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A STUDY OF FACTORS INFLUENCING THE SEDIMENT ACCUMULATION RATES IN STORMWATER MANAGEMENT PONDS

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ABSTRACT

Stormwater Management (SWM) ponds have been the most commonly used Best Management Practice (BMP) for controlling stormwater runoff in North America. The rate of accumulation of sediments and pollutants is uncertain, and highly dependant upon pond design, catchment characteristics and precipitation patterns. A wide range of sediment accumulation rates is reported in literature, ranging from 0.2 m^3/ha/year to 36.2 m^3/ha/year. Sediment removal from SWM ponds is costly and sometimes neglected by municipalities. Predicting the rate of accumulation, to aid municipalities in prioritizing their maintenance priorities and capital planning, relies on regular pond surveys. The long-term objective of the current project is to develop a data-driven modelling approach for forecasting of sediment accumulation rates in SWM ponds, based on data collected from a large number of surveyed ponds in Southern Ontario. This paper presents the methodology employed to collect the necessary information, consisting of 1) a literature review to determine the potential influencing factors, 2) a survey of relevant information availability in Ontario municipalities, 3) interviews with municipal staff, and 4) collection, organization and analyses of provided data. The results of analyses of collected information point to inconsistencies in availability and format of relevant data. A preliminary investigation of accumulation rates indicates lower values than those reported in similar studies in the past, although pointing to the same trend of decreasing performance of SWM ponds over time.

Keywords: Stormwater management ponds, sediment accumulation rates, detention ponds.

1. INTRODUCTION

Stormwater Management (SWM) in North America has evolved over the last several decades to include a number of Best Management Practices (BMPs) that reduce downstream impacts of runoff. The most commonly used BMPs in urban areas have been SWM ponds, designed to achieve one or more of objectives, including the minimization of downstream flooding and erosion, and minimization of pollutant discharges. Thousands of wet retention ponds, which feature a permanent pool in which the pollutants are removed through settling, have been constructed using a multitude of guidance documents. The remainder of this section presents a review of guidance recommendations for accumulated sediment removal, reported accumulation rates and factors influencing the accumulation rates reported in literature, and states the objectives of this research.

The performance of SWM ponds is time dependent and steadily decreases as the volume of accumulated sediment increases over time. This is generally recognized in guidance documents, albeit with different

levels of detail and guidance on the frequency of accumulated sediment removal. Sediment accumulation depends on a number of factors including rain intensity, rainfall duration, construction activities, street-sweeping, storage volume, drainage area characteristics and internal hydraulics (Sivakumar and May, 2009). USEPA (2009) states that the removal of accumulated sediment will vary based on the pond design parameters, and suggests removal from forebays when 60% of original volume has been lost, or a 5-year cycle, and removal from main cells when 50% of original volume has been lost, or a 20-year cycle. The guidance provided in Ontario (MOE, 2003) recognised that limited data is available on sediment accumulation and provided a set of curves for determining the sediment removal frequency as a function of facility type, storage and level of catchment area imperviousness. These curves are based on continuous simulation and the guidance manual recommended that the maintenance frequency should be refined with operational and maintenance experience. In general, the removal of sediment was recommended to limit the reduction in the average annual Total Suspended Solids (TSS) removal of the facility to 5%. Finally, sediment accumulation rates with different level of imperviousness ranging from 0.6 m^3/ha/year (35% imperviousness) to 3.8 m^3/ha/year (85% imperviousness) were suggested in the absence of monitored data.

As stated earlier, sediment accumulation rates in SWM ponds vary over a wide range, depending on a number of factors related to the catchment area characteristics, precipitation patterns and the pond design and operation, and this is reflected in literature and guidance documents (Richard, 2010). Pond age, depth, layout, water levels, the number of measurement points, catchment, characteristics, size, shape, vegetation and flow monitoring are the factors that should be considered when performing sediment accumulation rates measurements. A study by Greenland International Consulting (1999) reported the sediment accumulation rates ranging from 0.2 to 5.9 m^3/ha/year for eight surveyed ponds in Ontario. However, Drake and Guo (2008) conducted a survey of Ontario municipalities, and found that the vast majority of ponds were not monitored for performance and had not yet been dredged. Subsequent studies in Ontario have reported the sediment accumulation rates ranging from 0.5 to 5.9 m^3/ha/year (TRCA and CH2M Hill, 2016), with recommendations to assess the sediment depth at least every 3 to 5 years. Another study that involved a survey of 98 ponds (LSRCA, 2011) found that the accumulation rates ranged widely from 0.26 to 36.17 m^3/ha/year, resulting in more than half of the surveyed ponds dropping in performance to levels below those that should have triggered corrective action (i.e. sediment removal).

There are also several reported efforts to develop relationships between catchment parameters and observed sediment accumulation rates. In USEPA (1986), a probabilistic model that determines the depth of accumulated sediment as a function of pond characteristics and long-term rainfall. The model was later compared against nine studied ponds in Florida by Yousef et. al. (1993), indicating a significantly higher accumulation rates for a range of pond surface area (A_{pond}) to contributing drainage area ($A_{drainage}$) ratios. The measured rates ranged from 1.08 cm/yr ($A_{pond}/A_{drainage}$ = 0.12) to 4.20 cm/yr ($A_{pond}/A_{drainage}$ = 0.014), with a sharp increase observed when the $A_{pond}/A_{drainage}$ ratio is below 2%. Heal et. al. (2006) reported sedimentation rates ranging from -0.2 to 1 cm/year for three monitored ponds in Scotland. For a sand/gravel inflow, bottom sediments comprised silt and clay, with high water content (up to 80%, by volume), and accumulated at a rate of 2 cm/yr (bulk sediment depth) (Marsalek and Marsalek, 1997). A number of other studies also demonstrated the uneven distribution of sediment deposits due to uneven and widely varied flow patterns in individual ponds (e.g. Montgomery et. al., 1983; Heal et. al., 2006; Dominic et. al., 2016).

Although the sediment accumulation rates can vary over a wide range, limited efforts were made until recently to collect the data that could inform the development of a more accurate approach. In the past few years, hundreds of SWM ponds in Southern Ontario have been surveyed. Thus, there is a potential to develop a generalized approach for forecasting the sediment accumulation rates that could be applicable to other areas as well. However, before this possibility could be explored, an investigation involving several steps needs to be undertaken. This objective of this paper is to present the results of such investigation that encompassed the identification of relevant information, investigation on data availability and processing needs, and a methodology to capture the information in a form usable for the development of a data driven forecasting model.

2. METHODOLOGY

To reach the stated objectives, the following activities were undertaken: 1) a questionnaire was developed based on the literature review that includes all the factors contribute to sediment accumulation in SWM ponds; 2) interviews

were conducted with municipalities to follow-up of the survey for the collection of data; and 3) a database was developed considering the existing data provided by municipalities during the process of interview.

In this study, the factors contributing to sediment accumulation rates are divided into three parts: 1) Hydrologic Data, 2) Catchment Characteristics and 3) SWM pond characteristics. The issues for consideration are further described as follows:

1) Components that would be expected for gathering hydrologic data are historical precipitation records, snowfall, and snow melts measurement records, flow monitoring in ponds inlets and outlets, the level of pond monitoring records and records of water quality monitoring at pond inlet or outlet.
2) Catchment characteristics include the catchment areas to storm water management ponds, information regarding the road network and storm sewer collection network, information on impervious surfaces (roofs, roads/sidewalks, parking lots, driveways), land use breakdown (e.g. industrial, commercial, institutional, residential high/med/low density), information on catchment changes since SWM pond was constructed (e.g. construction activities), sediment control practices in the catchment (e.g. catch basin cleaning, street sweeping, road salting/sanding).
3) SWM pond characteristics include their design criteria (i.e. dry/wet pond, storage volume capacities, stage-storage curves, area, inlet/outlet structures, number of cells, sediment bay, length/width ratio, permanent pool depth, screening devices at inlet/outlet, etc.), sediment survey results (protocol followed in the survey, survey dates and results, sediment characterization, etc.), planting/ maintenance records and if ponds are used for irrigation purposes.

A questionnaire, shown in Table 1, was developed to clarify the information sought from municipalities that considered all the factors mentioned above. Almost fifty municipalities in Southern Ontario were contacted via email, with the questionnaire attached, of which five municipalities agreed to an interview and subsequent provision of data that they had available for the study. Once the data was collected the next step was to compile it in a usable format. The need for accurate and applicable data is the key factor for the development of the database. Master plans, reports, manuals, drawing digital images and spreadsheets were provided by municipalities. The database was populated with data provided by participating municipalities.

Table 1. Survey Questions

Group of factors	Survey questions
Hydrologic Data	1. Are historical precipitation records available? Yes - what duration (YEAR from - YEAR to, MONTHS of the year) and frequency (e.g. 15-min, hourly, daily) 2. Are there any records from snowfall and snowmelt measurements? 3. Are there any records of flow monitoring at pond inlet and/or outlet? 4. Are there any records of pond level monitoring? 5. Are there any records of water quality monitoring at pond inlet and/or outlet (either grab samples or concerted monitoring campaigns)?
Catchment Data	1. Are the catchment areas to SWM ponds delineated? Is this information available digitally? 2. Is information on the road network and storm sewer collection network available? Is this information available digitally? 3. Is information on impervious surfaces (roofs, roads/sidewalks, parking lots, driveways) available? Is this information available digitally? 4. Land use data available (industrial, commercial, institutional, residential high/med/low density)? 5. Is any information available on catchment changes since SWM pond was constructed (e.g. construction activities)? Are historic aerial images available? 6. Are there records available for catchment practices: catch basin cleaning, street sweeping, road salting/sanding practices, etc.?
SWM Pond Data	1. Are pond design or as-built drawings available? Have the ponds been characterized according to their design (i.e. dry/wet pond, storage volume capacities, stage-storage curves, area, inlet/outlet structures, the number of cells,

sediment bay, length/width ratio, permanent pool depth, screening devices at inlet/outlet, etc.?)
2. What information is available regarding the accumulated sediment (protocol followed in the survey, survey dates and results, sediment characterization, etc.)? Is this data available digitally?
3. Are planting/ maintenance records available?
4. Are any ponds used for irrigation?

3. RESULTS AND DISCUSSION

3.1 Survey Results

Information on 96 ponds was collected from the five municipalities. The ponds ranged in age from 3 to 33 years, with the average value of 15 years. Results from the survey and subsequent interviews indicated that all of five municipalities had implement some sort of monitoring programs for sediment accumulation in ponds. A sediment survey using the disk/rod technique is common practice by every municipality. Pond level monitoring and periodic water quality monitoring at inlet and outlet records were available for each pond. In addition, catchment area was calculated by all municipalities but only one of the five retained a record of catchment area delineation in digital format. It was generally acknowledged that some ponds within the municipality's jurisdiction will be approaching their designed capacity within the next three to five years, three municipalities reported planned clean-out projects and four are executing cleanouts at regular intervals. A wide variety of data shows the presence of accumulated sediments in each pond but many ponds have not been cleaned even though their capacities to remove solids at design levels are compromised. None of the municipalities had data readily available for catchment practices like street sweeping, road salting and catch basin cleaning. Similarly, no data was available for planting records and none of the ponds were apparently used for irrigation purpose.

3.2.1 Hydrologic Data

Precipitation records were generally not available from municipalities for the duration corresponding to age of the oldest ponds within their jurisdiction. In most cases, rainfall monitoring data were available for a few years, and in all cases the data covered non-winter months only. No snow measurements were available from any of the municipalities. Accounting for precipitation in a sediment accumulation forecast could be achieved using long-term records from Environment Canada, which operates gauges in or near each of the five municipalities, although these are typically not heated and removed in winter months. Only one of the municipalities surveyed maintains a network of level sensors across the ponds in their jurisdictions. Water quality sampling is carried out by the same municipality (grab samples at inlet and outlet) on an annual basis, while the same activity is performed by other municipalities less regularly and as a requirement of the facilities regulatory approvals. Sporadically collected water quality data are not suitable for inclusion in the eventual development of a sediment forecasting model.

3.2.2 Catchment Data

Catchment delineation for SWM ponds is generally available from all surveyed municipalities, typically from original design documents, but also in GIS format where delineation appears to have been updated. Similarly, road network and sewer network data is available, but again in a variety of formats. Impervious areas have been delineated in detail for one municipality, while the others provided the overall imperviousness of SWM pond drainage areas, in most cases from original design documents. Land use information is available for all municipalities. Although both vegetal cover and construction activities could have significant effect on sediment loading rates to SWM ponds, historic information on contributing catchments covering the period since their construction is not readily available. Information on catchment practices that also potentially influence sediment loadings to SWM ponds is very general and there is no historic information available in a usable format

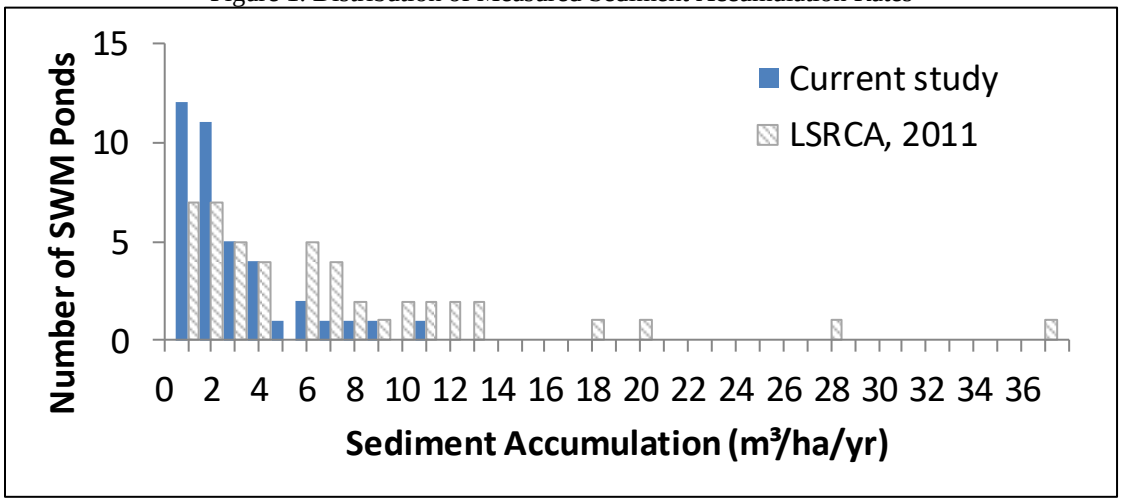
3.2.3 SWM Pond Data

Therefore, the information on ponds and other BMPs was available, however, the information is not captured in a consistent and uniform format since different consulting companies carried out the inspections and document reviews. All municipalities are in the process of developing electronic databases of their SWM facilities, but again, there is no generally accepted format on how to record design information, inspections and maintenance records, sediment survey results, etc. Basic design information (e.g. type of facility, number of inlets/outlets, forebay presence, pool depth, volumes, etc.) is recorded in most instances, albeit not in a consistent format, requiring further inquiries on data interpretation. Although detailed calculations of sediment volumes were not available, it appears that several different methods are used, and include: cut/fill computations comparing pond designs and current elevations, calculations based on equations for different geometric shapes (e.g. truncated ellipse, truncated cone, etc.) and spatial interpolation calculations based on dense measurements across the pond. This point is particularly important, since values derived using different calculation approaches can yield substantially different results (e.g. Norton, 2007).

3.2.4 Sediment Survey Results

As indicated above, the data was provided by the five municipalities in a variety of formats, with some pieces of information missing. So far, measured accumulated sediment volumes for 39 SWM ponds have been assembled and analyzed. Figure 1 compares the distribution of observed sediment accumulation rates for these ponds, and compares them against the values reported by LSRCA (2011). Almost two thirds of ponds included in this study (23 out of 39) had accumulation rates less than 2 m³/ha/yr, while the number of facilitates investigated by LSRCA that were in that range was substantially smaller (14 out of 49). Also, the high accumulation rates (> 11 m³/ha/yr) observed by LSRCA were not observed for any of the ponds in this study.

Figure 1. Distribution of Measured Sediment Accumulation Rates



The lower overall sediment accumulation in ponds studied here, compared to LSRCA (2011) is also evident in Figure 2, which plots the unit accumulation rates against the pond age, along with the trend indicated with best-fit logarithmic lines. Although there is a high degree of data scatter, the lines point to the general trend of newer ponds being more efficient at capturing sediment. This could be attributed to a number of factors, including the improvement in pond design experience and practice over the last two decades, and reduced overall removal of older ponds due to accumulated sediment. It is not possible to determine other causes of reduced sediment accumulation rates over time without considering the multitude of other potentially influencing parameters discussed earlier. However, a general trend of decreased performance of ponds, in terms of their ability to provide their water quality function, is clearly observable. Although the contributing drainage area imperviousness has a major influence on the runoff volumes and peak discharge rates of SMW ponds, Figure 3 does not indicate any relationship between imperviousness and corresponding long-term average sediment accumulation rates.

Figure 2. Measured Sediment Accumulation Rates for Differently Aged Ponds

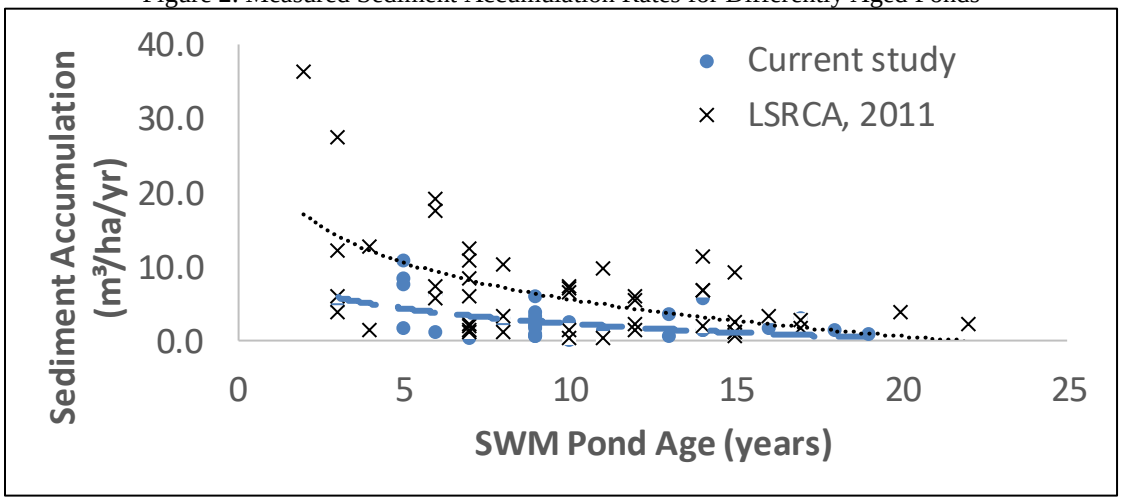
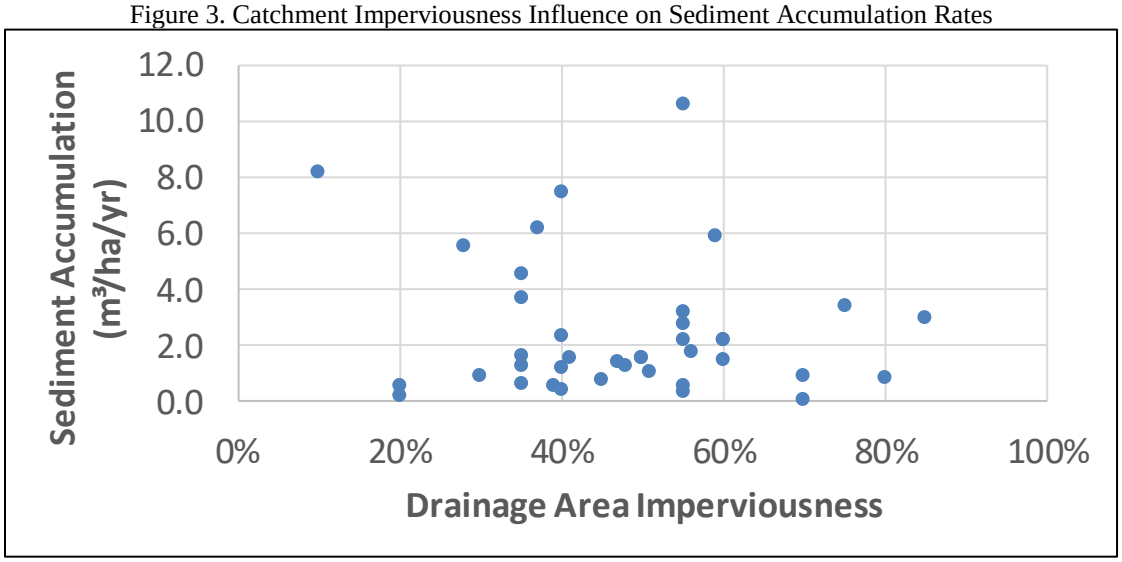


Figure 3. Catchment Imperviousness Influence on Sediment Accumulation Rates



4. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

SWM ponds have been the most commonly used BMP over the past two decades. Clear and relatively simple design guidance, relatively low cost and end-of-pipe management of runoff from developed lands were all factors that led to their widespread adoption in Ontario and elsewhere, somewhat in in contrast to the current efforts to increase the adoption of Green Infrastructure and Low Impact Development approaches. Although early guidelines stated the need for regular monitoring to determine sediment accumulation rates and needs for pond cleanouts, these efforts have intensified only recently, with realization that many ponds need urgent removal of sediments to maintain their intended functions.

The available guidance on maintenance frequency is provided in several forms: 1) based on the loss of original volume alone, 2) based on facility type, provided storage and catchment imperviousness utilizing modelling results, and 3) based on the decrease in annual TSS removal percentages. With the presumed relationship between the loss of volume and the corresponding loss in performance (i.e. percent TSS removal), and impracticality and absence of continuous or even periodic monitoring to determine actual removal rates, the volume of accumulated sediment is

clearly the most practical and adopted criterion applied to SWM pond cleanout decision making. With the sediment accumulation rates varying by an order of magnitude and near absence of studies that correlated accumulation rates with relevant hydrologic, catchment and pond characteristics, as the literature points out, capital planning of potentially very costly cleanout activities is difficult for stormwater managers.

From the limited analyses of sediment accumulation rates for ponds of different age conducted so far in this study, it is also evident that age of the pond has a major impact on the sediment accumulation rates. A single survey of the pond cannot be used to gain insight into either the temporal trend of its efficiency or the future sediment accumulation rate needed for capital planning. Another approach that municipalities are taking is to conduct two surveys of their ponds several years apart, in an effort to estimate the sediment loading rates. Although better than using a single survey, this approach also captures the performance (or accumulation rate) over a relatively short time window of pond operation, without considering the longer-term performance trend.

Prioritization of sediment removals has focused on most critical facilities, but a systematic approach for development of longer term capital programs to deal with years of accumulated sediment will require more frequent surveys or a numeric forecasting approach. In this respect, the quantity of data available from thousands of surveyed ponds offers interesting possibilities. However, as this study has illustrated, significantly more effort is needed to develop more standardized approaches, particularly for collecting information related to catchment hydrology and sediment surveys.

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