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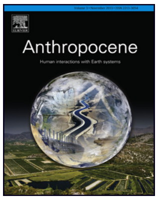

# Sediment budget approach to understanding historical stages of the Ottawa River in the context of land-use change, northwestern Ohio and southeastern Michigan, USA

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ABSTRACT

Many rivers in mid-continent North America are incised, cutting laterally into anthropogenic terraces, and having fluvial pavements. Treating these as “natural” rivers biases river restoration efforts. This study uses a sediment budget approach to evaluate anthropogenic change, based on stratigraphy (66 cores and 3 trenches), facies analysis (22 lithofacies), and geochronology (4 $^{14}$C dates, 6 OSL dates, and one date-stamped bottle). Five river stages can be discerned: (1) prior to ca. 5000 YBP, the river formed meandering point-bar sequences $\geq$1.5 m thick; (2) between ca. 5000 and 200 YBP, the river transported organic-rich sediment (“blackwater streams”) and was bordered by peat-forming riparian wetlands; (3) between ca. 200 YBP and the early-1960s the river transported mineral-rich sediment (“brownwater streams”), due to agricultural land clearance, which backfilled the previous riparian wetlands and produced an series of thin channel fills; (4) urbanization, starting in the early-1950s, resulted in sediment supply greatly exceeding sediment conveyance capacity, leading to 1.7 m vertical aggradation creating the fill-terrace morphology evident today; and (5) reduction in sediment inputs, starting in the 1980s due to no-till agriculture and revegetation of housing subdivision tracts, has produced bank erosion, tree fall, logjams, and degraded substrate with fluvial pavements. Stage 4 is interpreted as a time-specific (1950s–1980s) sediment pulse related to urbanization of the lower drainage basin, while the partly overlapping stage 5 is interpreted as fluvial reworking of intrabasinal storage (legacy sediment) under conditions of lower sediment input but higher water inputs (increasingly urbanized stormwater drainage networks). Regarding river restoration, the modern river is a recent and highly manipulated system that may not be sustainable.

## Introduction

A key concept of the anthropocene is that human activities or interactions cause changes to Earth–surface systems (Florsheim et al., 2013). This observation is particularly valid regarding human-caused, historical changes in river systems (Skalak et al., 2013). Efforts to mitigate human impacts on rivers has led to a >\$1 billion US year$^{-1}$ river restoration industry in the United States (Bernhardt et al., 2005), yet there remain critical misunderstandings about the goals of river restoration efforts. These misunderstandings could perhaps best be described as a disconnection between using relatively short-term projects to make changes in river systems that have changed (and continue to change) over long-term time intervals. Some of these misunderstandings could be resolved by evaluating the historical changes in a river system using sediment budgets.

A sediment budget, in conceptual form, is a mass balance equation accounting for sediment behavior as it transits through an Earth–surface system, such that:

$$\text{Inputs} = \text{Outputs} \pm \Delta\text{Storage} \tag{1}$$

For fluvial systems, inputs typically include soil erosion from upland sources, hillslope erosion produced by mass wasting processes, and bank erosion from channel proximal settings (in some cases, there may also be significant inputs from wind erosion or glacial processes). Outputs in fluvial systems are stream sediment loads (bedload, suspended load and dissolved load) which has also been called sediment yield (Leopold, 1956). Intrabasinal sediment

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storage reservoirs in fluvial systems may have three components: (1) colluvium (sediment storage in colluvial fans, rill/gully fill, or slope aprons), (2) alluvium (sediment storage on floodplains, in proximal channel elements such as alluvial ridges, in channel-fill deposits such as dunes and bars), and possibly (3) lacustrine sediment (in lakes and reservoirs). The movement of sediment from point-of-origin to point-of-exit from the drainage basin is referred to as sediment conveyance (Faulkner and McIntyre, 1996); while the ratio of sediment output (sediment yield) to sediment input (erosion) is called the sediment delivery ratio (Boyce, 1975; Walling, 1983). The accumulation of sediment in intrabasinal storage due to human impacts has been called "legacy sediment" (e.g., James, 2013).

As a strict accounting for the fate of sediment (typically measured as volumes of sediment), changes in any one of the various sediment budget components necessitate corresponding changes in one or several of the other components of Eq. (1). In North America, one obvious historical change was land clearance for agriculture following the arrival of European-American settlers. Studies indicate that deforestation of eastern North America during the late-1600s to late-1800s increased sediment yields by 2- to 100-fold, in comparison to pre-settlement conditions (Leopold, 1956; Ursic and Dendy, 1965; Wolman, 1967; Bormann et al., 1969; Meade, 1969; Davis, 1976; Webb, 2010; DeWet et al., 2011). Even greater effects, over smaller time and spatial intervals, have been linked to housing development construction sites and/or road construction sites (Fredricksen, 1965; Wolman and Schick, 1967; Judson, 1968; Soil Conservation Service, 1970). In contrast, recent historical changes in some watersheds, such as reductions in acreage farmed, reforestation, or improved soil conservation practices, have reduced sediment yields by as much as two orders of magnitude (Wolman, 1967; Davis, 1976; Trimble and Lund, 1982).

A question of interest is the cause-and-effect relationship between soil erosion (inputs) and sediment yield (outputs). Some studies have found short-term, matched responses between changes in land-use practices and sediment yields. Examples include a correlation between erosion from urbanized areas (measured as changing population density) and reservoir sedimentation rates (McCall et al., 1984; Gellis et al., 1996), or between erosion from agricultural fields (measured as changes in total acreage in production) and either stream sediment loads (Kuhnle et al., 1996) or reservoir sedimentation rates (Costa, 1975; Oldfield et al., 1980). Other studies have found more complex responses. In the Piedmont region of Maryland, high sediment yields were maintained even after the decline of agriculture post-1900 due to tributary incision and remobilization of intrabasinal sediment that had been stored since the early-1700s (Costa, 1975). In southeastern Pennsylvania, changes in sediment budgets have been attributed to construction of thousands of small mill dams, sediment storage in the infilled mill ponds (reservoirs), and release from storage following dam breaching (Walter and Merritts, 2008). In the Driftless Area of southwestern Wisconsin, sediment yields remained high from the mid-1940s to 1980s despite improved soil conservation practices (Knox, 1977, 1987; Trimble, 1981, 1983; Trimble and Lund, 1982). Such "persistent" sediment yields often result from changes in sediment source areas or in conveyance rates (i.e., remobilization of sediment from intrabasinal storage) that offset changes in land-use practices (Knox, 1987; Woltemade, 1994; Faulkner and McIntyre, 1996). In eastern Ohio, changes in reservoir sedimentation rates on the Chagrin River did not track changes in land-use (1840s–1990s) but did track the occurrence of historical floods (Evans et al., 2000). This "decoupling" of soil erosion rates from downstream sediment yield was attributed to the higher conveyance rates of major hydrologic events that remobilized sediment from intrabasinal storage.

This study originated from pre- and post-dam removal sedimentological and hydrological investigations on the Ottawa River in northwestern Ohio (Evans et al., 2013; Harris and Evans, 2014). The drawdown of the reservoir exhumed a peat horizon, which was later identified as the pre-settlement paleosol. This paleosol is now buried beneath 2.5 m of fluvial sediment that comprise matching "anthropogenic" terraces on each side of the modern channel. The goal of the project is to: (1) reconstruct the alluvial stratigraphy of the Ottawa River using sediment cores, trenches, and geochronology tools, (2) use facies analysis to reconstruct depositional environments, and evaluate the changes in sediment budgets implicit in this stratigraphy, (3) determine historical riverine stages in the context of changes in sediment budgets, as supported by historical data sets, and (4) discuss the implications of these findings with respect to river restoration efforts.

## Background

The Ottawa River forms a low-gradient, 446 km$^2$ watershed in northwestern Ohio and southeastern Michigan which flows into Lake Erie at Maumee Bay (Fig. 1). The watershed is highly urbanized within its lower reaches (from Lake Erie, or River Kilometer (RK) 0, up to RK18) within the City of Toledo, Ohio (2010 urban population of 287,208 people in an area of 218 km$^2$ or a population density of 1317 individuals/km$^2$). Further upstream (RK18 to RK40) the watershed is part of the outlying suburbs surrounding the City of Toledo (2010 greater metropolitan area population of 651,429 people in an area of 4193 km$^2$ or a population density of 155 individuals/km$^2$). Upstream of RK40 the watershed is predominantly used for agricultural (corn and soybean row crops) or for mixed use (pasture, parkland, or sand and gravel quarries) (Webb, 2010; Mannik-Smith Group, Inc., 2008; Gottgens et al., 2004; Gerwin, 2003). For the purpose of this paper, the watershed up to RK40 will be referred to as urban (making no distinction between urban and suburban).

Hydrologic data is available from USGS gage station #04177000 located at RK17.3 at the University of Toledo campus (Fig. 1). There are continuous stage-discharge records between 1945–1948 and 1977–present. Mean daily flow during this interval is 5.3 m$^3$ s$^{-1}$, and discharge for the 10, 25, 50, and 100 year floods are calculated as 91, 127, 170, and 219 m$^3$ s$^{-1}$ respectively (Harris and Evans, 2014). The Ottawa River is characterized by "flashy" discharges with relatively low base flows, high peak storm flows, and very short lag-to-peak (Evans and Harris, 2008; Harris and Evans, 2014). Similar behavior in other rivers in the region have been attributed to human activities such as draining wetlands, installing agricultural field tile drains, ditching, or channelizing tributaries (Baker et al., 2004). For the Ottawa River, flashy discharge responses to rainfall events are enhanced by the combination of agricultural impacts in the upper parts of the drainage basin and urbanization of the lower parts of the drainage basin (Evans et al., 2013).

The sediment rating curve (relationship of discharge versus suspended load) has remained relatively constant from the 1970s (Gallagher, 1978) to early 2000s (Harris and Evans, 2014) but the total sediment load has changed historically with a greater incidence of high discharge events. Bedload ranges from 10% to 35% of total sediment load. Short-term field bedload measurements document highly variable bedload transport rates ($Q_s$) ranging from essentially zero to $4.6 \times 10^{-6}$ m$^3$ s$^{-1}$ (Harris and Evans, 2014). The Ottawa River is an extension of Lake Erie until approximately RK8, with slopes approximately zero, and the channel substrate is dominantly silt and clay. Between approximately RK8 and RK26, the gradient of the Ottawa River is about $7 \times 10^{-4}$ m/m, and the channel substrates consist of moderately sorted, fine- to medium-grained sand that are armored with fine