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Research papers

Estimates of sediment trapping rates for two reservoirs in the Lake Erie watershed: Past and present scenarios

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ABSTRACT

Sediment accumulation can significantly impact the useful life of dams and the multiple functions served by those dams such as flood attenuation, hydropower, and water supply. However, there is only limited information, and even fewer physical measurements, assessing the rate of sediment accumulation in reservoirs behind dams. Many of the dams within the Great Lakes Watershed were constructed between 100 and 120 years ago, and there is reasonable concern that these dams and their associated reservoirs may be reaching capacity with respect to sediment storage. As a reservoir reaches its sediment storage capacity, there are numerous risks. Excess sediment can compromise the water intake for supply systems. Dam failure or removal can potentially allow large quantities of impounded sediment to migrate downstream, negatively impacting fish habitat and water quality. This research investigates the historical function of dams as sediment storage points. Also, this research assesses the effect of anthropogenic influences including land use change and dam construction on sediment yield and accumulation within the Lake Rockwell and Ballville Dam watershed. To better understand the historical and current sediment yield within the Lake Erie watershed, Soil and Water Assessment Tool (SWAT) models of the Lake Rockwell and Ballville Dam watersheds were developed. The resulting model suggests that the average of sediment accumulation rate within Lake Rockwell Dam reservoir varies between the minimum of 1.6 and the maximum of 4.6 $g/cm^2/yr$ from 1988 to 2007. Within the Ballville Dam reservoir, the rate varies between the minimum of 2.6 and the maximum of 23.2 $g/cm^2/yr$ from 1980 to 1999.

1. Introduction

It has long been known that human developments have impacted the quantity and quality of natural resources, including soil and water. As a result of land use changes and other anthropogenic influences, significant quantities of soil have eroded from the landscape, with subsequent delivery into rivers, reservoirs, and lakes with a potential infill of harbors and navigation channels. The U.S. Army Corps of Engineers are responsible for maintaining the navigability of the US waterways (navigational servitude) and typically spend between $20–40 million annually to remove 1.5–3.0 million m^3 (2–4 million yd^3) of sediment from channels and harbors that they maintain (Miller et al., 2013). Excessive sediment transport also deteriorates the natural habitat for some creatures. Some of the accumulating sediment may be contaminated with pollutants originating from industrial, municipal, and agricultural sources. For instance, nutrients can be adsorbed onto the sediments sourced from agricultural watersheds (Bosch et al., 2013). The nutrients may undergo desorption within a lake/reservoir and may become bioavailable which in turn could lead to excessive algae growth in the receiving waters. Many researchers have noted the importance of sediment-derived nutrient source resulting in increasing algae growth (Leote and Epping, 2015). In August 2014, a large microcystic algal bloom occurred due to an increase in bioavailable phosphorus in Lake Erie, a significant fraction of which could have been derived from the desorption of sediment-bound phosphorus, which resulted in drinking water restrictions to nearly half a million people. A study investigated the effect of reductions in nonpoint nutrient loadings in decreasing algal blooms in the western Lake Erie (Bosch et al., 2013). The effects of nutrient loading due to sediment transport and accumulation in waterways are not limited to the United States. Researchers have demonstrated the relationship between sediment size and

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the rate of sediment-water exchange of nutrients in the Marsdiep Basin, Western Sea in Netherlands (Leote and Epping, 2015). Of the total sediment that is mobilized in a watershed, a relatively small fraction reaches the outlet. The remainder is trapped in storage sites including floodplains and reservoirs. Typically the sediment and nutrient (both dissolved and particulate) delivery associated with the first flood event after a dry period has a much greater impact on water bodies and reservoirs (Ramos et al., 2015). These flood events can cause pollution spikes that last from a few minutes to several days, and can result in increased algae growth and contaminated water (Yevenes and Mannaerts, 2011).

Dams are constructed for multiple purposes, including the provision of water supply for residential and agricultural uses, flood control, and power generation. The reduced water velocity in the reservoirs created by the dams enhances the deposition of the sediments flow along with the river. Such deposition will ultimately shorten the useful life of these water structures. Accumulated sediment behind dams can reduce the flood-attenuation value of the reservoirs. In some cases, dams have degraded river ecosystems and have resulted in reduced fisheries (Stanley and Doyle, 2003). In the United States, the removal of unused and/or unsafe dams has increased in conjunction with efforts to restore fish passage and river ecosystems. Before any dam removal, extensive research is conducted to assess the quantity and quality of accumulated sediment within the reservoir and its fate. Dam removal can increase sediment delivery to the downstream reaches, resulting in decreased water quality and increasing sediment deposition in the channel, and potentially a downstream reservoir (Warrick et al., 2015). During the restoration of the Elwha River, Washington, USA, in 2013, two dams that were constructed in the early 1900s were removed. Subsequent investigations of the channel and floodplain geomorphic change were completed to evaluate the impact of sediment release due to the dam removal (East et al., 2015). Over 20 million m^3 of sediment had accumulated behind these two dams since their construction (Gelfenbaum et al., 2015). During the dam removal, 10.5 million tons (7.1 million m^3) of sediment was released, and about 1.2 million tons of sediment deposited along 25 km of floodplain and 18 km of the mainstem channel (East et al., 2015).

One parameter with the importance in estimating the life expectancy of dams is the *sediment trap efficiency* in the reservoirs. *Trap efficiency* is defined as the ratio of total weight of annual sediment accumulation behind a dam to the total weight of the annual sediment inflow to the reservoir. Sediment trapping efficiency is strongly impacted by the detention time (residence time) of water in the reservoir (Mahmood, 1987). Residence time depends on the relation between the size of the reservoir and the volume of water discharged by the streams into the reservoir. Brune in 1953 related the trapping efficiency within the reservoirs, with a residence time of water inflow (Brune, 1953; Gill, 1979). He also developed three curves for fine, medium, and coarse sediments (Brune, 1953; Gill, 1979). Trap efficiency can be estimated by measuring the difference between the sediment flux entering and leaving the reservoir or by examining long-term trends in the river sediment flux (Syvitski, 2003). Syvitski examined the trapping efficiency of dams on 488 rivers. He concluded approximately 26% of the global sediment traps behind dams (Syvitski and Milliman, 2007). Other researchers have suggested that 30% of the global river sediment load is accumulated within human-built reservoirs (Vörösmarty et al., 2003). Dendy (1974) investigated 17 small floodwater retarding reservoirs in the Southern and Western United States; he concluded although these 17 reservoirs size, shape, sediment load, flow, and velocity may vary widely, their trapping efficiency ranged from 81 to 98 percent for periods of 4–16 years (Dendy, 1974). Furthermore, the extent short-term remineralization of sedimentary material depends on the residence time of sedimentary material, the amount labile organic matter and other labile inorganic particulate matter which are prone to remineralization.

Climate factors such as wind speed and rainfall intensity, as well as geographic factors including topography, land cover, vegetation, and soil structure and composition, are the primary natural factors controlling the rate and magnitude of soil erosion (Toy et al., 2002). However, the major causes of soil erosion are anthropogenic. Human activities including urbanization, deforestation, and various farm practice result in elevated erosion rates (Jordan et al., 2014). For instance, sediment yield to Lake Pepin from the Mississippi River has increased by an order of magnitude since 1830 with European settlers (Engstrom et al., 2009). Land cover changes impact on the function of a watershed by changing the runoff pattern (hydrograph) and water quality (Randhir and Hawes, 2009). In the United States, deforestation and subsequent conversion of that land to agriculture or urbanization have greatly affected the rate of sediment delivery to watersheds. These land cover changes affect the total suspended sediment (TSS) load to the river. For instance, removing forest, and converting land to agriculture and pasture area results in increased TSS loading into the river. But in urban area describing a linear relationship between urban expansion and TSS loading is challenging (Jordan et al., 2014). Some agricultural practices such as agricultural tillage and tree removal have increased soil erosion and allowed runoff to deliver a considerable amount of TSS into receiving waters (Imeson, 2012). In response to decreased water quality, best management practices (BMPs) are being applied in many watersheds. These include the application of less destructive agricultural practices such as no-till operations, multi-stage channel design, and reduced fertilizer application.

Sediment transport to the Lake Rockwell and Ballville Dam impoundments, was assessed using the Soil and Water Assessment Tool (SWAT). SWAT is a physically-based continuous (daily time step) model and is used for the prediction of long-term water and sediment yields from a watershed. SWAT also simulates flow, nutrient, soil erosion and sediment yield from the watershed. This tool can predict the effect of climate change, land use change, reservoir management, agricultural practice, and groundwater withdrawals in the watershed (Neitsch et al., 2011). SWAT uses input data from GIS layers such as soil data, a digital elevation model (DEM), land use data, and climate data (precipitation, temperature, solar radiation flux, wind speed) to evaluate watershed hydrology, sediment yield (Neitsch et al., 2011).

The SWAT model evaluates a watershed by dividing the watershed into the smaller sub-basins, and each sub-basin is divided into the smaller units termed Hydrologic Response Units (HRUs). Within an HRU, the soil characteristics, land slope, and land use are assumed to be uniform. The use of HRUs is computationally efficient, allowing for large watersheds to be simulated over long periods of time. SWAT has been widely utilized throughout the world, also with applying SWATShare Tool, researchers can share their SWAT model and also access different SWAT models (Rajib et al., 2015). SWAT is used to track nutrient and sediment load in watersheds (Abbaspour et al., 2015; Yesuf et al., 2015), and to evaluate the anthropogenic impacts on the sediment budget (Creech et al., 2015). SWAT also has been used to assess the impact of climate change and agricultural BMPs on sediment and nutrient yields (Bosch et al., 2014; Schiefer et al., 2013).

The overall objective of the present research is to quantify the sediment accumulation rate within two reservoirs in the Lake Erie watershed through the development and analysis of a SWAT model of each reservoir. To evaluate the anthropogenic impacts, the present-day sediment yield rate is compared to that simulated for the pre-European settlement condition.