Journal of Hydrology 555 (2017) 926–937

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Forecasting the remaining reservoir capacity in the Laurentian Great Lakes watershed

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ARTICLE INFO

Article history:
Received 18 April 2017
Received in revised form 1 October 2017
Accepted 23 October 2017

Keywords:
Forecasting reservoir capacity
Sediment accumulation rate
Great Lakes basin
pre-European settlement
SWAT

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

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https://doi.org/10.1016/j.jhydrol.2017.10.052
0022-1694/

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.