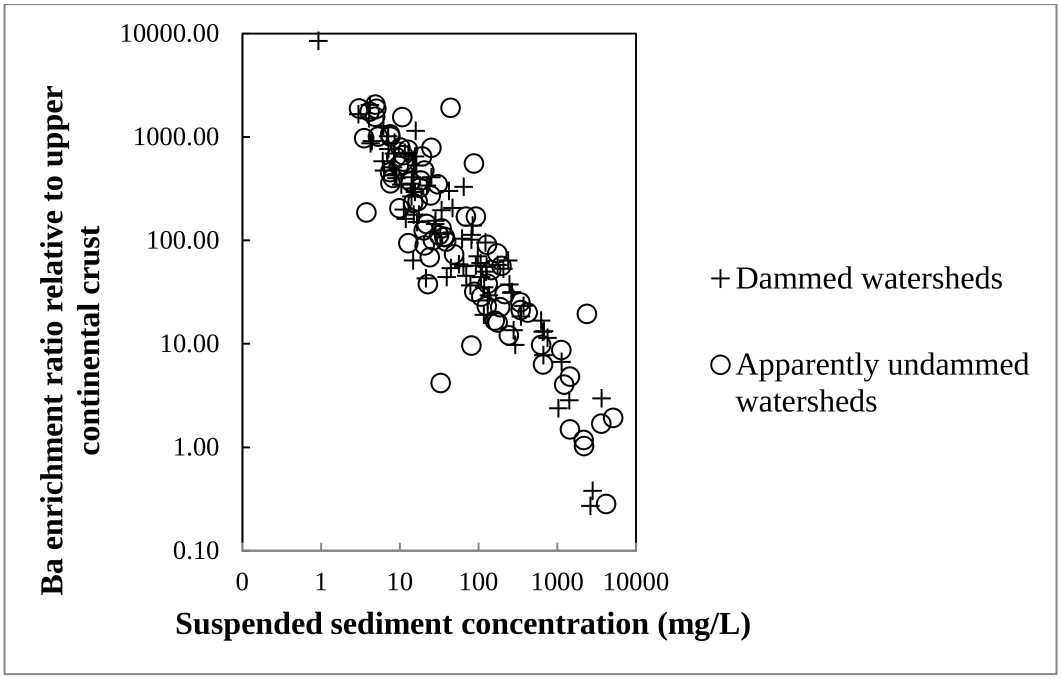

Figure 9(k): Represents the trace element Ba.

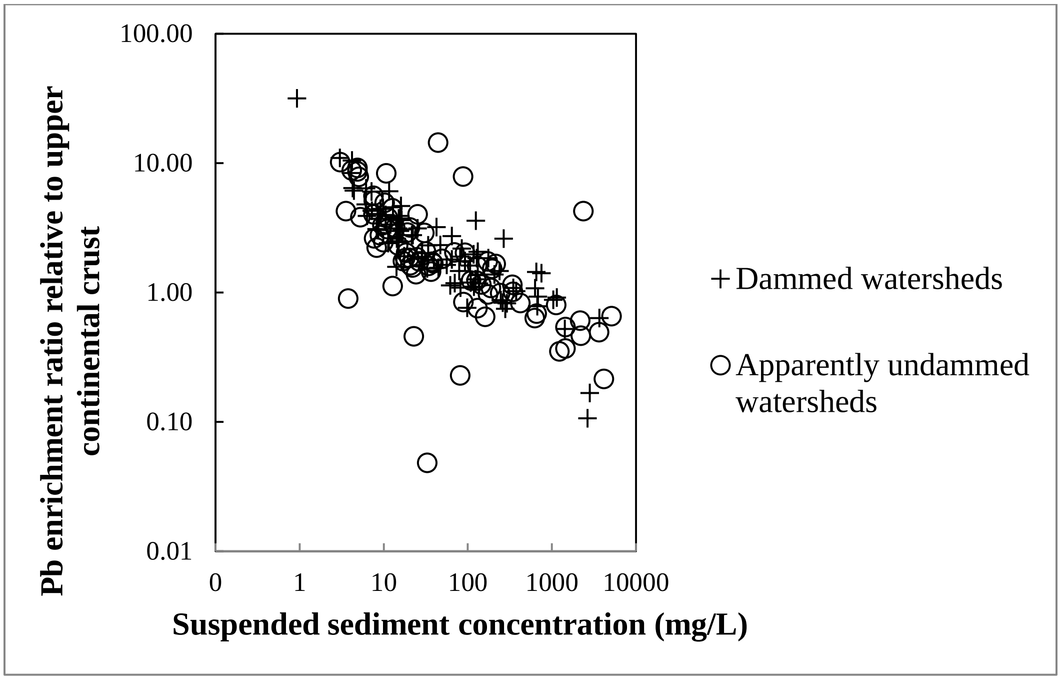

Figure 9(l): Represents the trace element Pb.

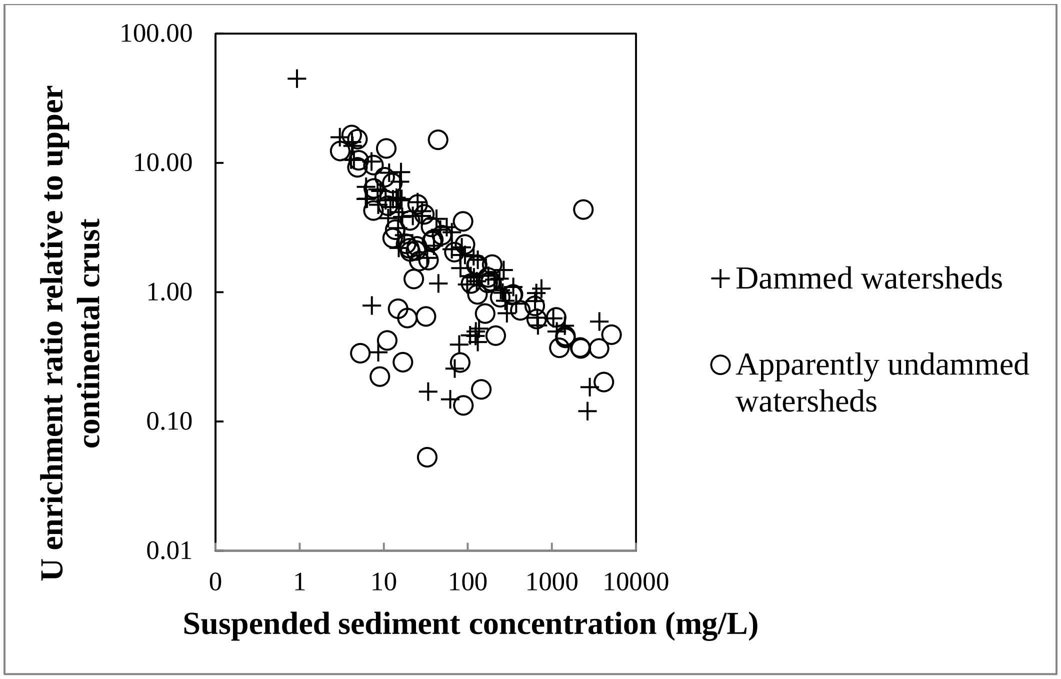

Figure 9(m): Represents the trace element U.

Figure 9(a-m): The relationship between elemental enrichment ratio relative to the upper continental crust and suspended sediment concentration for the suspended sediment samples collected from the group of previously dammed watersheds and the group of apparently undammed watersheds.

Discussion

The effects of mill dams on instantaneous suspended sediment yield

Here, a group of eight previously dammed watersheds and a group of eight similar apparently undammed watersheds were established to determine the relative impact that mill dams have on instantaneous suspended sediment yield. There was variation in the relationship between stream discharge and instantaneous suspended sediment yield for both watershed groups, which can be related to several factors including seasonality, land use, hysteresis, and sediment exhaustion (Walling and Webb, 1982). More importantly however, through this experimental design, it was found that both watershed groups transport similar, relatively high amounts of sediment, at least during the in-channel flow conditions sampled.

This similarity in sediment transport between watershed groups could be because only a small fraction of the flow events sampled came from higher flows, which may not be sufficient to show a difference in bank erosion and sediment transport. For example, only 28 of the 264 flow events sampled (11%) came from discharges $\geq 1m^3/s$. Additionally, stream discharge and suspended sediment data were collected for only one year and therefore seasonal effects on bank erosion processes were not sufficiently taken into account. Many researchers have indicated that the majority of bank erosion in silt and clay dominated bank material (i.e. legacy sediment) takes place during the winter months, through freeze thaw processes, which weakens stream banks, making them more susceptible to erosion (Wolman, 1959; Lawler, 1986; Wynn et al., 2008; Merritts et al., 2011). Over time, such a process, and more sampled high flow events, could indicate that more bank erosion and sediment transport takes place in the previously dammed watersheds, as there are more legacy sediments available for erosion. Alternatively, this similarity in sediment transport between watershed groups could indicate that bank erosion is not an important source of sediment due to, for example, floodplain storage (Trimble, 1999; Allmendinger et al., 2007), which could suggest that upland soil erosion is the most important source of sediment.

Policy implications

Due to the presence of actively eroding stream banks in the previously dammed and apparently undammed watersheds, bank erosion could be an important factor as to why both are transporting similar, relatively high amounts of sediment, at least for the in-channel flow conditions sampled. Stream restoration practitioners may interpret this to mean that a more widespread search and removal of legacy sediment material is needed, opposed to only concentrating on areas directly upstream from mill dams, as indicated in Merritts et al. (2011), to achieve a significant reduction in sediment transport derived from bank erosion. However, because the removal of legacy sediments from an entire watershed would be prohibitively expensive, time consuming and impractical, it should be confined to areas where bank erosion is likely to be most severe, such as directly upstream from a mill dam and around steep channel bends further upstream, and into undammed tributaries.

Alternatively, despite actively eroding stream banks being evident throughout the previously dammed and apparently undammed watersheds, it is possible that upland soil erosion was an important source of sediment. Gellis et al. (2009) found that within the mill dammed impacted Little Conestoga Creek, upland soil erosion made up 77% of the average annual suspended sediment load. In the present study, sediment input from the uplands was observed along roadways near agricultural land, which seemed to effectively transport upland sediments to nearby waterways, thereby likely contributing to the relatively high amounts of sediment being transported. Thus, it could be that the more widespread use of upland soil erosion prevention and sediment control practices are needed to minimize the uplands as a sediment source.

The effects of mill dams on the trace element composition of suspended sediments

As an additional part of this study, we wanted to determine whether suspended sediments in the previously dammed watersheds differ in trace element composition from background conditions, due to their different weathering history in a redox environment.

Overall, the suspended sediment trace element composition was similar in both watershed groups. A general downward pattern was observed for all trace elements analyzed, in that as the suspended sediment concentration increased, the elemental enrichment ratio relative to the upper continental crust decreased to a ratio near 1.0, which was most likely due to a grain size effect. Lev and Brocks (2007) found that trace element enrichment at lower suspended sediment concentrations is associated with clay particle transport, which decreases to a concentration similar to that in the upper continental crust as larger sediment particles are introduced during higher flow events. This similarity in suspended sediment trace element composition between watershed groups suggests that there is no unique chemical composition for suspended sediments transported out of the previously dammed watersheds, relative to background conditions.

Future work

More stream discharge and suspended sediment data are needed, over a longer time period, so that seasonal effects on sediment transport (such as freeze-thaw processes) can be better understood, and that more data can be represented. To sufficiently collect more suspended sediment data, automatic pump samplers would be needed so that samples could be collected during times of absence and throughout an entire storm hydrograph, thereby indicating when the majority of sediment transport takes place during storm flow.

Knowing the source(s) of sediment in the test watersheds is important, which according to recent literature, can be accomplished using additional sediment fingerprinting (Walling, 2005; Gellis et al., 2009; Banks et al., 2010). With this technique, a unique set of chemical characteristics are identified for a variety of potential sediment sources, both upland and in-channel, which are compared to the composition of suspended sediment collected from a wide range of flow conditions (Walling, 2005). An unmixing model is then used to determine the relative contribution of each source (Gellis et al., 2009; Banks et al., 2010). Additionally, using sediment budgets would help quantify erosion and deposition processes, and indicate where they are occurring, thereby answering the questions why are the watershed groups transporting similar amounts of sediment, and does more bank erosion occur in the previously dammed watersheds, over time? Gellis and Walling (2011) argue that using sediment fingerprinting and sediment budgets together will help identify erosion “hot spots,” which once controlled, can result in a more substantial reduction in sediment transport, without wasting money and resources on areas that are not important sources of sediment.

Conclusions

In this paper, a comparative analysis was used to show that a group of eight previously dammed watersheds and a similar group of eight apparently undammed watersheds were transporting similar, relatively high amounts of sediment, at least during the in-channel flow conditions sampled. This could indicate that the majority of mill dam trapped legacy sediments get released during specific flow events or seasonal periods (i.e. something that a more long term study would identify), or that bank erosion was not an important source of sediment and that upland soil erosion was most important. Furthermore, it was found that the trace element composition did not differ between the watershed groups, as both showed the same downward trend towards background conditions as suspended sediment concentration increased.

Because both watershed groups were transporting relatively high amounts of sediment, watershed managers may want to employ more widespread best management practices to control upland soil erosion, and or may want to consider searching for and removing legacy sediments from a more widespread area, as actively eroding stream banks were observed in the previously dammed and apparently undammed watersheds. However, before any sediment source mitigation is employed, it is important to utilize sediment fingerprinting to determine which sources of sediment are contributing most to the elevated sediment flux, and sediment budgets to determine where they are located. In doing so, money and resources can be utilized effectively in areas that are contributing most to the overall sediment flux.

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Curriculum vita

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Education:

- B.S., Environmental Science, Bridgewater College, Bridgewater, VA, 2008.
- M.S., Environmental Science, Towson University, Towson, MD, graduation scheduled January 2012.

Employment History:

- Interned as a STEP employee with United States Geological Survey, summer 2011-winter 2012. Tasks included: sediment analysis from various watersheds draining to the Chesapeake Bay, surveying stream channel cross sections.
- Graduate Assistant for Towson University: Department of Environmental Sciences, fall 2010-fall 2011. Tasks included: assistant to department faculty and staff.
- Interned with Maryland Geological Survey, summer 2009. Tasks included: measuring well depths, construction and interpretation of geophysical logs, and performing well pump tests.
- Interned with Maryland Department of the Environment, summer 2008. Tasks included: environmental compliance site investigations and reviewing falsified permit applications.
- Interned with Virginia Department of Environmental Quality, spring 2008. Tasks included: water quality data management and analysis, and macro-invertebrate sampling and analysis.

Presentations:

- Presented the topic “The Effects of Mill Dams on Suspended Sediment Yield, Baltimore County, Maryland” at the 41st Binghamton Geomorphology Symposium in Columbia, South Carolina, fall 2010.