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Research papers

Forecasting the remaining reservoir capacity in the Laurentian Great Lakes watershed

Fatemeh Alighalehbabakhani [a,*], Carol J. Miller [a], Mark Baskaran [b], James P. Selegean [c], John H. Barkach [a], Travis Dahl [c], Seyed Mohsen Sadatiyan Abkenar [a]

[a] Department of Civil and Environmental Engineering, Wayne State University, Detroit, MI 48202, United States
[b] Department of Geology, Wayne State University, Detroit, MI 48202, United States
[c] United States Army Corps of Engineers, Detroit District, Detroit, MI 48226, United States

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ABSTRACT

Sediment accumulation behind a dam is a significant factor in reservoir operation and watershed management. There are many dams located within the Laurentian Great Lakes watershed whose operations have been adversely affected by excessive reservoir sedimentation. Reservoir sedimentation effects include reduction of flood control capability and limitations to both water supply withdrawals and power generation due to reduced reservoir storage. In this research, the sediment accumulation rates of twelve reservoirs within the Great Lakes watershed were evaluated using the Soil and Water Assessment Tool (SWAT). The estimated sediment accumulation rates by SWAT were compared to estimates relying on radionuclide dating of sediment cores and bathymetric survey methods. Based on the sediment accumulation rate, the remaining reservoir capacity for each study site was estimated. Evaluation of the anthropogenic impacts including land use change and dam construction on the sediment yield were assessed in this research. The regression analysis was done on the current and pre-European settlement sediment yield for the modeled watersheds to predict the current and natural sediment yield in un-modeled watersheds. These eleven watersheds are in the state of Indiana, Michigan, Ohio, New York, and Wisconsin.

1. Introduction

Reservoir sedimentation is a serious problem in most regions of the world. Over time, deposition of sediment reduces reservoir volume and thereby shortens the useful life of the reservoir. Based on the measurement of sediment flux into and out of a reservoir, it has been estimated that approximately 30% of the global river sediment load is trapped within reservoirs (Vörösmarty et al., 2003; Syvitski and Milliman, 2007). It has been estimated that the world's reservoirs are losing their capacity at a rate of 0.5–1.0% each year (World Bank, 1998; World commission on dams report, 2000). Reliable estimates of the life expectancy of a dam are essential for the evaluation of dam's function, its viability and the economic feasibility as a water resource over a longer period. The useful life of reservoirs is limited by the excess sediment accumulating within the dam. Some of the important factors that affect the amount of sediment trapped in a reservoir include water and sediment discharge, sediment particle size, reservoir age, and reservoir geometry (Gill, 1979). *Reservoir Trap Efficiency* is defined as the total weight of annual sediment accumulation within a reservoir to the annual sediment inflow (Brune, 1953). There are some different approaches that have been proposed for estimating the reservoir sediment trap efficiency (Brown, 1944; Brune, 1953; Camp, 1945; Churchill, 1948). The difference between each method is their complexity and input variables.

There are more than 75,000 dams in the United States, there is an increasing concern that some of these dams are old and have reached to their sediment storage capacity. When reservoirs reach its storage capacity there are some risks including dam failure or dam removal. Following dam removals or failures accumulated sediments will continue to be scoured. Releasing the long-term accumulated sediment in a short-period from a reservoir is a serious threat to the natural environment and aquatic ecosystems such as fish and macroinvertebrate populations (Storlazzi et al., 2015). There is limited information and less physical measurement of accumulated sediment in the reservoirs. Therefore, before any dam removal the quantity and quality of accumulated sediment should be determined. One of the main objectives of this research is estimating the sediment accumulation rate for some reservoirs

* Corresponding author.
E-mail address: falighalehbabakhani@hrc-engr.com (F. Alighalehbabakhani).

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across the Great Lakes watershed and expanding the results to other reservoirs.

Peak flow events result in high suspended sediment discharge to a reservoir, so that in some cases, about half of the annual sediment discharge into a reservoir can happen from one pulse rain event happening in only one day or one precipitation event per year (Conaway et al., 2013; Grodek et al., 2012; Warrick et al., 2015).

Several important factors such as climate change (Parajuli et al., 2016), glacial processes (Hinderer et al., 2013), and human-induced activities (such as urbanization, deforestation, and changes in farm practices) in the watersheds can result in accelerated soil erosion rates (Jordan et al., 2014; Toy et al., 2002). Due to human disturbance, the sediment yield to Faga'alu Bay in American Samoa is 3.9 times larger than the natural sediment yield (Messina and Biggs, 2016). The sediment delivery to the Lake Pepin from the Mississippi River has increased by an order of magnitude, due to human interfere (Engstrom et al., 2009). In the Sao Fransico River in Brazil, since pre-European settlement, the sediment yield has increased from 7 million tons/annum (Mt/a) to 27 (Mt/a) (Creech et al., 2015).

In the present work, the sediment accumulation rate within the reservoirs was assessed by Soil and Water Assessment Tool (SWAT), measuring $^{210}Pb_{xs}$ and ^{137}CS vertical profiles, using the Geographic Information System (GIS)-based approach for reservoir sediment storage and comparing post and pre-construction dam capacity.

SWAT was developed for USDA Agricultural Research Service (ARS) in 1998. SWAT has been utilized to estimate the long-term water and sediment yield within a watershed. This tool has been widely used to assess the effect of applying different agricultural practices, climate change, land use change on the nutrient component, water, and sediment yield within a watershed (Bosch et al., 2011, 2014; Makarewicz et al., 2014; Rajib et al., 2016; Schiefer et al., 2013). SWAT can simulate water, sediment, and nutrient yield in a watershed by using input data from GIS layer such as soil physical characteristic, land use, digital elevation map (DEM), and weather data (Neitsch et al., 2011).

In this study, SWATCUP was used to calibrate the SWAT models. SWATCUP was developed (Abbaspour, 2015) for calibration, validation, and uncertainty analysis of SWAT models. In SWATCUP, uncertainty in parameters is displayed as uniform distribution range, which shows uncertainty in the parameter, observation data, variables, and conceptual model. The SWATCUP output is a propagation of the uncertainties in the parameters which is explained as the 95% probability uniform (95PPU) calculated at the 2.5% and 97.5% of the cumulative distribution of output (Abbaspour, 2015). The lower (L95PPU) and upper (U95PPU) boundaries of 95PPU correspond to 2.5% and 97.5% probability, respectively. M95PPU corresponds to 50% probability.

There are some quantitative statistical parameters including; p-factor, r-factor, standard deviation (R^2), Nash-Sutcliff efficiency (NSE), and percent bias (PBIAS) that can be used to evaluate the model performance. The p-factor is the percentage of observation data fell in the 95 PPU envelope, while the r-factor is the thickness of the 95 PPU region divided by the standard deviation of the measured data (Abbaspour, 2015). The p-factor greater than 70% and r-factor around one were suggested to be used for discharge calibration, while a smaller p-factor and a larger r-factor can be acceptable for the sediment calibration (Abbaspour, 2015). The NSE parameter evaluates how well a model can simulate the hydrologic and sediment behaviors, and PBIAS identifies the tendency of the simulated parameters to be larger or smaller than observation data (Moriasi et al., 2007). Moriasi et al. (2007) suggest that the NSE and R^2 value exceed 0.50 and the PBIAS be greater than ±55% for satisfactory model results.

To evaluate the sediment trapping rate within the reservoirs and forecast the capacity of the remaining reservoir, twelve reservoirs across the Great Lake basin were selected and modeled using SWAT. The watersheds were selected based on availability of flow and sediment gage both upstream and downstream of the reservoir, availability of pre- and post-construction bathymetric maps, availability of historic land use, and ease of field investigation. significant effort was devoted to selecting those watersheds that would provide the greatest detail of information (to support our modeling efforts) as well as greatest diversity of conditions (to support broad applicability).

In the previous study the SWAT models were developed for Ballville and Lake Rockwell Dam watersheds (Alighalehbabakhani et al., 2017). In the current study nine SWAT models were developed for the Webber, Riley, Upper Green Lake, Goshen Pond, Ford Lake, Potter's Falls, Brown Bridge, Independence, Mio, and Alcona dams.

Short-lived radionuclides, ^{210}Pb and ^{137}Cs, are widely utilized as chronometers in a time scale comparable to the lifespan of reservoirs. Atmospheric ^{210}Pb (half-life = 22.3 y) is constantly produced from the decay of ^{222}Rn which escapes primarily from land surface at a constant rate. This ^{210}Pb is eventually removed from the atmosphere by precipitation in generally less than two weeks' time scale and delivered at the surface of lakes and coastal ocean (as well snow, ice, continents) which is subsequently removed primarily by suspended particulate matter. The activity of excess ^{210}Pb (= total ^{210}Pb – parent-supported ^{210}Pb) then decreases as a function of time at a rate controlled by its half-life. The rate of decrease of excess ^{210}Pb with depth permits determination of sediment accumulation rate and therefrom ages of sedimentary layers.

Cesium-137 was first introduced into the environment from the continuous nuclear weapons testing beginning in 1951 (after the first nuclear tests conducted in 1945), and the fallout of ^{137}Cs (and $^{239,240}Pu$, ^{90}Sr, etc) reached a peak in 1963 (Baskaran et al., 2014). In a sediment core from North America, primarily there are two ^{137}Cs-time-markers: one corresponding to the introduction of ^{137}Cs to the environment in 1952 the second one corresponds to the peak of ^{137}Cs fallout in 1963. These two-time markers are common throughout the globe, as they correspond to weapons tests which released ^{137}Cs into the stratosphere that was subsequently distributed globally before being deposited onto earth's surface primarily in association with wet precipitation (Baskaran et al., 2015, 2014).

The next method used to estimate sediment accumulation rate was a bathymetric survey. Some reservoirs including Upper Green Lake, Lake Rockwell, Potter's Falls, and Mio were mapped prior to dam construction, giving an excellent starting point for the base conditions of the reservoir. GIS software was applied to subtract the pre-dam topographic elevations from the current reservoir sediment surface elevations; the difference between the two surfaces is the estimated total amount of sediment that has accumulated behind the dam since construction.

The overall objectives of this study are:

(1) estimating the sediment accumulation rate within a set of reservoirs and predicting the remaining capacity of the reservoirs using SWAT, radionuclide, and bathymetric survey method;
(2) determining the natural sediment yield to evaluate the effect of human interference on the sediment yield;
(3) extrapolating the predicted current and natural sediment yields through this study on 12 reservoirs to other reservoirs across the Great Lakes basin.

This work includes the field studies and modeling for a suite of reservoirs across the Great Lakes watershed.

2. Study area description

The location of the 12 reservoirs selected for this study is shown in Fig. 1. The characteristic of these study dams and their associated reservoirs were retrieved from National Inventory Website (Table 1). For more information regarding the study dams refer to Appendix A. Among these watersheds, Ballville, Webber, Riley, Upper Green, and Independence watersheds are dominated by agriculture in their watershed, while forests cover more than 50% of Potter's Falls, Brown Bridge, Mio and Alcona watersheds. Fractions of Lake Rockwell and Ford Lake have some areas developed, with some forested and agricultural areas. The land use breakdown in the watersheds of the study area are given in Fig. 2. The land use data were taken from the National Land Cover Database (Homer et al., 2007), and the weather data were retrieved from USDA Agricultural Research website (Table 2).

The United States Geological Survey operates several gages within the study area watersheds. The SWAT models were calibrated with the recorded mean monthly stream and suspended sediment discharge data obtained from gages. Data given in the Appendix B display each study watershed and the location of each gage and the graphs in the Appendix C show the measured peak stream discharge. In four dams (Ballville, Lake Rockwell, Potters' Falls and Independence), both suspended sediment and water discharge are available while in other reservoirs, only stream discharge data is available.

3. Materials and methods

3.1. SWAT model Setup and input data

The SWAT model inputs include soil type, a digital elevation map (DEM), land use, and weather data. Soil data were obtained from the Soil Survey Geographic Database (SSURGO) (Schwarz and Alexander, 2004), Digital Elevation Model (DEM) from the USGS National Elevation Dataset. Land use data were from the 2001 version of the National Land Cover Database (NLCD) (Homer et al., 2007). The weather data including precipitation, temperature, solar radiation, wind speed, and humidity were compiled by the USDA, ARS. The input data were overlapped to parametrize SWAT models. For calculation purpose, SWAT model divides a watershed into smaller sub-basins, and each sub-basin to smaller units called Hydrologic Response Units (HRUs). SWAT uses the Modified Universal Soil Loss Equation (MUSLE) to predict the erosion caused by rainfall and runoff. SWAT also keeps track of the sediment particle distribution from the landscape and routs them through channels and water bodies. Depending on the stream power and the composition of banks and bed sediment degradation or deposition can happen in the channel. In this study the Simplified Bagnold Equation was used for modeling sediment transport. This method assumes all sediment particles through the channel are silt and does not keep track of particle size. The Simplified Bagnold approach does not partition the channel erosion between stream bank bed, and this method assume the deposition only occurs in the main channel.

The SWAT models of Lake Rockwell and Ballville Dam were previously calibrated with SWAT-CUP tool to the recorded suspended sediment load and stream discharge (Alighalehbabakhani et al., 2017). In the current paper, the calibrating process of the remaining watersheds will be discussed. Among the uncalibrated watersheds, only Independence and Potter's Falls watersheds have recorded suspended sediment data for calibrating the SWAT models. Before calibrating the model to the sediment component, the models were hydrologically calibrated and validated (Appendix D shows the hydrology calibration curves for the study watershed). Potter's Falls and Independence models were calibrated to the mean monthly suspended sediment load using Gage 04233300 and 04193500, respectively. Collecting the bedload data from the study watersheds are outside of this study scope. Because of spatial and temporal variability with sediment transport, collecting and measuring the accurate bedload samples have always been difficult, time-consuming, and expensive (Diplas et al., 2008). In the Great Lakes basins the bedload material is small portion of the total sediment load; for the Sandusky and Cuyahoga rivers the bedload is less than 5% of total sediment load (Hindall, 1991). Therefore neglecting the bed load cannot change the model results considerably.

A comparison of the observed and simulated mean monthly stream discharge for calibration and validation period are listed in Table 3, indicating a successful calibrating and validating the mean stream discharge. However in the Mio and Alcona model at Gage 04137005 location (just downstream of Alcona Dam) for calibration and validation runs, NSE values were estimated to be 0.37 and 0.22, respectively. In general, the Mio and Alcona model underpredicts the flow during relatively dry periods, particularly downstream of the Mio Dam. This is likely because of the sandy

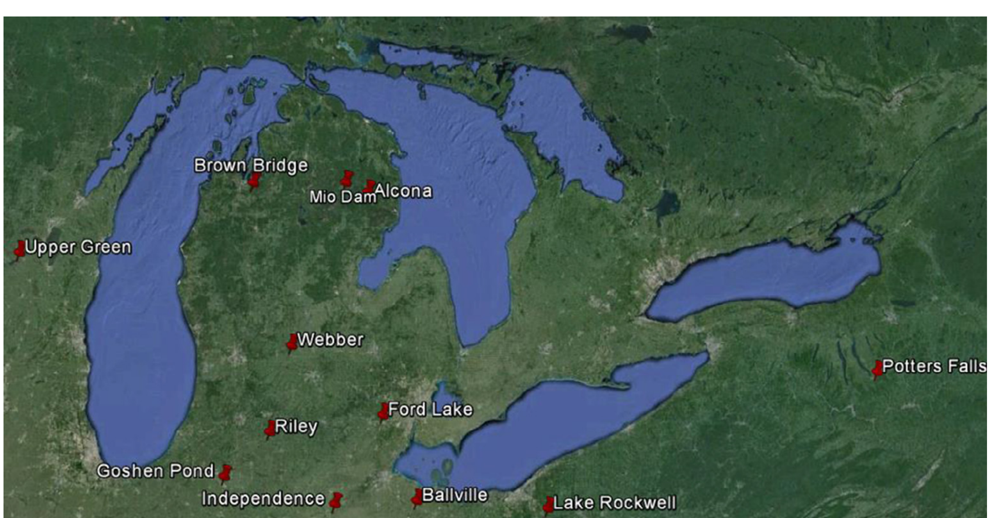

Fig. 1. Map of all selected reservoir sites.

Table 1
Physical data of dams and reservoirs studied (Data provided from the National Inventory of Dams website; http://nid.usace.army.mil).

Dam Name	Abbreviation	NID storage (m^3)	Drainage area (km^2)	Surface area (ha)	Dam height (m)	Year complete
Ballville	BV	2.96 E + 06	3.25 E + 03	3.60 E + 01	1.05 E + 01	1911
Webber	WB	7.40 E + 06	4.53 E + 03	2.70 E + 02	8.80 E + 00	1907
Riley	RI	6.67 E + 06	1.35 E + 03	2.10 E + 02	5.20 E + 00	1923
Upper Green	UG	4.94 E + 07	3.00 E + 02	2.97 E + 03	1.50 E + 00	1869
Goshen Pond	GP	3.82 E + 06	1.53 E + 03	4.90 E + 01	4.90 E + 00	1868
Rockwell	RW	2.25 E + 07	5.40 E + 02	3.30 E + 02	1.07 E + 01	1913
Ford Lake	FL	2.22 E + 07	2.11 E + 03	4.00 E + 02	1.04 E + 01	1932
Potter's Falls	PF	1.59 E + 06	1.20 E + 02	1.90 E + 01	2.29 E + 01	1911
Brown Bridge	BB	3.45 E + 06	3.90 E + 02	7.70 E + 01	1.40 E + 01	1921
Mio	MI	1.48 E + 07	2.85 E + 03	3.50 E + 02	1.16 E + 01	1917
Alcona	AL	3.08 E + 07	3.80 E + 03	4.30 E + 02	1.83 E + 01	1924
Independence	IN	4.03 E + 06	1.44 E + 04	2.20 E + 02	3.70 E + 00	1924

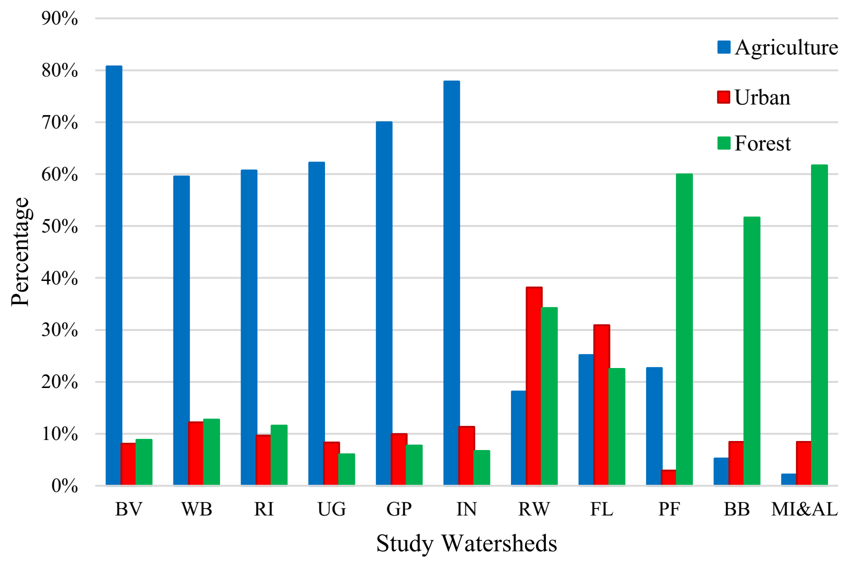

Fig. 2. Primary land use in study dam watersheds (data was provided from National Land Cover Database).

Table 2
Annual average weather data for watersheds studied (Data provided from USDA Agricultural Research website; https://www.ars.usda.gov/).

Dam name	Precipitation (mm)	Snow fall (mm)	Snow melt (mm)	Evapotranspiration (mm)	Potential evapotranspiration (mm)
Ballville	9.35 E + 02	1.00 E + 02	1.00 E + 02	5.46 E + 02	9.78 E + 02
Webber	8.43 E + 02	1.19 E + 02	1.21 E + 02	5.52 E + 02	9.26 E + 02
Riley	9.27 E + 02	1.29 E + 02	1.27 E + 02	5.48 E + 02	9.07 E + 02
Upper Green	7.73 E + 02	8.06 E + 01	8.50 E + 01	6.15 E + 02	1.02 E + 03
Goshen Pond	9.63 E + 02	1.08 E + 02	9.40 E + 01	5.17 E + 02	8.80 E + 02
Rockwell	1.07 E + 03	1.36 E + 02	1.35 E + 02	5.82 E + 02	9.03 E + 02
Ford Lake	7.97 E + 02	1.08 E + 02	1.10 E + 02	5.76 E + 02	9.79 E + 02
Potter's Falls	9.96 E + 02	1.60 E + 02	1.50 E + 02	4.98 E + 02	8.08 E + 02
Brown Bridge	8.16 E + 02	1.67 E + 02	1.63 E + 02	5.00 E + 02	7.11 E + 02
Mio and Alcona	8.26 E + 02	1.80 E + 02	1.72 E + 02	4.93 E + 02	6.88 E + 02
Independence	8.57 E + 02	6.30 E + 01	9.00 E + 01	6.11 E + 02	1.36 E + 03

soils in this watershed, and the relatively high proportion of base flow (during dry months, the volume of groundwater feeding the Au Sable River can be larger than surface water discharge to the river). The current version of the SWAT model does not have the capability to simulate interbasin transfers of groundwater.

The statistics comparing the observed and simulated mean suspended sediment load for calibration and validation periods are given in Table 4. The Independence model was calibrated to the mean suspended sediment load at Gage 04193500, the R^2 and NSE values are 0.53 for calibration and 0.55 for validation simulation, respectively which are acceptable. The Potter's Falls model was calibrated and validated to the mean suspended sediment load at Gage 04233300. Table 4 shows the p-factor, r-factor, R^2, and NSE that are in the acceptable range for the calibration run of Potter's Falls Model. For the validation period, p-factor and r-factors are acceptable, while R^2 and NSE are less than 0.50. The calibrated parameters of Potter's Falls, and Independence Dam, and their final values are given in Table 5.

Some of the reservoirs and corresponding watersheds undertook in this study do not have enough suspended sediment load data for calibrating and validating their models. These watersheds are Webber, Riley, Upper Green, Goshen Pond, Ford Lake, Brown Bridge, and Mio and Alcona (these two last dams are in one SWAT model) dams. For the calibration purpose, all eleven watershed are

Table 3
Hydrologic calibration and validation parameters at Gages in the studied watersheds. The R^2 is the coefficient of determination and NSE is the Nash-Sutcliffe simulation efficiency.

Study watersheds	Gage	Calibration			Validation		
		R^2	NSE	Description	R^2	NSE	Description
Webber	04116000	0.84	0.83	Good	0.85	0.82	Good
	04114000	0.83	0.77	Good	0.82	0.78	Good
	04113000	0.80	0.76	Good	0.81	0.77	Good
Riley	04096405	0.71	0.59	Satisfactory	0.80	0.71	Good
Upper Green	04030201	0.60	0.60	Satisfactory	0.85	0.85	Good
Goshen	04100500	0.79	0.73	Good	0.77	0.58	Satisfactory
Ford Lake	04174500	0.71	0.54	Satisfactory	0.77	0.54	Satisfactory
Potter's Falls	04233300	0.77	0.76	Good	0.65	0.55	Satisfactory
Brown Bridge	04126970	0.79	0.47	Satisfactory	0.60	0.56	Satisfactory
Mio & Alcona	04136500	0.68	0.55	Satisfactory	0.87	0.71	Good
	04137005	0.63	0.37	Unsatisfactory	0.78	0.22	Unsatisfactory
Independence	04193500	0.85	0.78	Good	0.87	0.79	Good
	04192500	0.83	0.79	Good	0.85	0.79	Good

Table 4
Sediment calibration and validation parameters at Gages within the watersheds studied.

Study Watersheds	Gage	Runs	p-factor	r-factor	R^2	NSE	Description
Potter's Falls	04233300	Calibration	0.76	1.19	0.59	0.59	Satisfactory
		Validation	0.61	0.79	0.14	0.12	Satisfactory
Independence	04193500	Calibration	N/A	N/A	0.53	0.53	Satisfactory
		Validation	N/A	N/A	0.55	0.55	Satisfactory

p factor: percentage of observation of the total data.
r-factor: thickness of the 95PPU region divided by the standard deviation of the observed data.
R^2: coefficient of determination.
NSE: Nash-Sutcliffe simulation efficiency.

Table 5a
Calibrated parameters and their final value for Potter's Falls model.

Parameter	Table	Description	Method	Value used
HRU_SLP	.bsn	Average slope steepness (m/m)	Replace	0.01–0.08
USLE_P	.mgt	USLE equation support practice	Replace	0.80–1.00
USLE_K	.sol	USLE equation soil erodibility factor	Replace	0.29–0.32
SOL_ROCK	.sol	Percent rock in soil layer (%)	Replace	24.5–33.5
ADJ_PKR	.bsn	Peak rate adjustment factor	Replace	0.56–0.85
SFTMP	.bsn	Mean air temperature (°C)	Replace	1.43
SMTMP	.bsn	Threshold temperature for snow melt (°C)	Replace	5.46
SOL_K	.sol	Saturated hydraulic conductivity (mm/hr.)	Replace	456.20
GW_DELAY	.gw	Delay time for aquifer recharge (days)	Replace	8.67
SLSUBBSN	.hru	Average slope length (m)	Replace	91.95
GW_REVAP	.gw	Groundwater "revap" coefficient	Replace	0.09

Table 5b
Calibrated parameters and their final values for Independence model.

Parameter	Table	Description	Method	Value used
RES_SED	.rsv	Initial sediment concentration in reservoir (mg/l)	Replace	1.13 E + 3
RES_NSED	.rsv	Normal sediment concentration in reservoir (mg/l)	Replace	1.13 E + 3
RES_D50	.rsv	Mean particle diameter of incoming sediment (μm)	Replace	41
NDTARGR	.rsv	Number of days to reach target storage (days)	Replace	2
GW_DELAY	.gw	Groundwater delay (days)	Replace	6.5
ALPHA_BF	.gw	Base flow alpha factor (days)	Replace	0.30
CN2	.mgt	SCS runoff curve number	Relative	0.05

classified into one of three groups based on the land use, climate data, soil characteristic, and slope of each. Within each group, there is at least one gaged watershed. The calibrated parameters (Table 5) of the gaged watershed have been applied for calibrating the un-gaged watersheds which are in the same group. Land use breakdown within the study watersheds is given in Fig. 2. Ballville, Independence, Goshen Pond, Upper Green, Riley, and Webber Dam are agriculturally dominated watersheds, while forests cover most of the watershed areas in Potter's Falls, Brown Bridge, Mio, and Alcona. Ford Lake and Rockwell Dam which have similar land use characteristics are in one group. The study watersheds in each group is similar regarding weather data (precipitation, snowfall, snowmelt, and evapotranspiration). As listed in Table 2, the differences between weather data in the un-gaged watersheds with the teammate gaged watershed are less than 15%, except Ford Lake watershed in which the precipitation is 26% less than the Rockwell watershed. The soil characteristics of each study watershed are similar, except Brown Bridge, Mio and Alcona watersheds where the soil is sandy, and the soil erodibility factor is low in comparison to the Potter's Falls watershed. Therefore for calibrating the Brown Bridge, Mio, and Alcona watersheds, none of the soil parameters of Potter's Falls were used. The calibrated parameters of Lake Rockwell Dam and Ballville Dam, and their final values have been previously discussed (Alighalehbabakhani et al., 2017).

3.2. Radionuclide method

^{210}Pb activities were determined by alpha spectrometry from the measured activity of ^{210}Po, assuming that ^{210}Po and ^{210}Pb were in radioactive equilibrium. An aliquot of 1.5–2.0 g of dried and pulverized sediment core sample was taken in 120 ml PFA (Savillex) digestion vessel. To the dried sediment sample, 0.75 ml of ^{209}Po spike (6.04 ± 0.02 dpm/ml) was added as an internal tracer. To the mixture, 10 ml each of concentrated HF, HNO_3, and HCl was added, and the sample was digested for 24 h at 90 °C. After the digestion is complete, the digested solution was dried on a hot plate and added 5 ml 6 M HCl and dried twice. Finally, the residue was taken in 10 ml 6 M HCl and diluted with 40 ml distilled water. The pH was adjusted to ~2.0 by adding ammonium hydroxide. Iron and other oxidants were reduced by the addition of ~0.5 g ascorbic acid. Polonium was plated by spontaneous deposition onto silver planchet and was analyzed by an alpha spectrometer with a surface barrier detector coupled to an octete-PC (ORTEC Co.).

For the measurement of gamma-emitting radionuclides, ~10–15 g of dried pulverized sediments was packed into ten mL counting vials and assayed. The activities of ^{226}Ra and ^{137}Cs were measured using a high-purity germanium well detector coupled to a Canberra InSpector multi-channel analyzer. There was no peak background for any of the radionuclides analyzed. The gamma ray detector was calibrated with sediment standards [IAEA-300 for ^{137}Cs (661.6 keV) and RGU-1 for ^{226}Ra (via ^{214}Pb and ^{214}Bi at 352 keV and 609 keV, respectively)] obtained from the International Atomic Energy Agency (IAEA). Typical resolution (full-width at half-maximum) was about ~1.3 keV at 46 keV and ~2.2 keV at 1.33 MeV (Jweda and Baskaran, 2011; Baskaran et al., 2015). Details on the data analysis for obtaining linear sedimentation rate and mass accumulation rate, determination of porosity and calculations of mass depth are given in (Baskaran et al., 2016; Kumar et al., 2016).

3.3. Bathymetric survey

Another technique which was used for estimating the sediment accumulation rate within several of the study reservoirs was subtraction of the pre-reservoir topographic elevations from current bathymetry. This technique was not applied for all reservoirs since some reservoirs do not have a historical topographic map of the river valley prior to dam construction. Some reservoirs including the Upper Green, Lake Rockwell, Potter's Falls, and Mio were mapped in 2010 using the Son Tek M9 river surveyor. The data from each reservoir were extracted from the river surveyor software using MATLAB software and imported into Microsoft Excel. The elevation of the water surface was collected from the dam owner on the day of the bathymetric survey was incorporated into the excel file to yield reservoir sediment surface elevations. Both historical topographic elevations and current sediment surface elevations were imported into ArcGIS, and then the two surfaces were subtracted using the Tin Difference tool in ArcMap 9.3. In the final step, the total volume of the deposited sediment converted to accumulated dry mass, and furthermore into the accumulated dry mass rate by dividing the results by the number of years between dam construction and the date of the bathymetric survey.

The bathymetric survey approach was also applied to Ballville reservoir by Evans et al. (2002). They created the 1993 bathymetric map by digitizing field data from Ohio Geological Survey; then the 1993 data were compared with 1911 historical map to estimate sediment trapping rate.

4. Results and discussion

The SWAT models of some watersheds including, Ballville, Webber, Riley, Upper Green, Goshen Pond, Lake Rockwell, Ford Lake, Potter's Falls, Brown Bridge, Mio, and Alcona dams were developed to estimate sediment accumulation rate within these man-made reservoirs. Ballville (Alighalehbabakhani et al., 2017), Lake Rockwell (Alighalehbabakhani et al., 2017), Potter's Falls, and Independence watersheds were calibrated with the mean monthly flow and the suspended sediment load recorded in the gages located within the watersheds. For calibrating watersheds with no sediment gages, calibrated sediment parameters of other watersheds which are similar in terms of land use, climate, topography, and soil characteristic were applied.

A SWAT analysis was completed to determine the sediment inflows and outflows in each study reservoir. The difference between these loads provides an estimation of the potential sediment accumulation rate within the reservoirs. The predicted sediment accumulation rates by SWAT for each reservoir except Lake Rockwell and Ballville reservoirs are shown in Fig. 3. As the graphs indicate, the sediment accumulation rate is changing over time for each reservoir. In some reservoirs, the sediment accumulation rate is fluctuating widely, while some others such as Potter's Falls, the sediment accumulation shows little variation over time.

The average of sediment accumulation rate within the study watersheds predicted by SWAT, radionuclide dating, and bathymetric survey are compared in Table 6. In each cell that represents the SWAT results there are three numbers; left and right numbers represent the minimum and the maximum of M95PPU in the simulation period, respectively and the number in the parenthesis shows the average of M95PPU data in the simulation period. For some reservoirs, the sediment accumulation rates examined by radionuclide dating and bathymetry survey fit very well with the predicted sediment accumulation rate region (95PPU) by SWAT; these reservoirs include Webber, Riley, Goshen Pond, Potter's Falls, Brown Bridge, Mio, and Alcona. However, for Upper Green reservoir both the bathymetric and radionuclide dating approaches predicted larger sediment accumulation than the SWAT model simulation. For the Ford Lake model, the radionuclide dating result is within the lower boundary of SWAT estimates. The reason for the differences between these three approaches is likely due to the assumptions and limitations associated with each approach. these include SWAT model assumptions which were explained in Section 3.1. There are some assumptions with radionuclide and bathymetric survey methods such as sediment particle size and bulk density and reservoir geometry. As Table 6 shows SWAT covers a wide range for the sediment accumulation rate estimation, while radionuclide and bathymetric approaches can provide an average sediment accumulation rate. SWAT can capture the uncertainty in the sediment models. SWAT predicts the higher sediment accumulation rate than two other methods (bathymetric and Radionuclide) except for the Upper Green and Goshen Pond watershed. However, in all cases the sediment predicted by the bathymetric and radionuclide methods were in the SWAT ranges. Among the study reservoirs, the Independence reservoir has the highest sediment accumulation rate and the Goshen Pond has the lowest rate. The high level of sediment inflow and the trapping efficiency can result in high sediment accumulation rate. However, in the Independence reservoir high level of sediment inflow can results in high sediment accumulation rate.

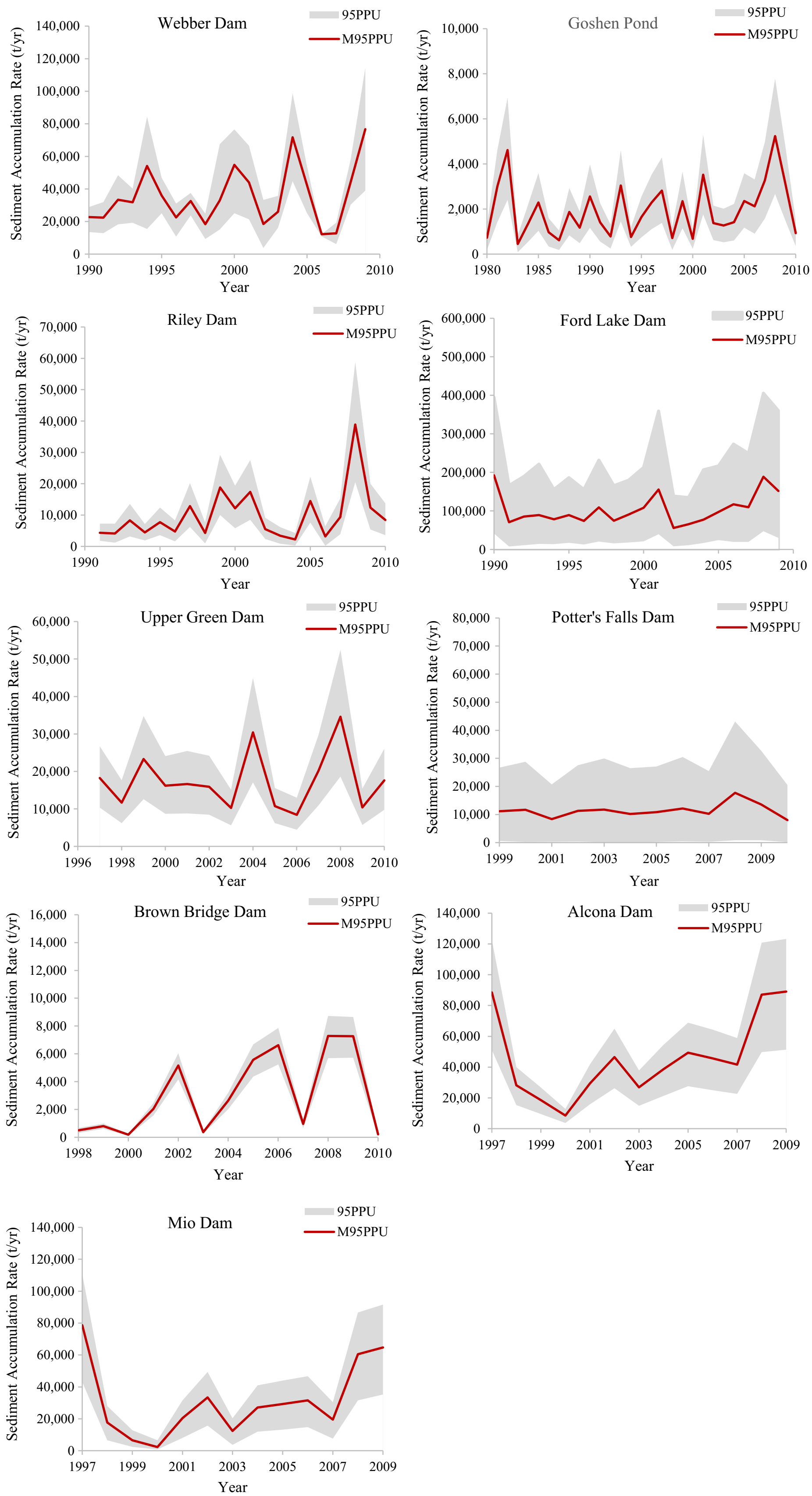

Fig. 3. Sediment accumulation rate within the reservoirs studied. The SWATCUP output is a propagation of the uncertainties in the parameters which is explained as the 95% probability distribution (95PPU) calculated at the 2.5% and 97.5% of the cumulative distribution of output. The lower (L95PPU) and upper (U95PPU) boundaries of 95PPU correspond to 2.5% and 97.5% probability, respectively. M95PPU corresponds to 50% probability.

Table 6
Inter-comparison of sediment accumulation rate in the reservoirs studied (10^3 t/yr).

Method	Webber	Riley	Upper green	Goshen pond	Ford lake	Potter's Falls	Brown bridge	Mio	Alcona	Independence
Bathymetric	N/A	N/A	80	N/A	N/A	12	N/A	17	N/A	N/A
Radionuclide	16	4	47	3	7	N/A	2	5	10	N/A
SWAT L95PPU*	4–45 (19)	0.2–20 (4)	4–18 (10)	0.1–3 (1)	8–47 (20)	0.1–0.8 (0.30)	0.1–6 (2)	1–43 (15)	4–51 (23)	N/A
SWAT M95PPU*	12–77 (35)	2–39 (10)	8–35 (17)	0.5–5 (2)	56–192 (104)	7–16 (10)	0.2–7 (3)	2–79 (31)	8–89 (46)	373–1093 (697)
SWAT U95PPU*	12–114 (50)	4–59 (16)	13–52 (26)	1–8 (3)	122–368 (209)	18–38 (25)	0.2–9 (4)	6–110 (46)	13–123 (64)	N/A
TE (SWAT Output)	23%	61%	93%	55%	78%	64%	71%	66%	73%	38%

* The results for SWAT simulations are displayed as Min-Max (Ave).

Prior to European settlement, the Great Lakes basin was heavily forested; however, with European settlement during the early 1800's, many forests were cleared for field crops and agricultural activities. Human activities including agricultural and construction practices, deforestation, and urbanization have altered the sediment yield and sediment delivery within Great Lakes watersheds (Mann et al., 2013). Since 1800's the human activities, have increased sediment yield, while dam construction has captured sediment load, resulting in a decrease of sediment delivery within watersheds containing dams and reservoirs (Syvitski et al., 2005).

In the present work, SWAT models were applied to evaluate the anthropogenic impacts on sediment yield across the Great Lakes basin. For estimating the natural sediment delivery in each of the study watersheds, the following changes were made to the calibrated SWAT models (baseline models). Natural vegetation land use for the state of Michigan (DTMB, 2002), Ohio (Ohio Department of Natural Resources, 2003), Wisconsin (Wisconsin Department of Natural Resources, 2006), and New York (Ellis et al., 2010) have been applied in the baseline SWAT models to characterize the pre-European settlement watersheds. All existing dams were removed from the SWAT models to allow sediment load to be delivered to the downstream reaches of the river. This research does not evaluate the effect of climate change, so it was assumed that the same climatic conditions existed for the natural sediment yield scenario and same climatic parameters as the pre-European settlement scenario were applied in the models. This study does not directly predict what the natural sediment delivery rates would be, while this method determined the sediment delivery rate that would have existed today if the European settlers did not alter the Great Lakes basin. Fig. 4 displays the pre-European land use breakdown within the study watersheds. The study watersheds were significantly covered by forest, except Ford Lake and Upper Green Lake watersheds. About 32% of Ford Lake and 28% of Upper Green Lake watersheds consisted of rangeland. The increased factors of sediment yield at individual dam locations (just upstream and downstream of the dam), and outlet of the study watersheds since European settlement are given in Table 7. As expected, review of Table 7 reveals that the sediment yield has increased since pre-European settlement within the study watersheds. Upstream of the dam, the increased factors of sediment yield were significantly higher than downstream of the dam. The reason for such a change is due to sediment trapping within the reservoirs. For those dams with higher trapping efficiencies, the percentage increase of sediment yields at upstream of the dam is considerably higher than downstream of the dam. For instance, in Upper Green Lake reservoir which has a 98% trapping efficiency, sediment yield has increased by a factor of 52 and four just upstream and downstream of the reservoir, respectively. The sediment yield changes both upstream and downstream of the Ballville reservoir with 12% trapping efficiency, are very similar.

Among the study watersheds, Ford Lake and Goshen Pond watersheds have the smallest change of sediment yield at the upstream of the reservoirs. While Independence watershed has the highest change of sediment yield since pre-European settlement. Prior to European settlement, the Independence watershed was significantly covered by forest; however, since 1800's, some parts of the forests were removed and agricultural land increased to 78%. Before European settlement, forest and rangeland covered 51% and 32% of Ford Lake watershed, respectively. The rangeland in the pre-European scenario induced sediment yield within Ford Lake watershed.

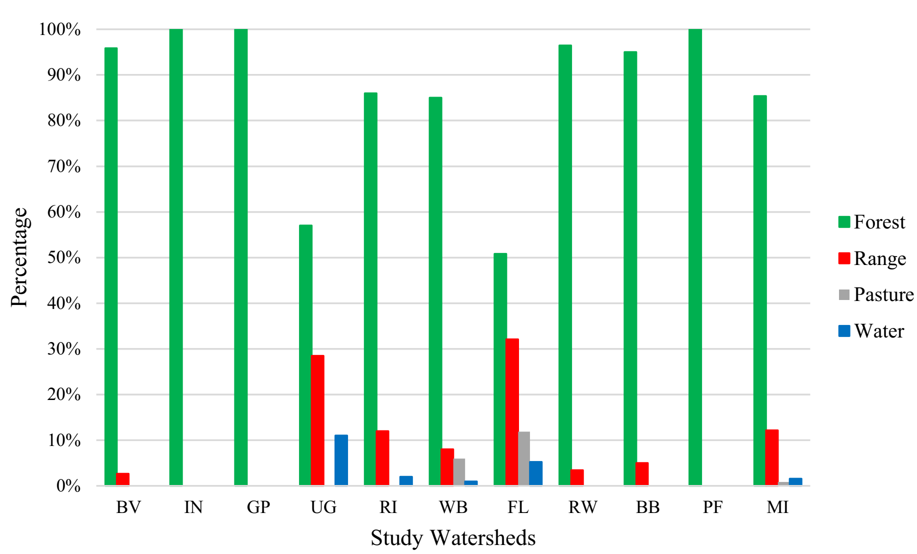

Fig. 4. Primary land use in study watersheds.

Table 7
Comparison of sediment yields under pre- and post-European scenarios.

Study watershed	The increased factor of sediment yield since European settlement			Dam density at upstream of study reservoir (1/ha)
	Just U/S of Dam	Just D/S of Dam	Watershed outlet	
Ballville	9	8	8	
Webber	11	9	24	0.13
Riley	29	12	12	0.15
Upper Green	52	4	4	
Goshen Pond	3	2	2	0.27
Independence	161	103	66	0.02
Rockwell	23	4	2	
Ford Lake	2	0.4	0.4	0.1
Potter's Falls	107	39	39	
Brown Bridge	10	2	2	
Mio& Alcona	–		3	0.03

Forest covered the vast majority of the Goshen Pond watershed, and with European settlers, this forest was cut down, and farmland expanded throughout the watershed. The sediment yield increased by a factor of three within Goshen Pond watersheds, which is due to a combination of the impact of land use change and dam construction. Because the dam density in this specific watershed is higher among the watersheds investigated in this study, a considerable amount of sediment load was captured by the upstream reservoirs.

To extrapolate results of this study across the Great Lakes basin, regression analyses were done on the current and natural sediment delivery. The regression analysis indicates a strong correlation between sediment yield and drainage area. In this study the number of observation data (the number of the reservoirs) is not large enough to capture the importance of other independent variables such as soil erodibility factor, relief factor, land use, and the reservoirs density on the sediment yield. Figs. 5 and 6 display the current and natural sediment yield versus the drainage area, respectively. The R^2 which represents how close the data are to the regression line is 0.55 and 0.56 in Figs. 5 and 6, respectively. For the sediment studies with high level of uncertainty in the model, observation data, and parameters the R^2 of the 0.55 is good enough. With the knowledge of drainage area of a watershed in the Great Lakes basin and applying the mathematical models which were developed in the present study, the current and pre-European settlement (natural) sediment delivery into the Great Lakes were estimated. The natural and current sediment delivery into the Great Lakes is summarized in Table 8.

Forecasting the remaining storage capacity is the overall goal of the present research. The following equation can estimate the volume of accumulated sediment within the reservoirs.

$$Vs = \frac{Q_s}{\gamma_s} \times n \quad (1)$$

where

V_s = Volume of settled sediment (m^3)
Q_s = Sediment accumulation rate (kg/yr)
γ_s = Bulk density of accumulated sediment (kg/m^3)
n = Reservoir age (yr)

The average sediment accumulation rate estimated by SWAT was plotted into the Eq. (1) to determine the volume of accumulated sediment. In SWAT, the transported sediment particle size is assumed to remain constant, and in all cases, the grain size corresponds to silt-sized (0.002–0.05 mm diameter particles) (Neitsch, et al., 2011). In this study the effects of dam overtopping and reservoirs dredging have not been evaluated. Since the study reservoirs are rarely dredged unless it is critical to the operation of the reservoir or there is contaminated sediment that requires removal. All study reservoirs are assumed to be continuously submerged, and the initial bulk density of sediment particle to be 1120 (kg/m^3) (Morris et al., 2008). The accumulated sediment may compact and consolidate for decades in a reservoir; Eq. (2) is used to calculate the sediment compaction over time (Lane and Koelzer, 1943).

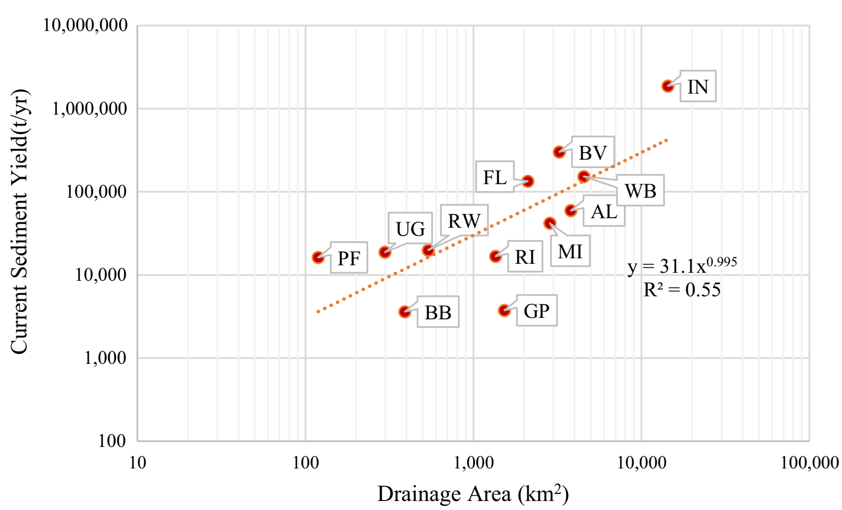

Fig. 5. Current sediment yield versus drainage area.

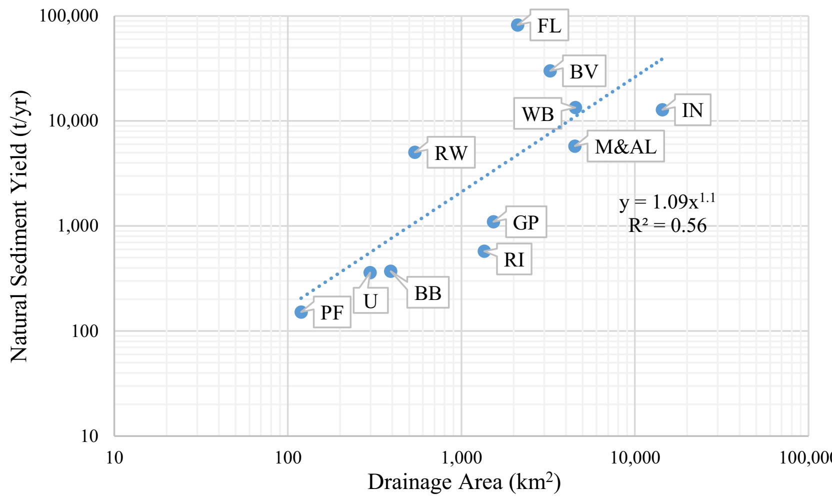

Fig. 6. Natural sediment yield versus drainage area.

Table 8
Natural and current sediment delivery into the Great Lakes from US side subwatersheds.

Lake name	Area, A (km^2)	Natural sediment yield, Qs (t/yr) Qs = 1.09 $A^{1.100}$ R^2 = 0.56	Current sediment yield, Qs (t/yr) Qs = 31.10 $A^{0.995}$ R^2 = 0.55
Superior	4.96 E + 04	1.52 E + 05	1.46 E + 06
Michigan	1.16 E + 05	3.86 E + 05	3.41 E + 06
Huron	4.11 E + 04	1.24 E + 05	1.21 E + 06
St. Clair	9.62 E + 04	2.52 E + 04	2.86 E + 05
Erie	4.63 E + 04	1.42 E + 05	1.36 E + 06
Ontario	7.52 E + 04	2.40 E + 05	2.21 E + 06

Table 9
Volume of accumulated sediment within the reservoirs.

Dam	Accumulation rate (t/yr)	Age (yr)	Bulk density (kg/m^3)	Present sediment volume (10^6 m^3)	Filled (%)	Remaining capacity (10^6 m^3)
Ballville	3.30 E + 04	105	1304	2.69	90	0.3
Webber	3.50 E + 04	109	1305	2.96	40	4.4
Riley	1.00 E + 04	93	1299	0.70	11	5.5
Upper Green	1.70 E + 04	147	1317	1.95	4.0	47.4
Goshen Pond	2.00 E + 03	148	1317	0.22	6.0	3.6
Rockwell	1.00 E + 05	103	1303	7.92	35	14.6
Ford Lake	1.04 E + 05	84	1295	6.75	30	15.5
Potter's Falls	1.00 E + 04	105	1304	0.83	52	0.76
Brown Bridge	3.00 E + 03	95	1300	0.22	6.0	2.2
Mio	3.10 E + 04	99	1302	2.36	16	12.4
Alcona	4.60 E + 04	92	1299	3.26	11	27.6
Independence	6.97 E + 05	92	1299	49.41	Full	Full

$$W_t = W_1 + B \log t \quad (2)$$

W_t = Specific weight of deposited sediment at the age of t
W_1 = Initial weight at the end of the first year of consolidation
B = Adjustment constant for compaction which is 91 for silt size particle (Lane and Koelzer, 1943).

The factors used to estimate storage capacity, and remaining capacities are given in Table 9. The results show the Independence and Ballville reservoirs are either at or near capacity, while the other ten reservoirs range from 6% to 52% filled. With respect to the Ballville reservoir, Evans et al. (2002) assessed the sediment accumulation rate in this reservoir. Their bathymetry data suggested the Ballville reservoir had lost 78% storage capacity to the sedimentation over the interval of 1911–1993. Based on Evan et al's prediction, with assuming a constant rate of sediment accumulation rate for the Ballville reservoir from 1993 to present, the Ballville reservoir was expected to reach its capacity by 2016. This present study shows the Ballville reservoir has reached 90% in 2016 of its capacity, which is close to Evan et al's prediction.

5. Conclusion

SWAT models of twelve reservoirs across the Great Lakes watershed were developed to estimate sediment accumulation rate within the study reservoirs. Sediment accumulation rate was also obtained using radiometric methods (^{137}Cs and excess ^{210}Pb) and the bathymetry survey approach to compare these results with calibrated SWAT models. The SWAT model results show that the Independence reservoir has already filled to its capacity, and the

Ballville reservoir has reached to the 90% of its capacity. However, with respect to the other ten study reservoirs, the modeling suggests that sediment occupies less than 52% of the total sediment storage capacity.

Another aspect of this research is determining the natural (pre-European settlement) sediment yield using SWAT model. For this purpose, in baseline SWAT models, the current land use data was replaced with pre-European settlement land use data. The constructed dams were also removed from the SWAT model to allow for simulation of unimpeded rivers and sediment transport to downstream reaches. The natural and current sediment yield data obtained were compared just upstream of the dam, just downstream of the dam, and watershed outlet. For several study sites, the dam is located at the outlet of the watershed, so the watershed outlet and just downstream of the dam coincide. Comparison of the pre- and post-settlement simulations suggest that human interference has increased sediment yield for all reservoirs except downstream of Ford Lake reservoir. In this research, the combination of dam construction and land use change has been evaluated. In those watersheds with low dam density and considerable land use change post-settlement (from forest to agricultural), the simulated sediment yield increased much more significantly than other watersheds.

The regression analyses were done on the SWAT model outputs from these eleven watersheds and were used to predict the current and natural sediment yield in un-modeled watersheds across the Great Lakes basin. The regression analysis indicates a strong correlation between sediment yield and drainage area. The drainage area of Great Lakes was plotted into the regression models to estimate how much sediment load drains into the lakes. This calculation was used to estimate the anthropogenic component of sediment delivery to the Great Lakes.

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We are grateful to Dr. James E. Almendinger, senior scientist in St. Croix Watershed Research Station for his insight into SWAT modeling related to this work. This research project was funded by the Detroit District, US Army Corps of Engineers under contract No. W911XK-14-C-0023.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jhydrol.2017.10.052.

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