Sediment Accumulation Rate within the Reservoirs in the Lake Erie Basin

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Abstract

During and after a particularly strong flood event, a considerable amount of sediment load delivers into the water bodies. A portion of the sediment that flows along with the river deposits within the reservoirs, and eventually shortens the lifespan of the reservoir. Many of the dams within the Great Lakes Basin are between 100 and 120 years old, and there is a reasonable concern that these dams and their associated reservoirs may be reaching their capacity for sediment storage. There are numerous risks associated with this situation. Dam failure or removal result in releasing sediment to the downstream and deteriorating the natural habitat, water quality, and depositing sediment on the flood plains and harbors. This research investigates the historical function of dams as sediment storage points in the Lake Erie Basin. To better understand the historical and current sediment yield within the Lake Erie watershed, the Soil and Water Assessment Tool model of Ballville Dam and Lake Rockwell Dam watershed were developed. SWAT predicted that the sediment accumulation rate within Ballville Dam reservoir varied between 10,000 and 92,000 (tn/yr) from 1980 to 1999, and within the Lake Rockwell Dam the rate was between the minimum of 57,000 and the maximum 167,000 (tn/yr) from 1988 to 2007.

Keywords: *Sediment Accumulation Rate, Reservoirs, Lake Erie, SWAT models, Flood Event*

Introduction

Soil erosion is a serious threat to the agricultural industry and natural ecosystems (Naqvi, et al., 2015). In a rainfall event, some eroded soil from the landscape delivers into the waterbodies. However, just some amount of mobilized sediment usually passes through the outlet of the watershed. The remainder is trapped in the temporary storages or reservoirs, and in the next rainfall events, they may move to the downstream and eventually deposit into the harbors (Ramos, et al., 2015). The Corps of Engineers who are responsible for improving and maintaining the rivers and harbors, spend a lot of money for dredging the accumulated sediments at the bottom of waterways to provide enough depth for shipping. Excessive sediment transport deteriorates the natural habitat, with spreading pollutants downstream. Pollutants and nutrients may adsorb on the sediment surface and be delivered into the water bodies, so the great habitat will be prepared for algae growth.

Dams have been built on the rivers to control flood and supply water and energy for different consumers. However, dams degrade river ecosystem, with changing the free- flowing river ecosystem to the impounded river. The dam wall blocks fish migrations, and impacts on the biological, physical, and chemical properties of rivers environment. When a river is blocked behind the dam, some portion of its sediment load may deposit behind the dam, and gradually reduce dam storage capacity. The rate of sediment accumulation within the reservoir depends on the reservoir capacity relative to the sediment flowing into the dam. In the Great Lakes watershed, there are many dams which are very old, unsafe, and no longer serve their purpose. The recent trend of the US is removing the old, and unsafe dams. With removing the dam, a huge amount of trapped sediment release to the downstream and eventually deposit on the flood plains and landscape. Therefore before doing any dam removal, extensive research should be done to estimate sediment trapping rate within the reservoir (Warrick, et al., 2015), and assess their consequences hazards.

Estimating how much sediment has been trapped within the reservoir is extremely tough, and complicated. Collecting sediment data is expensive and difficult. Therefore developing the watershed model that can predict the water and sediment yield in a watershed is very useful. In this research for estimating the sediment accumulation rate the Soil and Water Assessment Tool has been applied (Neitsch, et al., 2011). SWAT was developed by the researchers at the U.S. Department of Agricultural, Agricultural Research Service (USDA, ARS) in the mid-1990s. This tool is a physically based continues model, which can predict the effect of land use change, climate change, and implementing different agricultural practices on the water and sediment yield (Bosch, et al., 2014, Bosch, et al., 2011, Creech, 2014). The SWAT model inputs include soil type, land use data, elevation data, and climate data (temperature, precipitation, solar radiation and wind speed). After developing the SWAT model, for calibrating, validating and analyzing the uncertainty the model, SWAT-CUP tool has been applied (Abbaspour, 2015).

Study Area

Ballville Dam and Lake Rockwell Dam have been selected to study sediment trapping rate in the Lake Erie Basin. Ballville Dam was built in 1911 on the Sandusky River, in Sandusky County, in the State of Ohio. The Ballville Dam was used as the water supply for the City of Fermont. Lake Rockwell Dam is located on the Cuyahoga River, in Portage County, in the State of Ohio. Lake Rockwell Dam was built in 1913 to supply water to the City of Akron. Both Cuyahoga and Sandusky River watershed are the big watersheds within the Lake Erie Basin. Table 1 displays Ballville and Lake Rockwell Dam characteristic and their associated reservoir (National Inventory of Dams Website).

Table 1- Reservoir Data from USACE NID, April 2015

Dam Name	Drainage Area (mi^2)	Surface Area (acres)	Max Storage (acre-ft)	Dam Height (ft)
Ballville	1,254	89	2,402	34
Lake Rockwell	208	810	18,250	35

Land use in the Ballville Dam watershed is dominated largely by agricultural use, although there are some sparse areas of developed and forest. The average of slope in the Ballville Dam watershed is 2.3%. However, the lower part of the watershed has gently slope (below 1.5%), while the upper portion of the watershed has a greater variability in the slope. The land cover in the Rockwell Dam watershed consists of mostly a developed area, forest, and some farm land. Upstream of the Rockwell dam is mostly covered by forest and cropland. The largely developed area such as Cleveland and Akron are in the downstream of the dam, around the outlet of the watershed. The average of slope in the Rockwell Dam watershed is about 6%. However, the west portion of the basin is the steepest, and north- east is the flattest part.

The United States Geological Survey (USGS) operates several gages in the Cuyahoga River. Gage 04202000 (with the contributing drainage area of 151 mi^2), and gage 04206000 (with the drainage area of 404 mi^2) record stream discharge. Gage 04208000 (with a drainage area of 707 mi^2) records stream discharge and suspended sediment concentration. The flood frequency analysis at the outlet of Rockwell Dam watershed predicted 100-yr and 500-yr rainfall events are corresponding to 19,000 and 21,000 (cfs) stream discharge. Since the construction of the Lake Rockwell Dam, some flood happened which their corresponding flow exceeded 500-yr flood event.

There are also some USGS gages in the Ballville Dam watershed. Among these gages, gage 04198000 recorded suspended sediment concentration from 1950 to 2002, and stream discharge since 1923, except for 1936-1938. Gage 04198000 (with a drainage area of 1,251 mi^2) is the nearest gage upstream of the Ballville Dam. Based on the statistical- frequency analysis at gage 0419800, 500-yr recurrence interval event is about 34,000 (cfs), and 100-yr is about 30,000 (cfs). Since the Ballville Dam construction, three big floods happened in 1913, 1978, and 1984 which exceeded 500-yr flood event.

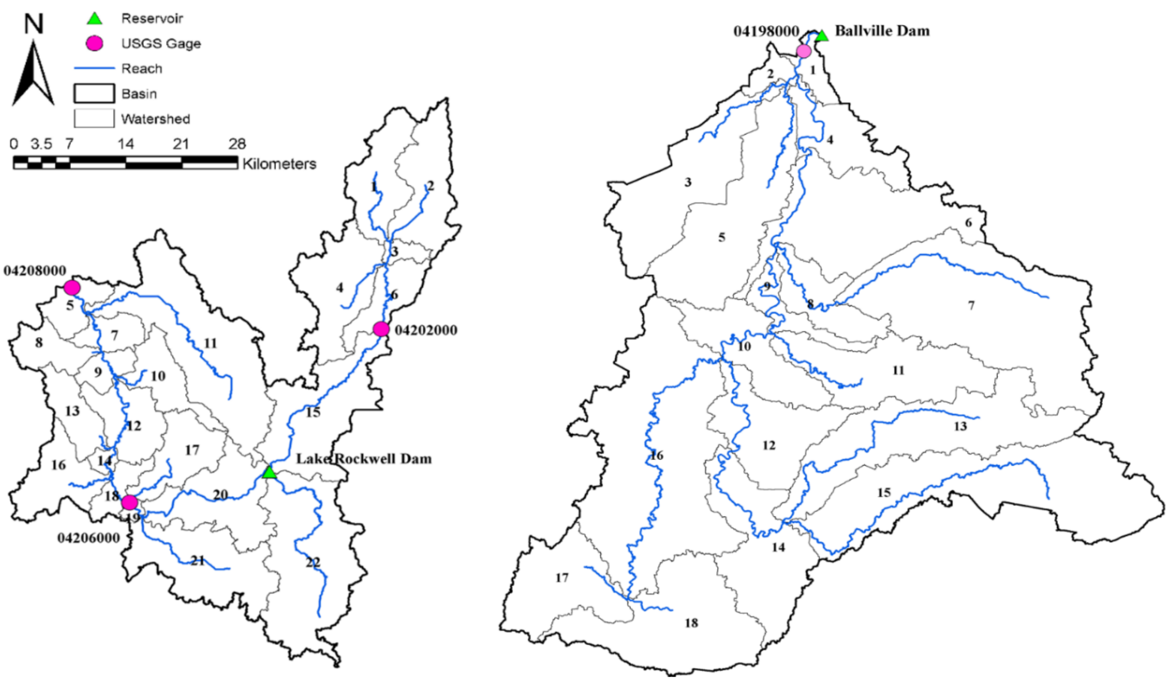

Figure 1- Lake Rockwell Dam, and Ballville Dam Watershed

Material and Method

In order to understand how sediment load accumulated within the reservoirs in the Lake Erie Basin, the SWAT model of Ballville and Lake Rockwell Dam watershed have been developed. The input data including, land use from National Land Cover Databases (NLCD), (Homer, et al., 2007), soil structure from STATSGO database (Schwarz, et al., 2004), topography from USGS National Elevation Dataset (NED), reservoirs dimension from NID website, and weather data from USDA-ARS database, were overlapped to parameterize the model. The SWAT tool divided the Ballville Dam watershed into the 18 subbasins, the dam, and the gage 04198000 are in the subbasin 1 (Figure 1). The Rockwell Dam watershed consists of 22 subbasins, the dam, is in the subbasin 15, gage 04202000 in subbasin 6, gage 04206000 in subbasin 19, and gage 04208000 in subbasin5. In the Ballville Dam watershed, five years from 1975 to 1980 have been considered as a warm up period. The model is calibrated from 1980 to 1989 and then validated from 1990 to 1999. Rockwell Dam model was run from 1983 to 2007, including five years for model warm-up (1983-1988), ten years for calibration (1988-1997) and finally the other ten years for validation (1998-2007). Calibration and validation of the two study watersheds were achieved for hydrology and sediment components by adjusting influential variables in SWATCUP. SWATCUP has been developed to calibrate the SWAT models, The output of this tools is the propagation of the uncertainty in the parameters shown as the 95% probability distribution (95PPU), which are calculated at the 2.5%, and 97.5% the cumulative distribution of results (Abbaspour, et al. 2015). Several factors including p-factor and r-factor are identified to aid in the quantification of the goodness of fit between simulated and observed values. P-factor is the percentage of observation data in the 95PPU region, and r- factor represents the thickness of 95PPU. P-factor bigger than 70% and r-factor of around 1 are acceptable ranges, although for calibrating the sediment component smaller p-factor and bigger r- factor are acceptable (Abbaspour, et al. 2015). The Nash- Sutcliffe efficiency and percent bias have also been suggested for assessing the model performance (Moriasi, et al., 2007). The model can be assessed as satisfactory if NSE and R^2> 0.5, and PBIAS ±25% (Table 2).

Table 2-Hydrology calibration and validation at Lake Rockwell and Ballville Dam Model. Note that the p-factor, r-factor, coefficient of determination (R^2), Nash-Sutcliffe simulation efficiency (NSE), and percent bias (P-BIAS) are in the satisfactory range in calibration and validation period.

Hydrology	R^2	NS	P-BIAS
Calibration			
Lake Rockwell			
Flow_Out_05	0.84	0.77	-17%
Flow_Out_06	0.66	0.64	-3%
Flow_Out_19	0.81	0.80	-7%
Ballville			
Flow-Out-01	0.69	0.67	15%
Validation			
Lake Rockwell			
Flow_Out_05	0.84	0.82	-8%
Flow_Out_06	0.69	0.58	14%
Flow_Out_19	0.80	0.77	7%
Ballville			
Flow_Out_01	0.84	0.82	8%

Sediment	p- factor	r- factor	R^2	NS	PBIAS
Calibration					
Lake Rockwell					
SED_Out_05	0.78	1.08	0.71	0.71	0%
Ballville					
SED_Out_01	0.76	0.95	0.63	0.63	-3%
Validation					
Lake Rockwell					
SED_Out_05	0.84	1.60	0.74	0.72	-14%
Ballville					
SED_Out_01	0.76	2.09	0.68	0.68	4%

Results and Discussion

As it was explained in the last section, the models were successfully calibrated and validated to the known average monthly flow, and sediment load. Figure 2 displays a comparison between the simulated and observed average monthly sediment load in Ballville Dam and Lake Rockwell Dam watersheds.

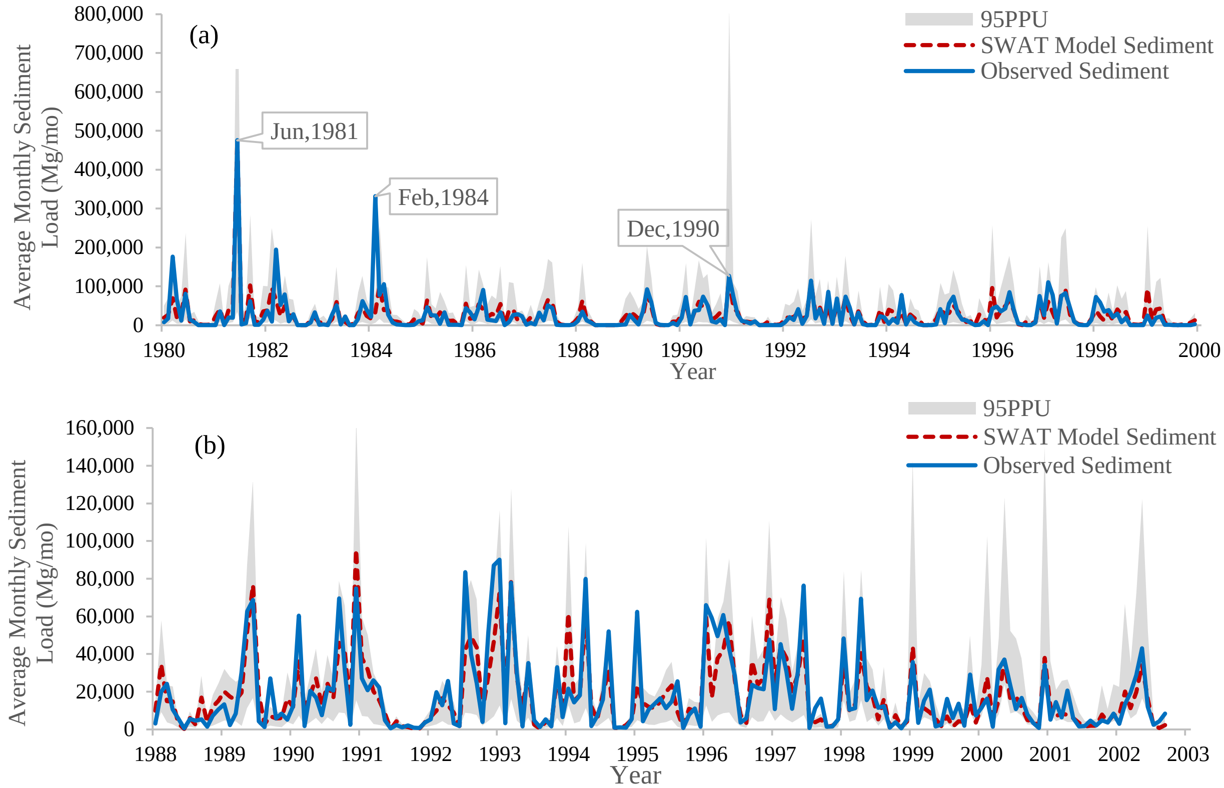

Figure 2- (a) Calibrated (1980-1989) and validated (1990-1999) Monthly Sediment Load at Gage 04198000 in the Ballville Dam Model, (b) Calibrated (1988-1997) and validated (1998-2007) Monthly Sediment Load at gage 04208000 in the Rockwell Dam Model

In the Ballville Dam model, flood events in Jun, 1981 (which exceeded 500-yr recurrence interval) and February, 1984 resulted in big spikes in the sediment yield in these months. In the Rockwell Dam watershed, stream discharge in simulation period was less than 50-yr recurrence intervals (or 18,000 cfs). Uncertainty analysis has been done on the sediment load that flows into the dam and exits the dam. Then the difference of the loads was calculated to estimate the potential sediment accumulation rate within the reservoirs (Figure 3). The SWAT model predicts that the average rate of sediment trapping within Ballville Dam reservoir is varying between 10,000 and 92,000 (tn/yr) (or 2.6 and 23.2 g/cm^2/yr). James E. Evans also concluded the annual sediment accumulation rate within Ballville Dam reservoir is between 1.7 and 4.3

($g/cm^2/yr$) based on Cesium-137, and Lead-210 dating from 1978 to 1993 (Evans, et al., 2002). He also concluded that 78% of the storage capacity of Ballville Dam has already been filled by the sediment load from 1911 (the year that dam was built) to 1993. In the Rockwell reservoir, the average rate of sediment accumulation is fluctuating from 57,000 to 167,000 (tn/yr) or (1.6 to 4.6 $gr/cm^2/yr$) between 1988 and 2007.

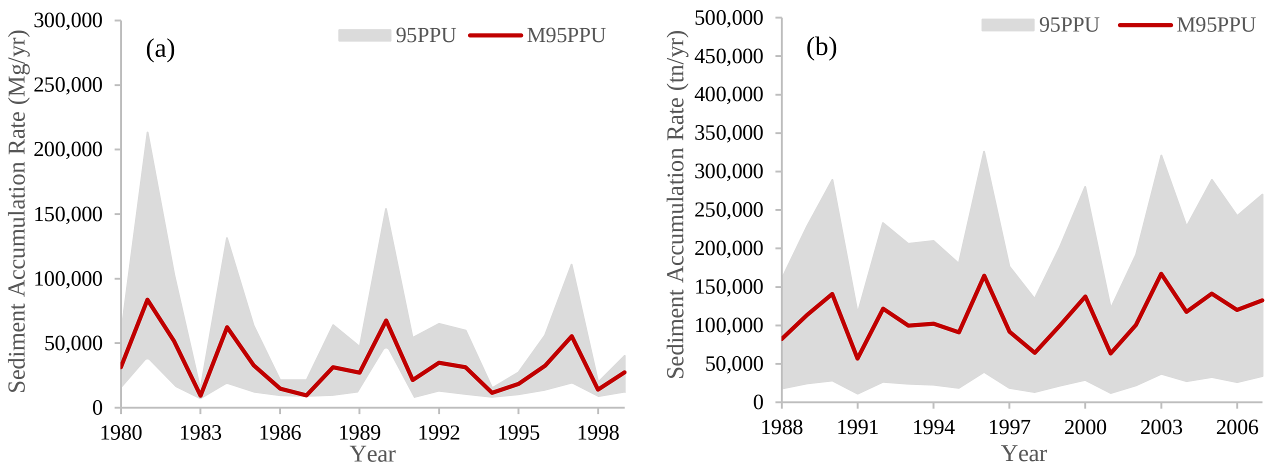

Figure 3- Sediment Accumulation Rate within the reservoir (a) Ballville Dam, (b) Rockwell Dam

Conclusion

SWAT estimated that 12% of the sediment that flows into the Ballville reservoir have been annualy accumulating within the reservoir, while this ratio is 85% in the Rockwell Dam reservoirs. A primary reason for the small trapping efficiency in the Ballville reservoir in comparison to the Rockwell Dam, is small residence time of water in the reservoir, such that settling of the finer particle does not occur. Therefore, the most important factors that sediment trapping efficiency depend on are the reservoir geometry, and the characteristic of sediment load that flows into the reservoir.

The SWAT models can also be used at predicting the sediment accumulation rate within the reservoirs in future. Evaluating the potential relations between sedimentation trend and climate change is very help at decision making for keeping or removing dams in future.

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