MULTIPLE USE AND DISTURBANCE: CHANGING LAND USE AND SEDIMENT TRAPPING BEHIND LOW-HEAD DAMS

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INTRODUCTION

Human beings have altered the natural landscape in profound and oftentimes destructive ways. One of the most fundamentally destructive human alterations of the natural world is the construction of dams; dam removal has been gaining public support in recent years (Babbitt, 2002). Regulation of streams has exerted a more profound effect on the character of the world's rivers than pollutants (Ward and Stanford, 1979). The interaction between land use and hydrologic disturbance of streams is an important example of multiple disturbances of ecosystems. The hydrological effects of damming streams have been well-studied (Poff and Hart, 2002; Hart et. al., 2002; Pizzuto, 2002; Gregory et. al., 2002; Johnson and Graber, 2002) as has the effects of agricultural runoff on stream and estuarine ecosystems (Muller et. al., 2002; Wu et. al., 2002; Leonard et. al., 2001; Riise et. al., 2000). We are slowly moving toward an understanding of multiple disturbances and away from a "one problem – one solution" method of dealing with multiple uses of streams (Findlay, 2003).

Because dams fundamentally alter hydrologic regimes, their removal might help restore damaged ecosystems (Gregory, 2002). However, when contaminants such as pesticides and metals are trapped in the impoundments behind dams the restoration of a river's hydrologic regime may be less important than avoiding downstream pollution from the release of sediment-bound contaminants (Findlay, 2003). The character of sediments trapped behind dams must be understood before intelligent decisions can be made regarding removal, and the contamination of dammed sediments cannot be fully understood without knowledge of local land use. The interactions of multiple uses of a watershed complicate the problems and make solutions more elusive.

Dams

Dam removal is a current and contentious issue across the country, particularly in the Hudson Valley (Schmidt and Cooper, 1996). Human beings have been altering the flow of natural rivers and streams for over 5,000 years (Poff and Hart, 2002). In the US alone, there are approximately 76,500 large and over 2 million small (low-head) dams (Poff and Hart, 2002). 85% of dams in the US will end their operational design lives by 2020 (Doyle et. al., 2003). The major reasons to remove dams are: 1) the dam is approaching the end of its lifespan, 2) the reservoir has filled with sediment, 3) the dam is causing environmental damage and 4) returning rivers to their natural states may have economic and social benefits (Cantelli et. al., 2004). Small dams, while often the oldest, in the worst shape, and overall the best candidates for removal, are generally less studied than large dams (Poff and Hart, 2002). A study of 14 small dam removal cases in Wisconsin found that decisions regarding removal were generally made with incomplete or inaccurate information and in emotionally charged and divisive atmospheres (Johnson and Graber, 2002).

Dams fundamentally alter the natural landscape and river hydrology on both the local and landscape scales by altering the downstream flux of water and sediments, changing water temperature and creating barriers to the upstream and downstream movement of organisms and nutrients (Poff and Hart, 2002). On the local scale, dams capture sediments, store water and lead to thermal stratification of impounded water (Poff and Hart, 2002). On the landscape scale, dams fragment ecosystems and alter earth surface processes, including decreased sedimentation downstream and disruption of hydrologic flux to oceans (Poff and Hart, 2002). There are certain general effects of removal that are common to most dams, including erosion and lowering of the channel bed (incision), as well as the development of a coarse-grained surface layer (armor) in the riverbed downstream of the dam location (Pizzuto, 2002). For natural stream processes to be restored, or at least in order for the stream to attain a stable equilibrium form, upstream fill formerly behind the dam must be removed and the stored sediments must move downstream (Pizzuto, 2002). The height of sediment behind a dam is considered the greatest environmental challenge with dam removal (Gregory et. al., 2002). This challenge is made all the greater when there is not only a large amount of sediment trapped behind dams, but the sediment is contaminated with pesticides and trace metals. The most important ecological benefit of dam removal is probably the restoration of hydrologic regimes (Gregory, 2002), however dams also fundamentally alter macroinvertebrate assemblages (Pollard and Reed, 2004) and the detrimental effects on migratory fish runs have been well documented (Haynes et. al., 2001; Schmidt and Cooper, 1996).

Land Use

There may be interactions between river regulation and land use on the quality of sediments and benthic habitat available to stream biota. Studies typically focus on the effects of a single disturbance on aquatic ecosystems, but compound disturbances may produce effects that are different than two single disturbances occurring in isolation. The Hudson Valley has historically been a highly agriculturalized area of the country and is currently experiencing increased development (Findlay, 2003). Agricultural and urban lands lead to a significant amount of near-surface or overland water flow, which in turn leads to faster runoff into streams (Hopkinson et. al., 1995). In recent years, there has been an increase in forest cover as farms and fields have been abandoned and reforestation has occurred (Findlay, 2003). Unfortunately, despite the increase in forest cover throughout the region, residual contamination and continued non-point-source-pollution (NPSP) from existing agriculture and urbanized land mean that many of the Hudson Valley streams remain highly contaminated (Findlay, 2003). Agricultural runoff has high sediment loads, and these sediments are often bound to pesticides that were applied to fields (Davidson et. al., 1980). Many pesticides, particularly organo-chlorides such as DDT and atrazine, are very stable and bioaccumulate in the environment (Leithe, 1975). The agricultural structure of a catchment and the type and amount of pesticides used have an enormous impact on how much sediment reaches streams and the contamination level of that sediment (Muller et. al., 2002).

Along with amount of runoff entering a river, the size of sediment particles is an important factor in stream contamination, because smaller particles often have higher pesticide concentrations (Wu et. al., 2002). Organic matter content is also important; the higher the organic content of sediment washed into a river, the more likely it is that pesticides are bound to the sediment particles (Wu et. al., 2002). Large particles contain more organic material, but the finest particles have more surface area to which pesticides can sorb, therefore the most contaminated soils in the Wu study were both the largest and smallest particles (Wu et. al., 2002). In two other similar studies of organo-chloride pesticides in different catchments, the largest particle size sorbed more contaminants than either of the smaller sizes because of the higher organic matter content (Leonard et. al., 2001; Riise et. al., 2000). For trace elements and heavy metals, the smaller the particle size the higher the contamination (USGS, 1994).

Land use affects stream metabolism and organic matter turnover (Young and Huryn, 1999). Native forests have higher community respiration, lower primary productivity and relatively lower amounts of material in transport than any form of pasture land or plantation forest (Young and Huryn, 1999). Land use also affects the C:N ratio in stream sediments; more available terrestrial organic matter leads to a higher C:N ratio (Wolfe et. al., 2002). According to Hart and his colleagues, assessing the risk of dam removal should involve not only knowing the total volume and particle size distribution of the sediment within an impoundment, it also must involve analysis of current and former human uses of the watershed (Hart et. al., 2002). The interaction of multiple disturbances illustrates the full effects of human alteration of the natural world.

Hypothesis

I anticipate results showing that land use has an effect on the characteristics of sediments trapped behind low-head dams. There should be more sediment with higher organic matter content trapped behind dams in areas of heavy agriculture and development due to increased runoff in non-forested areas. Increased organic matter content usually indicates that there will be more pesticide contamination in the sediments because pesticides bind to organic matter.

I expect that sediments with higher organic matter content will have a higher rate of biological oxygen demand (BOD). I also anticipate that the BOD rate will decrease with depth across dam sites since the organic matter available to support respiration should decrease in older sediments.

METHODS

Study Sites

I studied seven low-head dams on five Hudson River tributaries: Fishkill Creek, Wappinger Creek, a tributary of Wappinger Creek, Little Wappinger Creek and a tributary of Little Wappinger. The locations of the dams were scattered throughout Dutchess County and all eventually empty into the Hudson River (Figure 1). Stream sizes and age of the dams varied. Upstream land use was determined with USDA aerial photos dating from 1936 up through 2000 as well as on-site assessment. GPS locations of dams were obtained after identifying ones that were accessible, effective at trapping sediment, and on rivers that were not too large to safely sample. I determined land use upstream from the study dams based on visual inspection of the sites and aerial photos. I then qualitatively assessed the human impact on the land upstream of all of the dams. I assessed urban and residential areas as high impact, agriculture as middle impact, and forested land as low impact. No quantitative methods were used for this classification scheme; the ranking of dams according to human impact is a relative measure.

Sampling Methods

I took a core sample from behind the dam at each site as close to midstream as possible. Several "composite" samples were also taken at each dam consisting of surficial sediments from each side and middle of the stream. GPS coordinates were recorded for all sampling sites. The core sample was taken with a steel corer according to USGS and EPA sampling protocols for sediments (www.usgs.gov, www.epa.gov) in order to keep the sediment in its original depositional layers. The core samples were taken at midstream a few feet above each dam in order to get the deepest core possible. All sediment samples were brought back to the lab and refrigerated before processing.

Lab Procedures

I separated each core sample into 2 cm layers (surface-2cm, 2 cm-4cm etc), which indicate relative age of the sediments behind the dams. These relative ages are important for comparing the characteristics of the older depositional and newer depositional sediments. Each core sample was in a plastic tube. Using a wooden rod affixed with a plastic disk, I pushed 2 cm of each core sample out of the tube and then sliced them off into plastic bags. I repeated this for each layer of each core sample. Three small pieces of each layer of each core were taken to test for biological oxygen demand (BOD) and two small pieces of each layer of each core were taken to measure water content and organic matter content.

Analyses

I analyzed the sediment for water content, organic matter content, and BOD. To determine water content, I took two small samples from each level of each core sample and left them in a dryer at 105^{o}C for three days. I then subtracted the dry weight from the wet weight of the samples to find water content. For the organic matter content, I took all of the dry samples of every layer from every core and combusted them in a furnace at 450^{o}C for 7.5 hours. I left the samples in the furnace overnight to let them cool and then removed them after 26 hours. I determined the organic matter content by subtracting the ash weight of each sample from the dry weight of each sample.

Determining BOD was a much longer process. For each layer of each core sample I took three small sections and put them each in different BOD bottles filled with de-ionized, room-temperature (approximately 65^{o}F), aerated water. I then took an initial measurement of BOD and waited two hours. I remeasured the BOD in each bottle at different two, four and eight hour intervals for at least 24 hours. I then calculated the rate of BOD, which was a negative exponential function

RESULTS

The sediment characteristics were different for each of the seven study dams. The BOD rate was generally higher for the dams with more development (higher human impact) upstream (Figure 2). This makes sense given inputs of human waste from developed areas. BOD rate is also indicative of a higher organic matter content, which increases the likelihood of pesticide contamination.

Despite the BOD rate results, there was no apparent pattern of organic matter content for the different dams studied (Figure 3). I anticipated that there would be more organic matter in the sediments trapped behind dams in more developed areas, but this hypothesis did not bear out for the seven dams studied. The organic matter content was different for the different dam sites, but there did not appear to be a trend.

There was a correlation between the BOD rate of the sediments trapped behind the different dams and the organic matter content of the sediments (Figure 4). I hypothesized that the correlation would be quite high, but it was surprisingly low ($r = -0.2963$, $R^2 = 0.0878$).

One of the most interesting results of this study was that the BOD rate was roughly the same for the oldest and the newest sediments at each dam site (Figure 5). I initially anticipated that the BOD rate would be higher in the youngest sediments irregardless of land use above the dams because the oxygen level and organic matter upon which the biological entities depend for metabolism should decrease with depth. This was not the case, however.

CONCLUSION

For the seven low-head dams studied, I can say that greater "human impact" land use upstream in the dam's watershed seems to be linked to a higher BOD rate. Higher BOD in sediments can lead to lower oxygen in the stream water for other organisms, including benthic invertebrates and fish (Wood, 2001). "Acceptable" BOD rates for water quality can vary between streams, but the BOD rates should decrease linearly (Wood, 2001). In this study, however, all of the samples from all of the levels of the different study sites had BOD rates that decreased exponentially. The logical reason for higher BOD rates in the more impacted sediments would be higher organic matter content, but based on these seven sites, that is not the case. In the absence of more organic matter, I am not sure what has led to the higher BOD rate in the sediment trapped behind dams in more developed areas. One possible explanation could be that there are more bacteria in this sediment. More bacteria would use available oxygen faster than sediments without the influx of bacteria. The water flowing over the most human-impacted dam, "FK4", smelled like raw sewage (unfortunately I was waist-deep in it). Human waste generally contains high bacteria loads. This qualitative assessment indicates that there may be large quantities of bacteria entering the stream via human waste, but this assumption would have to be tested.

I can also conclude, based on these seven study sites, that BOD is correlated with organic matter content. The correlation here is weak, but based on the literature I believe that if more dams had been sampled the relationship would be stronger.

Problems and Further Study

This study was plagued with problems from the very beginning. The greatest obstacle was the difficulty I had in simply finding dams to study. It was difficult to determine the coordinates of Dutchess County dams. Once I knew the coordinates it was almost as difficult to locate the dams. Most of the dams located were unsuitable for the study because of size, inaccessibility or armored sediments that could not be sampled. The result of all of these difficulties is that the study sites are not random and not replicated, which means that any results I obtain only apply to my seven study sites and cannot be extrapolated to any other low-head dams. Because of this, I cannot legitimately draw any conclusions about general characteristics of sediments trapped behind low-head dams. I also cannot run a regression analysis taking land use into account, because there is no way to know if the seven dams I used with their qualitatively determined land use history accurately represent the different Dutchess County land-uses. I have pages of data about seven locations along Hudson River tributaries, but I cannot legitimately run many statistical tests on any of it.

Another problem that I encountered was the lack of data on Dutchess County streams. Decades ago there were flow meters along Hudson River tributaries, but these have not been replaced as they fell into disrepair and most have either been removed or have washed away in flood events (USDA, personal communication). Without access to flow meters, it is very difficult to know the age of the sediment studied. I did process samples to test for lead levels in the sediments, which helps determine age, but I had to leave for graduate school before the samples were tested.

Since it took so much of my summer to find study sites, I was not able to run many of the analyses that I wanted to upon the sediment I collected. I was unable to test for pesticides, and I was also unable to determine particle size of the sediments collected. My ambition was much greater than my time. I now know that I must work to create manageable study designs. Otherwise, as was the case here, all of my time is spent on the mundane, and not enough is spent on research. I might have embarked on a different study from the beginning had I known how difficult it would be to carry out a study of low-head dams.

All of this is not to say that my experience at IES was not a great learning experience, but much of what I learned is what not to do next time. First and foremost, next time I will learn ahead of time what political situations may impede my study (i.e.: post-9/11 regulations limiting access to dam locations). Next time I will focus more on experimental design so that if there is some reason that study location and sample collection is difficult I will not be left with so few statistical options. Unfortunately, I did not know enough about experimental design at the beginning of the summer to realize that my lack of experimental units and replication was problematic. However, in spite of some experimental flaws, my time at IES was well spent.

There is valuable research to be done regarding dams and the characteristics of impounded sediments that may impact dam removal. More Hudson River tributary dams should be sampled, and all of the samples should be tested for pesticide concentrations, not just for pesticide surrogates such as particle size and organic matter content. Another important area that warrants further study is sedimentation rates behind the low-head dams along Hudson River tributaries. If researchers know the rates of sedimentation, the age of the different sediment layers can more accurately be determined. If the dates of deposition for the sediment layers are known, we will have a better understanding of the environmental persistence of the contaminants in these streams and also perhaps get an idea of how contamination has changed over time. Contaminant analyses and sedimentation rates will provide important information and help lead to more informed decisions about which dams must be removed, restored or repaired. As more and more dams reach their operational age limits, these decisions will have to be made sooner rather than later. Society can make better informed environmental decisions regarding our streams when we know more about the characteristics of sediments trapped behind low-head dams.

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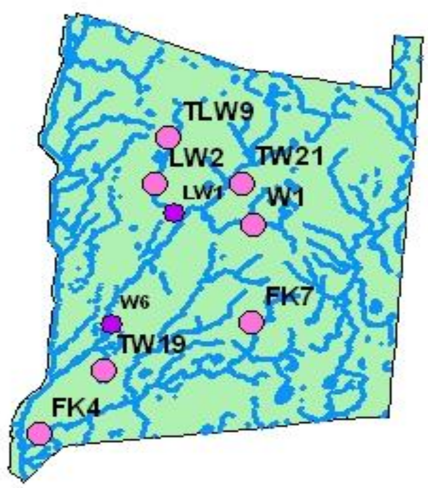
APPENDIX



Legend:
- Large Pink Circles: Study Dams
- Small Purple Circles: Dams I was not able to sample because of gravelly sediment
- Left Boundary of Map: Hudson River
- Code Names:
  - **W**: Wappinger
  - **TW**: Wappinger tributary
  - **LW**: Little Wappinger
  - **TLW**: Little Wappinger tributary
  - **FK**: Fishkill

FIGURE 1: Dutchess County Study Sites (numbers indicate individual dams)

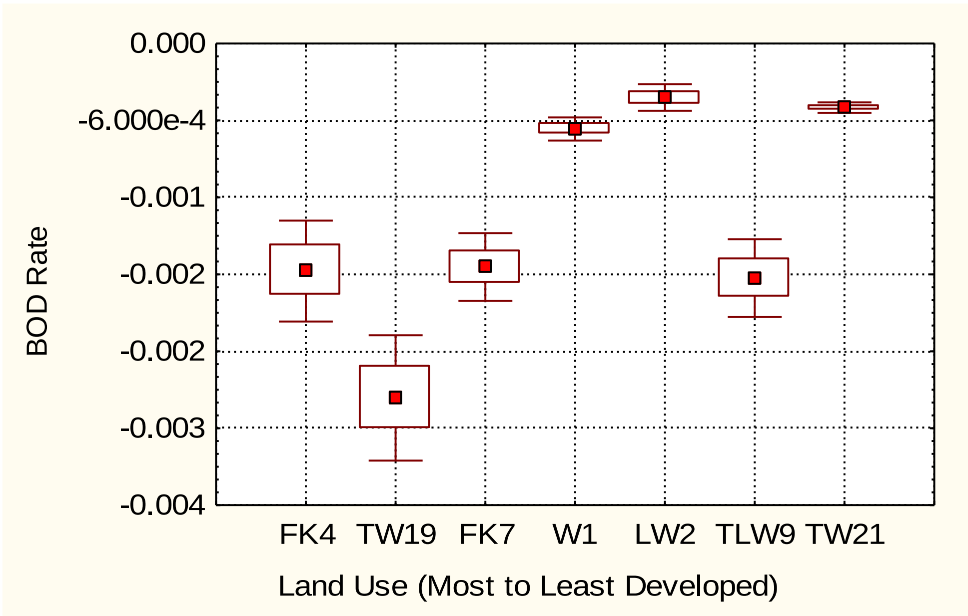


FIGURE 2: Rate of Biological Oxygen Demand for sediment trapped behind each dam not accounting for depth of sediment. The y-axis indicates the rate at which the oxygen is used.

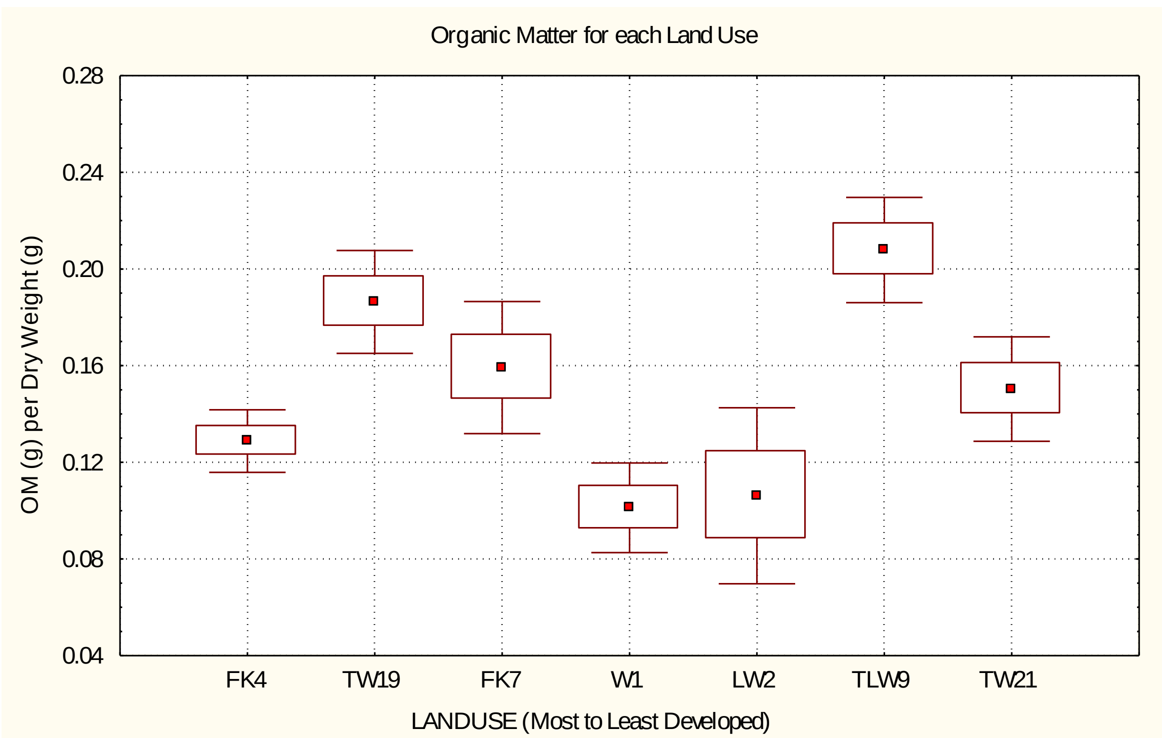


FIGURE 3: Organic Matter Content (OM) of sediment behind different dams not considering sediment layer depth.

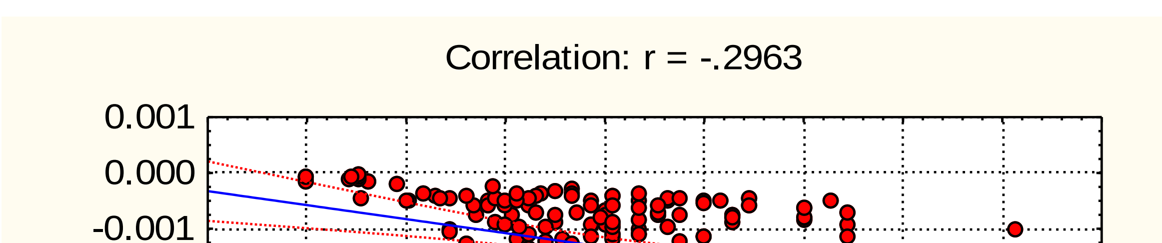


FIGURE 4: BOD rate regressed onto organic matter content (OM)

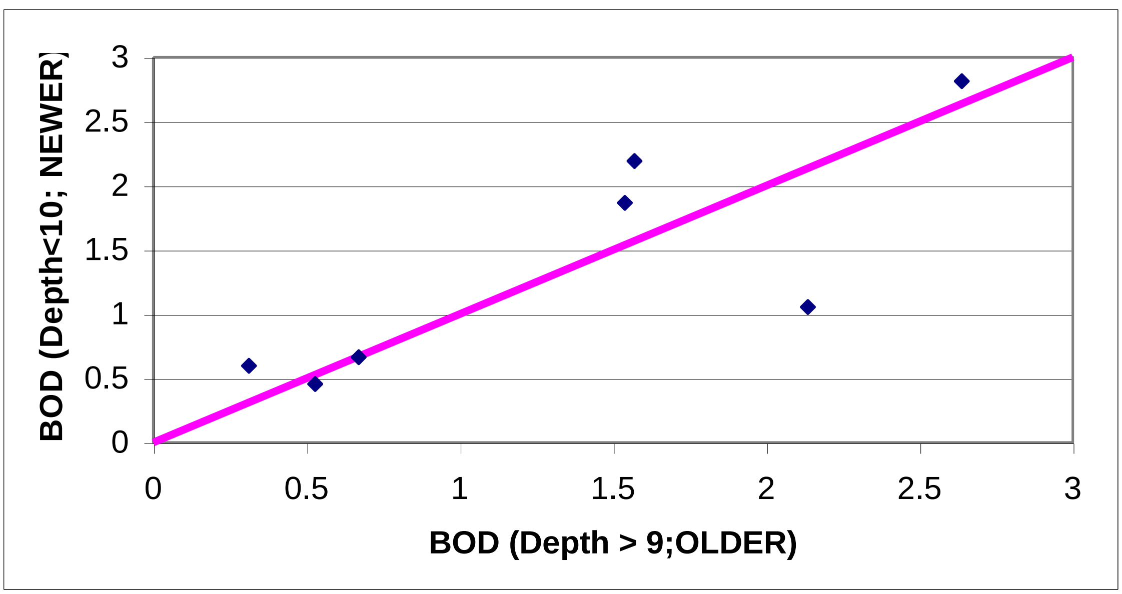


FIGURE 5: "Older" and "Younger" sediment BOD Rates are roughly the same across all study sites

"The proper role of science is to light candles in dark corners. It should reveal paths that can guide and improve decisions by society,"
~ Bruce Babbitt, former US Secretary of the Interior