Technical Memorandum

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Subject: Applying Lake Routing in the Prioritize, Target, and Measure Application (PTMApp)

Date: May 2, 2017

INTRODUCTION

The effect of lacustrine ecosystems on the fate and transport of sediments and nutrients is critically important in regions such as the Upper Midwest, where receding glaciers left great numbers of lakes and wetlands in their wake. Large wetlands, lakes, and reservoirs modify the fate and transport of suspended sediment, nitrogen, and phosphorus as biogeochemical processes including sedimentation and burial, bio-assimilation, and denitrification (specifically for nitrate-nitrogen) capture and reduce loads. Because of this impact, these waterbodies should be included in predictive modeling software practitioners use to prioritize and target water quality projects and programs.

This Technical Memorandum (TM) describes the theory applied and technical approach used within the Prioritize, Target, and Measure Application (PTMApp) to simulate the effect of large wetlands, lakes, and reservoir systems on suspended sediment, total phosphorus (TP), and total nitrogen (TN) loads. PTMApp is a tool used by local water resource practitioners to plan implementation for and estimate the impacts of Conservation Practices (CPs) on the landscape. The presence (or absence) of downstream lakes can affect the magnitude of pollutant loading from a particular field to the receiving waterbody; therefore, lake effects must be included in water quality models. For example, a large wetland or lake located between a field and a downstream impaired waterbody will alter the fate and transport of sediment and nutrients. If a CP was placed upstream of the lake, its effect would be dampened because pollutants retained by the CP would have been retained in the lake anyway. The inclusion of lake routing within water quality models (in this case PTMApp) generates outputs that allow users to better estimate existing watershed conditions and make appropriate decisions on where to best place CPs based on those existing conditions to maximize benefits to downstream waterbodies. Adding this feature to PTMApp also provides nutrient budget data for large wetlands, lakes, and reservoirs to facilitate the development of lake-specific implementation plans.

MODELING THEORY AND PROCESS

LAKE ROUTING[1] IN PTMAPP

Lakes are modeled in PTMApp through the inclusion of a lakes shapefile. A polygon representing each lake must be included in the shapefile for it to be modeled. This shapefile must include a distinct identifier (in numeric form through an integer) and a surface area (in acres) for each lake. The 'Build Lakes Data' tool populates other important morphometric information and pollutant removal efficiencies for each lake based on the methods shown in the following paragraphs.

For the purpose of this analysis, and within the dataset included in PTMApp's Base data, lakes were defined as having:

1) A surface area of 10 acres (4 hectares) or more;
2) An average depth no less than 3.3 feet (1 meter); and
3) Designation as a lake with the Minnesota Department of Natural Resources' (MNDNR) Public Waters Database

The lake dataset included in PTMApp's Base Data Geodatabase was downloaded from the MNDNR's Watershed Suite dataset and are the Level 9 Autocatchment Lakes. Only lakes fitting the above requirements were included in the PTMApp Base Data Geodatabase. The user must manually modify the shapefile to include other large wetlands, lakes, or reservoirs excluded from the MNDNR data.

The retention of sediment and nutrients in lakes is a function of several factors, including lake morphometry (specifically surface area, volume, and mean depth), hydraulic residence time, drainage area to the lake, local meteorology/climatology, trophic state, and the activity of aquatic floral and faunal communities (Kalff 2002; Harrison et al. 2009; Powers et al. 2013). Lake morphometry, residence time, drainage area, and local meteorology/climatology (via annual runoff) were each used explicitly to estimate pollutant removal efficiencies for lakes. Other environmental and biogeochemical factors are summarized implicitly in the settling velocity term applied to each pollutant.

To estimate the volume of water in each lake, regression analysis was performed using existing data for lakes across the State of Minnesota to determine a predictive relationship between lake surface area and volume. The MNDNR Lake Basin Morphology feature class (downloaded from the MN Geospatial Commons) includes lake information digitized from bathymetric maps and analyzed for other morphometric indices for 1,347 lakes throughout the state. Lake volume in each of these 1,347 lakes was calculated by multiplying the depth of water in each cell by the cell area and summing across all cells within the lake polygon. Applying a natural log transformation to compare lake surface area with volume for each lake yielded the following relation,

$$Ln\ (LV) = 1.149 * Ln(LSA) + 1.5711$$

Where,

$$LV = Lake\ Volume\ [acre - feet]$$

[1] Although termed "lake routing", this method is applicable to any large storage area including wetlands, lakes, or reservoirs, where an explicit understanding of the fate and transport of sediment and nutrients is desired.

$$LSA = Lake\ Surface\ Area\ [acres]$$

The log-transformation was applied to improve the fit of the regression ($R^2 = 0.82$; $P < 0.0001$ by ANOVA at a 5% significance level). Simplifying the equation yields,

$$LV = LSA^{1.149} * 4.812$$

This equation was used to determine lake volume for all lakes.

Mean lake depth (LD) was estimated by dividing lake volume (LV) by lake surface area (LSA),

$$LD = \frac{LV}{LSA}$$

Where LD is expressed in feet.

Lake hydraulic residence time is an important factor for estimating the net sedimentation term (for sediment and nutrients) in lakes as it essentially estimates the amount of time water (on average) remains within the waterbody before flowing out (Kalff 2002). Increased time within the lake increases the chances the particle drops out through sedimentation, is assimilated (in the case of nutrients), or is otherwise used within the lake system. Hydraulic residence time was defined as the lake volume divided by the rate of water entering the lake,

$$HRT = \frac{LV}{LI}$$

Where,

$$HRT = Hydraulic\ Residence\ Time\ [years]$$
$$LI = Lake\ Inflow\ [acre - feet/year]$$

For the purposes of this analysis, lake inflow (LI) was presumed to equal lake outflow. Although this assumption may not apply in all circumstances, it is likely accurate in most lakes where annual surface evapotranspiration is relatively modest compared to overall water input and lake volume (Kalff 2002). Conversely, the assumption may not hold for very shallow lakes and wetlands where annual surface evapotranspiration may be high as compared to water inflow and lake volume. Applying this assumption, LI could be estimated based on the lake's drainage area and the annual runoff that the drainage area received,

$$LI = LDA * AR$$

Where,

$$LDA = Lake\ Drainage\ Area\ [acres]$$
$$AR = Annual\ Runoff\ to\ the\ lake\ [feet/year]$$

The area draining to each lake was determined using the Watershed tool in GIS. The maximum flow accumulation cell in each lake polygon was assigned as the pour point of the polygon and the total number of cells flowing to that pour point was characterized as the lake's drainage area.

Annual runoff was estimated using the area weighted mean runoff from the US Geological Survey (USGS) gaging station data within HUC-8 watersheds and averaging those means over a 20-year (1995-2014) period (**Figure 1**; shown in inches/year). Therefore, each HUC-8 watershed had a single annual runoff value for all lakes contained within the watershed.

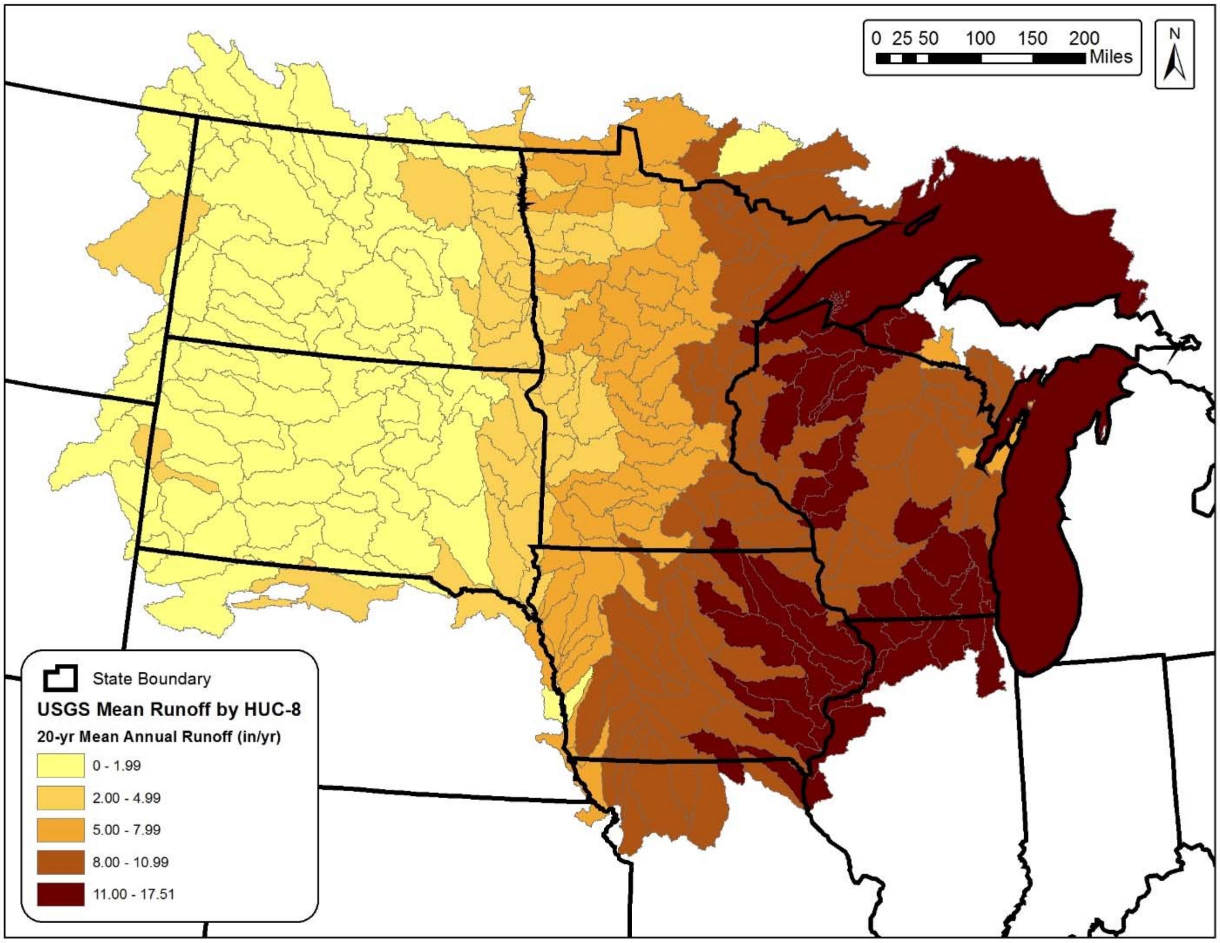

Figure 1: Mean annual runoff (inches/year) at outlets to hydrologic unit code 8 (HUC-8) watersheds as measured by US Geological Survey (USGS) gages. Runoff was averaged over a 20-year record from 1995-2014.

The sediment removal efficiency, or the net sedimentation of sediment (R_{TSS}), for each lake was estimated by the equation,

$$R_{Sed} = 1 - e^{\frac{-V_S * HRT}{LD}}$$

The nutrient removal efficiency, or the net sedimentation for nutrients (R_N,or R_{TP} for TP and R_{TN} for TN), was estimated following Harrison et al. 2009 as,

$$R_N = 1 - e^{\frac{-V_S}{H_l}}$$

Where,

$$H_I = Hydraulic\ Load\ [feet/year] = \frac{LI}{LSA}$$

V_S , the pollutant settling velocity, was estimated to be 10 feet/year for sediment, 8 feet/year for TP, and 5 feet/year for TN for lakes across Minnesota. Sediment and TP settling velocities were estimated from calibrated MN Soil and Water Assessment Tool (SWAT) models and other documentation (Arnold et al. 2009; Almedinger & Ulrich 2010; Three Rivers Park District 2011). The TN settling velocity was estimated from Harrison et al. (2009) and examples provided in Alexander et al. (2002) for a variety of lakes and reservoirs in the US and Canada.

LAKE ROUTING AND TREATMENT TRAINS

Sedimentation rates for sediment, TP, and TN in lakes was applied to upstream pollutant loadings using the treatment trains process. This process, in which CPs in sequence affect the performance of each other, often compounding and increasing treatment moving downstream, was outlined in a previous PTMApp TM (Deutschman et al. 2015). Annual load and yield estimates are summarized within PTMApp at the field or "catchment" scale.

One notable modification to treatment trains to accommodate lake routing addresses the problem that the contributing drainage areas to lakes is often much larger than PTMApp catchments, which average about 40 acres in size. Multiple catchments typically comprise the contributing drainage area to a lake. Treatment trains, as it applies to CPs, modifies the yield and loads at the catchment scale to account for the combined removal efficiency of sediment and nutrients from one or more CPs. As the drainage area to most lakes includes many catchments, the removal efficiencies for lakes were applied at the priority resource points only, and are not reflected in the catchment loading tables. The sediment and nutrient loads and yields delivered to a lake must be "back calculated" using the load delivered to the priority resource point representing the lake outlet and the estimated removal efficiency.

WETLANDS AND OTHER LENTIC SYSTEMS

The methods outlined in this TM exclusively estimate sediment, TP, and TN removal efficiencies for large wetland, lake, and reservoir ecosystems. Other lentic systems, such as small lakes (those not fitting the "lake" definition of greater than 10 acres in surface area and 1 meter in mean depth) and wetlands, can also alter the fate and transport of sediment and nutrients by retaining pollutants through sedimentation, assimilation, and a variety of other biogeochemical processes. Small wetlands can be especially effective at removing TN through denitrification. On the other hand, small wetlands can oftentimes be a source of nutrients and other particulates, and this is often driven by seasonal dynamics in the wetland and surrounding watershed. These systems can often be much more complex (in terms of nutrient cycling) than deep lacustrine systems, which makes it more difficult to generalize benefits base on the morphometric features of the waterbody. Therefore, small wetlands and lakes were not included with this analysis.

If removal efficiencies for a waterbody are known and the user wishes to include it when determining pollutant loads, morphometric and retention efficiency values for the waterbody can be input manually by the user and included when running PTMApp. More information on the process needed to add and model smaller waterbodies in PTMApp can be found in the user manual.

PRIORITY RESOURCE POINTS AND PROCESSING TIME

As sediment, TP, and TN removal efficiencies are resolved only at priority resource points (and not at the catchment-scale, as CPs are), the user must add a priority resource point at the outlet of each lake to determine the lake's impact on pollutant fate and transport. It is recommended that the user assign the lake's priority resource point as the highest flow accumulation cell in the lake polygon. This is recommended to (1) confirm the priority resource point is placed on the flow path moving through the lake and (2) to ensure that the sediment and nutrient removal efficiencies are applied to each cell within and draining to the lake.

The number of lakes included in the PTMApp input data should also be considered when determining the amount of time available to run any PTMApp model. As a lake-specific priority resource point is needed to estimate the impact of the lake on sediment, TP, and TN loading, each additional lake will very likely lead to an additional priority resource point. Adding additional points can greatly increase processing times because sediment, TP, and TN loading and CP load reduction must be resolved at each priority resource point. Therefore, a balance should be made between the number of lakes to include and the processing time available to the modeler for PTMApp to run. As PTMApp processing time can vary based on drainage area, grid size, and scale, it is impossible to generalize an amount of processing time per resource point.

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