Preliminary Assessment for Improved Design Criteria for Construction Sediment Control Ponds

Prepared for

TORONTO AND REGION Conservation
for The Living City

Fisheries and Oceans Canada
Pêches et Océans Canada

Prepared by

Clarifica Inc.

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clarifica

Clarifica Inc.
Tel: (905) 505-0080
Fax: (905) 737-5553
e-mail: clarificainc@home.com

clarifica

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Toronto and Region Conservation Authority
5 Shoreham Drive
Downsview,
Toronto, ON M3N 1S4

Attention: Mr. Glenn MacMillan, Water Management Supervisor

RE: Preliminary Assessment for the Improved Design Criteria for Construction Sediment Control Ponds

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Dear Sir,

I am pleased to submit this report entitled "Preliminary Assessment for Improved Design Criteria for Construction Sediment Control Ponds". This report incorporates comments received from the TRCA and other reviewers after the first draft submission.

Construction activities have been identified to be one of the main sources of contamination to receiving streams. Although sediment control measures have been required at construction sites for almost two decades, their effectiveness and implementation have remained unchanged in spite of clear indications that problems still persist. To address the erosion and sediment control (ESC) problems associated with urban construction sites, the Toronto and Region Conservation Authority (TRCA) has undertaken a number of initiatives to assess the effectiveness of existing ESC practices and for the development of improved ESC guidelines and improved pubic awareness.

This report, entitled "Preliminary Assessment for Improved Design Criteria for Construction Sediment Control Ponds", documents the progress towards the ultimate development of improved design criteria for construction sediment control ponds. This report includes:

1. **Section 1**: a background review of:
    a. construction site runoff and its impacts on receiving waters,
    b. existing legislations for erosion and sediment control in construction sites,
    c. initiatives undertaken by TRCA for addressing construction sediment problems.

2. **Section 2**: a literature review on influencing factors that affect soil erosion in construction sites and performance of sediment control facilities.

3. **Section 3**: a comprehensive review of particle size distribution (PSD) in runoff from urbanized and urbanizing catchments. Available data sets on PSD are analyzed to determine the practical size limit for planning and designing effective runoff quality control facilities.

4. **Section 4**: a development of a preliminary analysis methodology for modelling sediment control ponds to predict their sediment removal performance and eventual receiving water protection.

Based on the findings to-date, it is noted that the particle size distribution of stormwater runoff and their settling characteristics have a major influence on the long-term suspended solids removal performance of SWM facilities and construction sediment control ponds. It has been observed that the particle size distribution of stormwater runoff is highly positively skewed, tending towards finer particle ranges (i.e., silt and clay). In most cases, particle size is less than 100 μm. Conversely, current SWM facility design criteria (MOE, 1994) assumes that more than 50% of the particles are greater than 100 μm.

This progress report also presents the preliminary planning and development of a continuous simulation model for assessing the generation and treatment of stormwater runoff in a typical construction environment. When additional monitored field data becomes available and is analyzed, the results will be updated to include model calibration and verification and ultimately to develop a generalized, improved design criteria for construction sediment control ponds.

Sincerely yours,

CLARIFICA INC.

Dr. Pradeep Behera

Acknowledgements

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In kind support has been provided by Clarifica Inc. as our commitment to improve the management and quality of water resources in Canada.

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1 INTRODUCTION

1.1 General

Stormwater runoff from developed and developing areas continues to be one of the major sources of pollution loading to our nation's surface water bodies. In spite of enormous public expenditure in sewerage and drainage infrastructure, pollutant loading from urban runoff continues to have significant impacts on receiving waters and remains a formidable obstacle to achieving water quality goals. However, the continuous efforts by various levels of government, conservation authorities, municipalities and local communities have addressed a number of challenges of stormwater pollution problems and have succeeded in many fronts. It has been demonstrated that post-development strategies to prevent and control urban stormwater pollution are effective and can be economically and environmentally advantageous. As we control runoff pollution from urbanized areas (i.e., post-development conditions), the pollution from urbanizing areas has become more distinct. Construction activities are a major source of stormwater pollution in urbanizing watersheds as they have potential to increase the natural erosion and sediment transport rate. Recently, a Great Lakes Science Advisory Board Workshop (2000) to assess the status of non-point source pollution control in Great Lakes Basin identified that construction sites are significant sources of sediments to urban streams. As many Canadian jurisdictions are undergoing rapid expansion, the runoff pollution problem from construction sites will increase resulting in impaired receiving waters, degraded aquatic habitats and risk to public health.

1.2 Construction Site Runoff

In the developmental cycle of watersheds, construction is the most damaging phase for the receiving waters and aquatic resources because polluted stormwater runoff from construction sites is often discharged into local rivers and streams. Construction activities disturb land and often provide a favourable environment for accelerated erosion during rainfall and runoff. For example, grading activities remove protective ground cover resulting in the exposure of underlying soil. The movement of heavy construction equipments loosen the exposed soil. The excavation of soil and stock piling of soil and construction materials leaves the soil to be transported easily by runoff. Because the soil surface is unprotected, soil and sand particles are easily washed off by rainfall and runoff (or snowmelts) during wet weather events contributing to a significant amount of sediment and other non-point source pollutants to the local receiving waters. Soil erosion from a construction site without proper soil erosion and sediment control practices in place can discharge sediment load between 50 to 500 tons/ha/year – this is ten to hundred times greater than typical soil losses on agricultural lands and 1000 to 2000 times those of forested land (MTRCA, 1994 and Dodson, 2000). Over a short period of time, construction sites can contribute more sediments to streams and rivers than that was deposited previously over several decades. For example, Schueler and Lugbill (1990) observed a number of Piedmont construction sites in Maryland and found that the average total suspended solids (TSS) concentrations in uncontrolled runoff was about 4,145 mg/L. The TSS concentration from all construction sites that were at different stages of construction ranged between 24 mg/L to 51800 mg/L. Figure 1.1 illustrates the effect of erosion and sediment control measures on TSS concentrations from the Piedmont construction sites. It was observed that the TSS concentration typically increased with the stage of constructions at a site. For example, median TSS concentration during initial clearing and grading stages was 488 mg/L and during active construction was 700 mg/L.

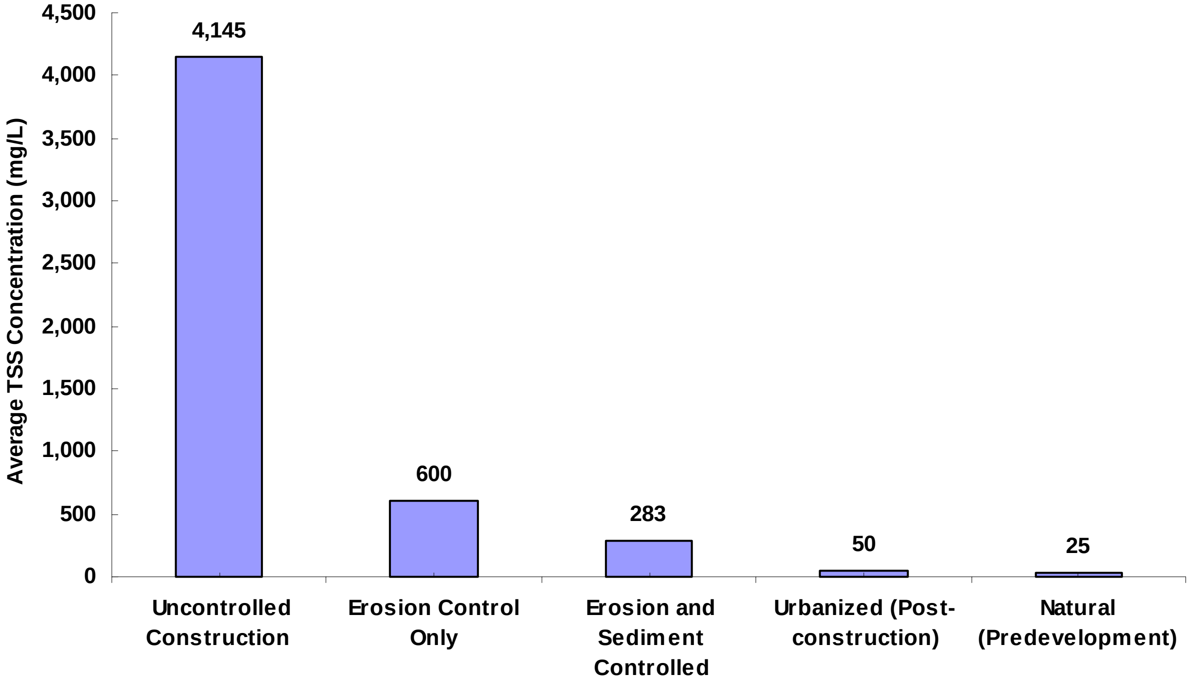

Figure 1-1: Effect of erosion and sediment control measures on TSS from Piedmont construction sites (From Schueler and Lugbill, 1990)

1.3 Problems Associated with Erosion and Sedimentation

The excessive sediment releases in runoff can have several types of adverse impacts, which include environmental, engineering, economical and social. These impacts have been summarized and documented in a previous study ‘Investigation to Develop an Improved Sizing Approach for Sediment Control Facilities’ (Clarifica, 2002). Some of the significant problems associated with excessive sediment releases, especially from construction sites are identified as follows:

1. Soil erosion is the major cause of stormwater pollution from construction sites and sediment is the most important constituent. Stormwater runoff which carries the eroded soil and sediments eventually reaches a local stream/river, or a lake where water slows down, allowing the particles to settle to the bottom of the streambed or lake. The gradual build up of silt and clay layers on the streambeds can choke the river and stream channels and can cover the areas where fish spawn and plants grow, and reduce the hydraulic capacity of the channel.

2. The effects of excessive sediment loading on receiving waters include the clouding of waters causing aquatic respiration problems, the deterioration or destruction of aquatic habitats, deterioration of aesthetic value, and accumulation of bottom deposits that inhibit normal biological life. Sediment can destroy spawning areas and food sources resulting in harming fish and other aquatic wildlife. Nutrients carried by the sediments can also stimulate algal growths and consequently accelerate the process of eutrophication.

3. The construction of buildings and roads typically requires the use of toxic materials such as petroleum products and building materials including asphalt, sealants, concrete, pesticides, fertilizers and herbicides which may pollute the stormwater runoff from the construction site. These materials can be toxic to aquatic organisms and can degrade the quality of drinking water and water used for recreational purposes.

4. Sedimentation in SWM facilities, streams, and channels significantly reduces the design capacity which may result in possible structural failure, overflows and potential floods. Uncontrolled sedimentation may require frequent maintenance and dredging to restore the facilities to their design capacities.

5. The eroded soils and sediments can restrict and reduce effective flow areas for urban drainage systems, clog street catchbasins, sewers, swales and plug culverts causing damage to public properties.

6. The eroded soils can create dust causing air pollution and mud tracking in rain periods in adjacent areas which can impair public relations.

1.4 Erosion and Sediment Control Initiatives

1.4.1 Applicable Legislations and Technical Guidelines

A number of federal, provincial and local regulations exist to address soil erosion and sediment control (ESC) from construction sites. They include *Federal Fisheries Act* R.S.C, 1985; *Ontario Water Resources Act*, R.S.O, 1990; *Environmental Protection Act*, R.S.O, 1990; *Conservation Authorities Act* (1990); *Topsoil Preservation Act*, R.S.O. 1990; and *Ontario Environmental Bill of Rights* (1994). From these legislations, the *Topsoil Preservation Act*, (1990) effectively allows municipalities to implement by-laws that regulate and prohibit the removal of topsoil. For example, municipalities including Brampton, Markham, Uxbridge and Mono regulate ESC through the Topsoil Preservation By-law whereas Mississauga and Ajax regulate through Erosion and Sediment Control By-laws. Failure to comply with legislations relating to ESC can result in fines and/or jail time. In most of these legislations, the developer/contractor/consultant is liable for proper implementation of ESC measures.

Typically, an ESC regulation requires the developer/contractor to submit a plan that contains measures to reduce soil erosion (i.e., erosion prevention) and practices to control sediment that will be eroded during construction activities (i.e., sediment controls). Once the ESC plan is reviewed and approved by the municipality or conservation authority, the regulation then requires the developer/contractor to install and maintain specified measures and practices throughout the construction phases. A construction site may be inspected for compliance, and if found lacking, the regulating authority may take appropriate action for violation.

To support these regulations, a number of technical guidelines have been developed. They include:

- The MNR Technical Guidelines – Erosion and Sediment Control (1989),
- The Toronto and Region Conservation Authority (TRCA) Erosion and Sediment Control Guidelines for Construction (1994), and
- The MTO Drainage Management Manual (1995-1997).

1.4.2 Erosion and Sediment Control Study Initiatives

Despite the existence of number of regulations presented in the previous section, stormwater runoff from construction sites has been identified as a main contributor to water pollution problems. The Toronto and Region Remedial Action Plan recognizes stormwater runoff as one of the three major pathways for pollutants to enter our watercourses; however, it has received the least amount of attention in terms of developing remediation measures (Metro Toronto and Region Remedial Action Plan, 1994). As a result, the TRCA has initiated a multi-step progressive approach to address soil erosion and sediment control problems, especially in determining the effectiveness of current ESC processes in order to bring forward an awareness among the development and construction industry, municipalities and other related authorities.

Erosion and sediment Control initiatives began in 1990's when it was recognized that there were concerns regarding implementation of ESC measures and guidelines as well as their effectiveness. To address the issue, a number of committees were formed and documentations were developed. For example, the TRCA Executive Committee and the document '*Clean and Clear: Keeping Soil on Construction Sites and Out of Streams'* by the MTRCA and Ministry of Environment (MOE). In 1999, the TRCA initiated a process to address the management concerns of runoff sediments from urban construction activities, particularly in the sensitive headwater streams in the Great Lakes Basin. The TRCA evaluated its own participation in addressing erosion and sediment control problems and identified the potential issues in erosion and sediment management to pursue in future.

Table 1 provides the chronological development of erosion and sediment control initiatives that are initiated and/or supported by TRCA and its collaborating partners, which include the current, and future plans. These initiatives are often collaborated with several government agencies, Universities, Research Institutions, Municipalities, Developers and Private Consulting agencies. These initiatives have been undertaken systematically such that the problems can be addressed over a reasonable period. Initially, the initiatives were devoted to understand the management problems and effectiveness of existing ESC practices. The next step was to develop appropriate regulations. Currently the attention is devoted to developing effective technical criteria and stakeholder awareness to address the problem.

Table 1-1: Chronological development of erosion and sediment control initiatives

Year	Initiatives/Outcomes	Partners
Feb. 1989	E&SC Technical Guidelines	MNR
Jan. 1993	E&SC Practices Study	TRCA, MOE
Apr. 1994	E&SC Guidelines for Construction	TRCA
Jan. 1997	SWMP Research and Development	Mississauga et. al.
Apr. 2001	Urban Construction Study	TRCA, Greenland Inc.
Mar. 2002	Investigation to Develop an Improved Sizing Approach for Construction Sediment Control Ponds	DFO, TRCA, GLSF, Clarifica Inc.
Apr. 2002	Model By-Law	TRCA, Clarifica Inc.
Mar. 2003	Sediment Control Pond Monitoring Study	Ryerson University, NWRI, TRCA, RH, GLSF, MOE, Environment Canada
Mar. 2003	Preliminary Assessment for an Improved Design Criteria for Construction Sediment Control Ponds	TRCA, Clarifica Inc., DFO, GLSF, MOE, Environment Canada

E&SC – Erosion and Sediment Control, SWMP – Stormwater Management Practices
MOE – Ministry of Environment, MNR – Ministry of Natural Resources
GLSF – Great Lakes Sustainability Fund, DFO – Department of Fisheries and Ocean
NWRI – National Water Research Institute, RH – Richmond Hill
TRCA – Toronto and Region Conservation Authority

The potential issues in erosion and sediment management that are currently studied/recently completed include the adequacy of the ESC planning process, the appropriate selection of sediment control best management practices, and their maintenance and effectiveness during the construction phases. The recommendations that were suggested include development of efficient practical solutions to control erosion and sediment from urban construction sites which can improve the existing provincial standards and would help to achieve the overall receiving water quality goals.

One of the current initiatives deals with the development of improved technical criteria for construction sediment control ponds, which is presented in the following section.

1.5 Development of Improved Design Criteria for Construction Sediment Control Ponds

To provide more reliable storm water management (SWM) facility design criteria for construction sites, the TRCA initiated a continuous flow and water quality monitoring assessment in a typical SWM pond operating under a construction environment with other collaborating partners. The monitoring program is under progress for the Ballymore SWM facility located in the Town of Richmond Hill.

The information collected in the monitoring study at the Ballymore SWM facility will be used to evaluate the effectiveness of SWM facilities designed in accordance with the MOE Stormwater Management Practices Planning and Design criteria (Level 1 water quality control) for treating and controlling the runoff generated under urban construction activities. The assessment will also lead to recommendations in the form of specific design facility improvements under construction settings and relating effluent to receiving water habitat protection.

In order to develop improved design criteria for construction sediment control ponds, a detailed performance modeling of the sediment pond system, which provides the comprehensive analysis of the system, is required. The results of the ongoing monitoring activities will be incorporated in a continuous simulation model for performance analysis of the system that would provide the relation between design configuration and sediment control effectiveness. The objective of the study ‘Development of Improved Design Criteria for Construction Sediment Control Ponds for Receiving Water Protection’ ties-in favourably with the ongoing investigations to develop design guidelines for the urbanizing watersheds. The following text describes the work plan for this study:

- Review and summarize literature on construction sediment control ponds and recent research literature on the construction sediments.

- Review and summarize the influencing factors for erosion and sedimentation.

- Review and evaluate the practical limit of particle size that can be treated by sediment control ponds/SWM ponds based on results from previous monitoring studies.

- Assess technical analysis tools that can be used to predict sediment generation from construction sites and on-site storage-treatment controls.

- Collect and analyse the climatic and hydrologic, construction site and sediment data for the study catchment and Ballymore SWM facility.

- Develop a continuous simulation model by calibrating and verifying with field monitored data.
- Conduct a performance analysis of the continuous simulation model under various physical scenarios.
- Based on an assumed performance measure for the sediment control pond (e.g., % removal of TSS load or numerical TSS effluent concentration) the improved design criteria for construction sediment control ponds will be developed.
- Evaluate theoretically the effects of design criteria (i.e., treatment level) on receiving waters.
- Documentation.

1.6 Purpose of this Report

In the previous sections, it was noted that construction activities, which occur between predevelopment and post-development watershed conditions, could induce a number of unacceptable environmental impacts to our receiving waters (Sections 1.1 to 1.3),. To address this problem, a number of initiatives including promulgation of new/revised regulations, improvement of effectiveness of existing erosion and sediment control practices, enhancement of effective implementation procedures and evolvement of awareness of the issues among public and stakeholders, have been undertaken (Section 1.4). Among these initiatives, major technical issues are to evaluate the adequacy of existing design criteria of construction sediment control ponds, particularly related to their effectiveness in controlling construction sediments and the development of improved design criteria for receiving water protection. The relevance of this issue is important as the new/revised regulation (i.e., Model By-law) recommends the implementation of sediment control ponds for construction sites greater than 5 hectares. In this context, this report is prepared as a preliminary assessment report for the study "Development of Improved Design Criteria for Construction Sediment Control Ponds for Receiving Water Protection" which is a follow-up study to the 'Investigation to Develop an Improved Sizing Approach for Sediment Control Facilities', by Clarifica, (2002) and 'Sediment Control Pond Monitoring Study' by Ryerson University (2002-2003). The purpose of this report is to review the relevant literature for the study and to identify the critical issues that will assist in the development of improved design criteria for construction sediment control ponds for receiving water protection. For example, analysis of the factors that influence soil erosion in construction sites, and particle size distribution of suspended solids in stormwater runoff and their role in quality control performance of sediment control ponds.

2 Existing Design Criteria and Factors Influencing Performance of Construction Sediment Ponds

This section provides some general details of existing design criteria for construction sediment controls in Ontario especially within the TRCA jurisdiction, and reviews the design criteria for sediment control for construction sites in United States. In addition, factors that potentially affect the performance of erosion and sediment control measures are reviewed and summarized.

2.1 Design Criteria for Construction Sediment Control in Ontario

The existing ESC processes including the design of sediment control measures and their effectiveness are reported in the "Urban Construction Sediment Control Study" prepared by Greenland International and TRCA (2001). In that study, monitoring programs were conducted to evaluate the performance of ESC practices that are commonly used throughout the construction industry. A number of necessary improvements in the existing practices were identified, especially in ESC design process, review and enforcement protocols. One of major recommendations was to provide sediment control ponds for large construction sites in addition to other ESC measures. The construction sites having sizes more than 5 ha are required to provide sediment control ponds as an interim measure and this recommendation was subsequently incorporated in the Model ESC By-law for the municipalities (2002). The recommended interim ESC criteria for sizing sediment control pond include:

- The sediment control pond volume should consist of a permanent pool and active storage component. As per MOE SWMP Manual, the permanent pool component should be sized for a minimum of 125 m^3/ha or to the ultimate SWM facility permanent pool volume (whichever is greater) for removing sediments. This interim criteria is based on Table 4.1 in the MOE Stormwater Management Practices Planning and Design Manual (1994). The active storage component should be sized for a minimum of 125 m^3/ha of runoff and released over a minimum 24-hour period.
- The permanent pool for the sediment control ponds should be cleared of sediments periodically to maintain sufficient treatment volume. The permanent pool must be cleared the accumulated sediments when there is a 5% reduction in treatment efficiency. The consultant should note on their drawings the minimum allowable depth of permanent water to assist the contractor in determining when the pond requires sediment removal.

2.2 U.S. Construction ESC Criteria

Through the National Pollution Discharge Elimination System (NPDES) regulation under the National Storm Water Program, the U.S. EPA regulates stormwater discharges from construction sites, which include cleaning, grading, excavation and construction activities. This regulation promulgated in two phases – Phase I and Phase II.

Phase I began in 1990 that requires a NPDES stormwater discharges permit for construction sites with disturbed land area of two hectares (five acres) or greater. The NPDES permits available for stormwater discharges from construction sites are of two types: a general permit and an individual permit. The EPA has used general permits as a tool to accommodate the large number of dischargers (including from construction sites) that are included in National Storm Water Program. The individual permits are traditional permits with permit requirements that are specific to the facility named in the permit (Dodson, 2000). Many states have developed their own general permits for construction stormwater discharges as per EPA recommendations. For example, Michigan requires a permit coverage including a pollution prevention plan for construction sites having sizes over two hectares in the Phase I.

The Phase II program, which began in 2002, requires that construction sites greater than 0.4 hectares (one acre) in size will have requirements similar to those for sites greater than 2 hectares. Municipalities in urbanized areas need to comply with six minimum measures to reduce pollution from stormwater to the maximum extent possible (Cowles, 2001). The six minimum control measures, which consists of different Best Management Practices (BMPs), are to be applied appropriate to the source, location and climate. The practices listed in the menu of BMPs have been provided by EPA to be representative of the types of practices that can be applied successfully to achieve the minimum control measures. The control measures fall into following six categories:

1. Public education and outreach on stormwater impacts;
2. Public involvement/participation;
3. Illicit discharge detection and elimination;
4. Construction site stormwater runoff control;
5. Post-construction storm water management in new development and redevelopment;
6. Pollution preventions/good housekeeping for municipal operations.

The temporary sediment basins are usually designed for the disturbed areas larger than 2 hectares and can be a temporary structure or permanent stormwater control measure. The design criteria for construction sediment control pond vary from state to state. For example, Maryland recommends a storage volume of 255 m^3/ha as the sizing criteria for sediment control ponds with half of the storage should be provided as permanent pool (Schueler and Lugbill, 1990). This criterion was established on recommendations of a monitoring study that was conducted to evaluate the sediment trapping efficiency of sediment traps and basins utilized at construction sites (1990) in Maryland. Before this monitoring study the sizing criteria for construction sediment basins was 127 m^3/ha. The increase in storage volume was recommended for following reasons:

- To entirely contain the sediment-laden runoff from small and moderate size storm events, so that it can settle out before next storm;
- To provide a minimum of 2 to 6 hours of detention during larger storms when settling rates are the greatest.
- To provide half of the storage as permanent pool to protect against resuspension and to promote better settling conditions.

2.3 Factors Affecting Performance of Erosion and Sediment Control Measures

The performance of sediment control ponds can be influenced by a number of factors. In this section, a review of these factors is presented.

The performance of erosion and sediment control measures is influenced by a large number of inter-related factors. The most important factors that influence erosion include:

- Soil characteristics of the site/catchment
- Topography
- Climate
- Soil Cover

The factors that influence the performance of sediment control measure, especially sediment control ponds include (Schueler and Lugbill, 1990):

- Particle size distribution of incoming sediment
- Geometry of sediment controls
- Available storage volume in the sediment control
- Presence of standing water
- Construction site history
- Sediment flocculation
- Proper design of ESC plan
- Proper installation and maintenance

These factors are briefly described in the following sections

2.3.1 Factors Influencing Erosion

Soil Characteristics

The degree of soil erodibility in an urbanizing catchment can be determined by four important soil characteristics (Carriaga and Tuncok, 2001):

1. *Soil texture* refers to the size and proportion of the particles comprising the soil sample which is typically classified on the basis of three soil class – clay, silt and sand. In terms of erodibility, clay possesses binding characteristics making soil resistant to erosion. However, once the particles are dislodged or dispersed, they can be easily transported and are difficult to settle out.
2. *Organic matter* is the material comprising of all plant and animal litter that is in various stages of decompositions. Generally, it improves soil condition, reduces surface runoff, and lowers the erosion potential of the ground surface.
3. *Soil structure* refers to the arrangement of soil particles into aggregates. A granular structure increases the soil's ability to absorb water while compacted soil results in higher surface runoff, thus increasing the erosion potential.
4. *Soil permeability* is the ability of the soil to transmit water and air through the soil column which is influenced by soil structure, texture and organic content. High soil permeability indicates high absorption capacity, which decreases surface runoff and erosion potential.

Topography

Three topographic factors which provide the most critical information about the degree of erodibility include (Carriaga and Tuncok, 2001):

1. *Orientation of slope* ascertains the effectiveness of climatic forces to influence soil erosion.
2. *Degree of slope* affects the flow velocity and energy of flow influencing directly on the erosive energy to dislodge, disperse and transport soil particles.
3. *Length of the slope* affects both runoff quantity and depth of flow.

Climate

Climatic conditions are considered as a significant influence on the erosion potential of any land surface. The principal climatic factors affecting soil erosion are rainfall and runoff, snowmelt, temperature and wind. Rainfall causes the breakdown of aggregates and dislodgement and dispersion of soil particles while runoff, which is an excess rainfall after losses, exert forces to further dislodge and transport sediments to the downstream receiving water body. Temperature affects the degree of dislodgement, dispersion and transport of particles. Alternate freezing and thawing from extreme weather conditions can cause expansion of soil, decrease in cohesive strength and increase in moisture content which facilitate erosion of soil particles. In addition, temperature affects the settling and transport of soil particles. At lower temperatures, settling and transport rates are slower (Carriga and Tuncok, 2001). Wind velocity and eddies cause the dislodgement of dry soil particles from the exposed land surfaces providing higher erosion rates.

Soil Cover

Soil cover typically refers to surface cover of the land by vegetation (e.g., grass, shrubs, trees) or by artificial materials such as mulches, wood chips, crushed rocks etc. Vegetative cover is considered as the most effective form of erosion control as it (i) serves as a natural shield against impact of raindrops, (ii) decrease the velocity of surface runoff, (iii) holds and stabilizes the soil particles. Non-vegetative cover involves the application of artificial treatment on the ground to protect the soil from erosive actions associated with rainfall, runoff, wind, and temperature.

2.3.2 Factors Influencing Sedimentation

Particle Size Distribution of Incoming Sediment

The primary objective of a sediment control pond is to remove sediments from the runoff so that the relatively improved water quality can be discharged off the construction site. The removal of sediments within the pond is based on the settling of incoming sediments, which is mostly influenced by the particle size distribution of the solids and their settling velocity. In general, larger particles (i.e., sand) settle faster than fine-grained clays. For construction sites, the key question is what are the factors that determine the particle size distribution of incoming sediments. Theoretically particle size distribution is a function of parent soils of the contributing construction site. For example, a silt-loam soil is typically composed of about 30% sand, 40% silt and 30% clay. However, Schueler and Lugbill (1990) reported that the actual particle size distribution of construction site runoff is strongly skewed towards fine-grained particles. As mentioned in the previous section fine-grained soils are easier to detach, dislodge and disperse which allows them to be transported via runoff more easily than coarser particles.

The particle size distribution and settling characteristics of sediment particles in stormwater runoff are presented in the following sections.

Geometry of Sediment Control Facilities

The geometry of a sediment control facility can affect the flow condition within the facility; especially a properly designed facility can provide an environment that changes the dynamic flow (incoming runoff) to quiescent flow condition which would enhance settling of solid particles. Actual field condition is a dynamic one where turbulence and short-circuiting are common phenomenon which will never provide the quiescent condition and adequate settling time. In this regard, the sediment control pond geometry is very important. Conventional sedimentation basin design principles typically require 5:1 length to width ratio to achieve ideal settling condition (i.e., plug flow). Furthermore, the length of flow path from inlet (s) to outlet should be maximized to prevent short-circuiting (Schueler and Lugbill, 1990).

Available Storage Volume in the Pond

The sediment removal efficiency of a sediment control pond is strongly influenced by the available storage capacity within the pond. As per existing design criteria the amount of storage provided for the treatment is a function of contributing drainage area, land use (i.e., percent imperviousness), detention time and treatment level. In general, the larger storage capacity will increase the treatment efficiency because the size of storage will capture a spectrum of storms. This can be determined by evaluating the overflow rate which is a function of inflow rate and pond surface area. Thus, settling will be maximized when pond storage volume and/or surface area is increased. Another factor that affects the removal efficiency is the volume of storage capacity in relation with the volume of runoff produced by different sized storms. For example, if the incoming runoff volume is less than the storage volume of the pond, the entire runoff volume will be captured by the pond and will be treated until the next runoff event arrives. Conversely, if the incoming runoff volume is significantly larger than the pond storage volume, a fraction of storm runoff will be bypassed/ overflowed with little or no treatment. Therefore, to obtain a long-term reliable and high efficiency treatment of sediment performance, it is important to provide adequate storage volume. In addition, as sediments accumulate over the time, storage capacity decreases which affect the long-term performance over time.

Presence of a Permanent Pool

There can be a significant difference in performance of sediment control ponds that are designed as a dry pond (without permanent pool) and wet pond (with permanent pool). In some cases, the ponds are intentionally designed to dewater as quickly as possible between the events through the control of outflow rate, allowing infiltration and/or evaporation. From a performance standpoint, the key question is whether the presence of permanent pool has any influence on the treatment efficiency of the pond. There are several advantages of having a permanent pool in a sediment control pond with respect to sediment removal and which include the following evident benefits:

- Permanent pool acts as a barrier to the resuspension of previously accumulated sediments and prevents scouring of the bottom of the control device. This is very critical for fine-grained particles that are very common in construction sites.

- Permanent pool creates a better settling environment than a dry pond as it decreases the energy of incoming runoff and thus reduces the turbulence within the pond resulting in quiescent condition.

- Permanent pool can reduce the sediment concentration of the “first flush”, which is typically very high for construction sites, and can provide better treatment efficiency.

Construction Site History and Erosion Potential

It has been observed that there is an intrinsic relationship between construction phases (or construction sequencing) and sediment releases in runoff from the site. In this section different construction phases and their influence on erosion and erosion control measures are discussed. The construction history in a site/sub-watershed can be divided into five distinct stages. The division is based on the modelling convenience rather than exact stages. The construction stages are:

1. Stage 1: Stripping topsoil and grading for access

2. Stage 2: Full clearing and grading
3. Stage 3: Installation of storm drainage systems and roads
4. Stage 4: Active construction of structures
5. Stage 5: Site stabilization and completion of construction activity

In order to illustrate the effects of construction history in a site/sub-watershed on erosion and hydrology, an idealized form is developed and presented in Figure 2.1.

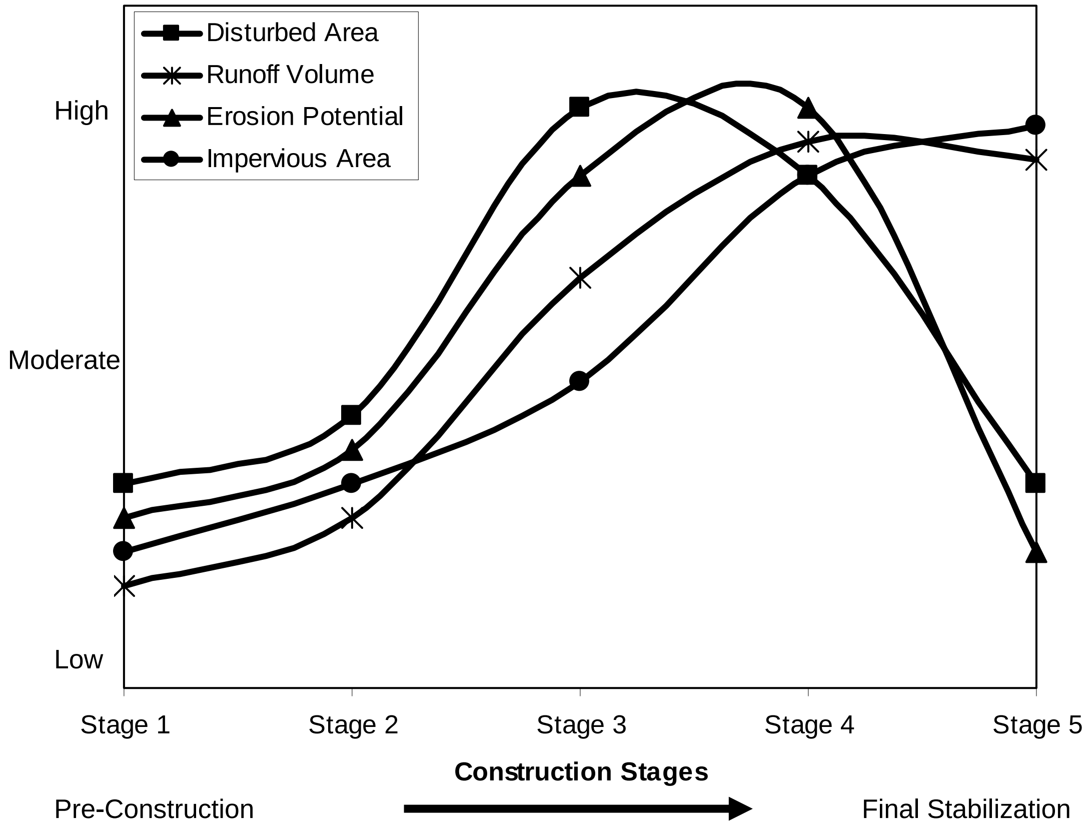

Figure 2-1: Idealized illustration of the effects of construction site history on erosion and hydrology

Stage 1: Stripping topsoil and grading for access

Storm runoff volumes and rates during the pre-construction stages are low relative to other stages because of vegetative cover and high hydrologic losses and consequently the erosion potential is small. At this stage ESC measures (e.g., sediment control pond, sediment trap) are typically installed and they can have their greatest effective capacity. During the pre-construction clearing storm runoff volumes are slightly increased, however, much of the site still remains undisturbed. Erosion rates can be moderate to high in disturbed areas, depending on the effectiveness of soil cover and other erosion controls. Construction site entrances (Figure 3) need to be planned and designed to prevent soil from leaving the site. A gravel construction entrance built to proper specification (e.g., a minimum of 30 m with a minimum depth of 15 cm) can significantly reduce the amount of soil leaving the site. Depending upon the site conditions effective capacity of erosion control measures remains original standards.

Figure 2-2: Construction site entrance

Stage 2: Full clearing and grading

This stage prepares the site for construction of roads and drainage system and involves extensive site clearing conducted by heavy equipments (Figure 4). Storm runoff volume increases considerably due to greater soil compaction and grading. The disturbed area of the site reaches its maximum extent. Erosion rates are moderate to high depending upon the site condition and earth moving activities. Sometimes by loosening large amounts of soil due to earthmoving activities, runoff can carry substantial amounts of sediment to flow into storm drains or sediment control structures. The effective storage capacity of the sediment control ponds begins to decrease with the accumulation of sediments.

Figure 2-3: Heavy Equipments for clearing and grading

Stage 3: Installation of storm drainage systems and roads

The outlet storm volume increase greatly after the installation of storm pipes, because of their efficient drainage conveyance. After installation, the site is subjected to compaction and laying out of roads, which increases the imperviousness resulting in more runoff volume. At this stage, the efficiency of the sediment control pond may decrease because of previously accumulated sediments and greater runoff volume.

Stage 4: Active construction of structures

Storm runoff volumes reach their maximum level depending upon the site condition as the construction site progress towards ultimate imperviousness and remaining areas becomes compacted. Storm drain systems are functional efficiently conveying the runoff and sediments to the sediment controls. Although the disturbed areas subject to erosion are significantly reduced, the erosion rates often very high from the remaining disturbed areas (i.e., non-floor area in a lot) due to the reduced effectiveness of temporary stabilization techniques. The washoff of sediment tracked onto the impervious area become an important source of sediment mostly due to construction vehicles and piling of construction materials. Effective capacity of sediment controls reaches their lowest level during this stage.

Stage 5: Site stabilization and completion of construction activity

In this stage the construction site is mostly converted to post-development catchment where disturbed areas are permanently stabilized by vegetation (e.g., sodding). Accordingly, the imperviousness of post-development governs the storm runoff volumes. Runoff volumes may be slightly less than the previous stage because of stabilization of disturbed areas with vegetation. The main source of sediments will be from the washoff of solids from the impervious surfaces rather than the erosion from disturbed areas. At this stage typically all the sediment controls are removed. In the case where the ultimate SWM pond was used as sediment control pond, the accumulated sediment needs to be cleaned to hand over to municipality.

Sediment Flocculation

For construction sediment control ponds where the concentration of suspended solids is typically very high, flocculation can be an important factor for removal of suspended solids. The high concentration of suspended solids can increase the net settling velocity of the particles due to flocculation effects, which is due to interference effects (Metcalf and Eddy, 1979). In this case, the number of particulates per unit area is high and they settle together with a higher rate than the discrete settling. Flocculation becomes dominant for fine-grained soils such as clays and silt, where the primary particles can coalesce due to electrochemical attraction among the particles. The laboratory settling studies of urban runoff by Randall et al. (1982) suggests that the amount of sediments removed through settling increases with increasing initial concentration of TSS (Table 2). It is noted that the laboratory condition is non-dynamic unlike the actual field condition which characterized by turbulence and short-circuiting.

Table 2-1: Time required to achieve 60% removal at 4 ft depth

Initial TSS, mg/L	15	35	38	100	155	215	721
Settling time, hours	38	24	8	5	1.0	1.5	0.5

Proper Design of an ESC Plan

Proper design of an ESC plan can have significant influence on the amount of sediment discharged from the site. For large construction sites sediment control ponds will be more effective if the ESC plan can prevent sediments from leaving the site. The ESC plan should clearly outline the erosion control measures with respect to construction sequence, and where and how stream/wetland/forest protection measures are employed. It is important that earth moving contractors should read grading and ESC plans routinely such that stream protection measures are not disturbed. An effective ESC plan is one which combines the standard specifications of individual ESC practices and how these practices are maintained in the field. The major elements of an effective ESC plan include [Urban Construction Study (2001) and Schueler and Holland, (2000)]:

1. Minimize needless clearing and grading
2. Protect waterways and stabilize drainage ways before any constrction
3. Phase construction to limit soil exposure
4. Immediately stabilize exposed soils
5. Protect steep slopes and cuts
6. Proper installation of ESC measures
7. Install perimeter controls to filter sediments
8. Employ advanced sediment settling controls, sediment control ponds
9. Adjust ESC plan at construction site
10. Assess ESC practices after storms
11. Certify contractors on ESC plan implementation

<u>Proper Installation and Maintenance</u>

Proper installation and maintenance of sediment control ponds and ESC measures can have significant effects on the removal of sediments from the runoff. Special attention is required during the installation of inlet and outlet structures, pipe spillways for sediment control ponds.

Sediment control ponds require routine maintenance to remain effective. The permanent pool for the sediment control ponds should be cleared of sediments periodically to maintain sufficient treatment volume. The permanent pool must be cleared the accumulated sediments when there is a 5% reduction in removal efficiency. If the outlet becomes clogged with sediment, it should be cleaned to restore its flow capacity. The structure should be inspected after significant runoff events to check for damage or operational problems.

The best way to decrease the amount of sediment leaving the sediment control pond and sediment traps is to reduce the amount of sediments entering them which can be achieved by appropriate application of vegetative and non-vegetative ground covers.

3 Particle Size Distribution of Stormwater Runoff

In the previous section, we found that particle size distribution (PSD) of solids in urban runoff has a direct influence on the treatment of runoff, particularly the performance of SWM facilities. In this section a comprehensive review of PSD of runoff solids from urbanized and urbanizing catchments is attempted. Available data on PSD of solids are analyzed to determine the practical limit of particle sizes for planning and design of effective runoff quality control devices, especially SWM facilities.

In stabilized catchments, many sources of sediments found in stormwater runoff include atmospheric deposition, anthropogenic activities on the impervious areas (e.g., traffic activities on roads and parking lots) and soil erosion from pervious areas. These solids vary in size from microscopic clay to fine gravels. The particle size distribution of sediments is dependent upon many factors which can be attributed to watershed conditions, vehicular activity, percent imperviousness, wind patterns, climate, rainfall/runoff characteristics and de-icing materials. On the other hand, in urbanizing catchments, construction activities are the primary sources of solids in stormwater runoff because of soil erosion and sediment transport. These solids whether from urbanized or urbanizing catchments constitute a significant source of pollution to water quality of receiving waters as described in section 1. Total solids typically found in urban runoff include both total suspended solids (TSS), the portion of solids retained by a filter (i.e., 0.45 μm) and total dissolved solids, the portion that passes through the filter.

It is well recognized that most pollutants of concern have a high affinity for the TSS in stormwater runoff and for soil particles. As these pollutants are attached to the solids, the removal of TSS will also remove many of the other pollutants (Stahre and Urbonas, 1990; and MOE 1994). Therefore, the most logical way to treat stormwater is through sedimentation and infiltration. The treatment of stormwater runoff by storage facilities (e.g., SWM ponds) occurs primarily through sedimentation and by vegetative controls (e.g., grass swales) occurs through filtration. SWM facilities remove suspended solids and associated pollutants by providing residence time for particles to settle through primarily gravitational settling. The settling of particulates is characterized by the settling velocity that is directly related to particle size distribution (PSD) of runoff (e.g., Stokes law). Therefore, the estimation of removal of suspended solids (or treatment level) requires knowledge of PSD of stormwater and corresponding settling velocity characteristics.

3.1 Particle Size Distribution of TSS

Two types of approaches are typically employed to measure the PSD of solids found in stormwater runoff. First, measurement of particle size of solids that are found in the street surfaces and other impervious surfaces (Sartor and Boyd, 1974 and Sutherland et al., 1998) assuming that these particles end up with urban runoff. Secondly, the direct measurement of particles sizes in the stormwater runoff, particularly in TSS concentration (Randall, 1982 and U.S EPA 1983). Furthermore, in the recent years many field studies have been undertaken related to stormwater quality control devices (e.g., SWM facilities and oil grit separators) to understand the effectiveness of treatment devices, where the PSD of influent and outflow runoff are measured (SWAMP studies).

Sediment particle sizes range from big, bulky cobbles to microscopic clays. To analyze the characteristics of stormwater sediments from treatment perspective a general classification of sediment particles ranging from average diameter from 10^{-4} to 10^{6} μm are shown in Figure 3.1.

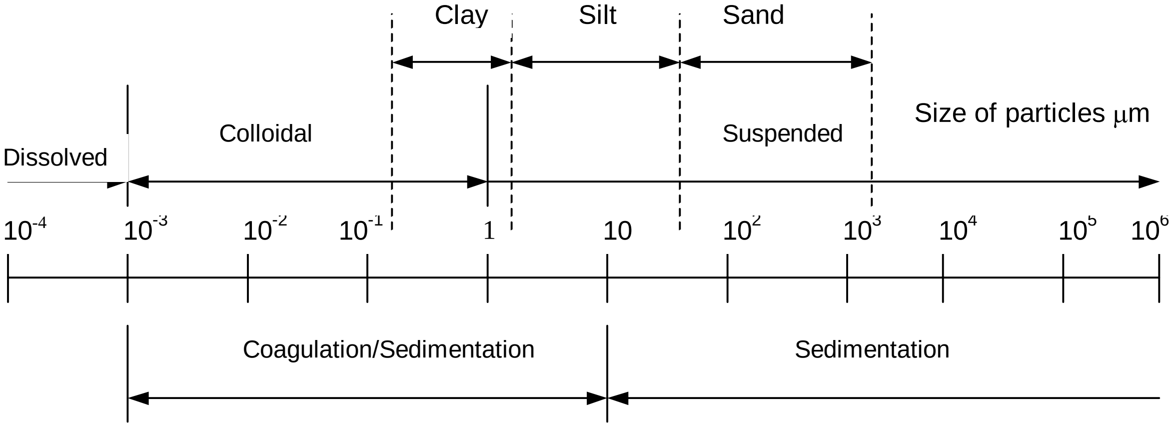

Figure 3-1: Characteristics of sediment particles (Metcalf and Eddy, 1979)

Laboratory PSD and settling tests of TSS along with associated other runoff pollutants were conducted by Whipple and Hunter (1981) and US EPA NURP program (1983) and have been continuing since then. Many studies have documented PSD in stormwater runoff around the world and some of the stormwater runoff PSD data is presented herein for reference.

The measurement of stormwater PSD is typically conducted by two types of techniques – traditional sieve analysis and advanced optical technique. The PSD data presented herein follows the Standard Methods of PSD measurements. Table 3 presents the PSD of stormwater runoff samples collected from oil grit separators located in various places in Ontario. It is observed that in most of the cases more than 80% of influent particles are smaller than 75 μm. The data collected in other U.S sites by suggests the similar conclusions that the runoff contains more fine-grained particle sizes.

Table 3-1: Strormwater runoff PSD collected from Oil Grit Separators located in different places in Ontario

Particle Size (μm)	% Finer			
	Residential Area, Guelph	Municipality Road, North York	Exxon Gas Station, Markham	Cosco Parking Lot, Burlington
4000	97.5	99.5	99	99.5
2000	97	99	98	99
750	96.5	98.5	96	98
425	96	97	93	92
250	95	93.5	88	89
150	94	91	82	86
75	**88**	**88**	**71**	**82**
45	63	79.5	15	59
33	62	76	14.5	58.5
25	61	74	14	58
18	58	69	13.5	57
12	54	63	13	52
8	49	58	12	50
6	43	50	10	41.5
4.5	38	38.5	7.5	31.5
1.5	23	29.5	7	23

Source: Graham Bryant, CHI discussion group.

Randall et al. (1982) collected the stormwater runoff samples from three shopping center parking lots in Virginia and analyzed the PSD of a range of suspended solids concentrations (Table 4). They reported that over 80% of the total particles found in runoff were less than 25 μm.

Table 3-2: Stormwater samples from three shopping center parking lots in U.S.

TSS (mg/L)	% Finer						
	15 μm	25 μm	35 μm	45 μm	55 μm	65 μm	> 65 μm
15	64	85	92	95	97	98	100
35	48	68	79	85	89	94	100
38	54	77	87	92	95	97	100
100	52	75	86	92	95	97	100
155	54	79	91	95	97	98	100
215	63	85	94	98	99	100	100
721	65	92	96	98	99	100	100
Average	57	80	89	93.3	96.6	98.3	100

Source: Randal et al., 1982.

In another study conducted by the U.S. Federal Highway Authority, the PSD of stormwater samples from highways indicated that the majority of particles were less than 88 μm (Table 5).

Table 3-3: PSD of Highway runoff samples

Wet Sieving Analysis of Highway Runoff Composite Samples					
Particle Size	Sacramento	Harrisburg	Milwaukee	Effland	Mean value
≤ 44 μm	79 %	76 %	73 %	87 %	78 %
≤ 88 μm	90 %	88 %	80 %	95 %	87 %

Source: Rinkers Materials

From the above studies it is observed that PSD of suspended solids stormwater runoff (in North America) is biased towards FINER particle size ranges, i.e., predominantly fines. Very few particles larger than 1000 μm are found in stormwater runoff and most of the particle sizes are within 100 μm.

In order to evaluate the performance of SWM facilities within Greater Toronto Area, a consortium of local and provincial stormwater agencies have been initiated few studies under Stormwater Assessment Monitoring and Performance Program (SWAMP). The PSD of TSS observed in two SWM facilities during the monitoring program are presented in the following section.

3.1.1 PSD of TSS at Harding Park SWMF

The Harding Park storm water management facility (SWMF), a wet extended detention pond with wetland, is located in the town of Richmond Hill. Harding Park facility has three cells, including a shallow forebay, a six-foot deep permanent pool and a small wetland, designed for Level 2 protection.

The study of PSD of TSS for the Harding Park SWMF reported that the median particle size of average PSD was approximately 4.5 and 2.3 μm at the inlet and outlet, respectively. Particles greater than 4 μm accounted for 55% of the inlet PSD compared to 35% of the PSD at the outlet, indicating size selective removal of TSS. On the other hand, particles less than 4 μm accounted for 45% of the inlet PSD compared to 65% of the PSD at the outlet, indicating resuspension of settled particle or certain smaller size particles never able to settle out.

Table 6 summarizes the particle class mass proportions and performance of Harding Park SWMF. The analysis assumes negligible density differences among size categories and includes only 5 storms for which PSD data were available at the inlet and outlet. Particle size masses are calculated for sizes between 1.7 to 999 μm because laboratory analysis of suspended solids from which masses are derived, excludes particle sizes less than 1.69 μm. By volume, this 'omitted' fraction accounts for 26% and 36% of all particles at the inlet and outlet respectively. Among size classes greater than 1.7 μm, removal efficiencies for TSS ranged from 48% to 81%, and as expected, higher performance was associated with larger particle size classes.

Table 3-4: Particle size class mass, mass proportion and performance (n=5)

Particle class	Size Range	Inlet Mass (kg)	Inlet (%)	Outlet mass (kg)	Outlet (%)	Performance (%)
Fine to coarse sand	62 –999 μm	54	3.8	10	1.1	81
Silt	3.7 – 62 μm	652	51.7	229	33.5	65
Clay	1.69 – 3.7 μm	245	18.8	127	28.9	48
Fine Clay*	0.17 – 1.69 μm	-	25.7	-	36.5	-
Total		951	100	366	100	61

Laboratory measurement of TSS concentrations only included size fractions greater than 1.5 to 2 μm; therefore masses could not be calculated for the 0.17 to 1.69 μm size fraction

From the Table 6, it is apparent that 96.2% of inlet mass constitute particle sizes less than 62 μm and 98.9% of outlet mass constitute particle sizes less than 62 μm. The particle size of 3.7 μm or less comprises 44.5% of inlet mass and 65.4% of outlet mass indicating that the effluent contains mostly very fine particles.

3.1.2 Pond-Wetland SWM Facility, Markham

The Markham SWMF, is a wet pond with wetland retrofit located in Upper Morningside tributary of Rouge River Watershed. This multi-objective SWM facility was designed to provide flood, erosion, water quality control and base-flow augmentation. It has three cells, including a sediment forebay, large wet pond and wetland.

This SWAMP study has provided the PSD of TSS concentration at various locations, (i.e., inlet, wet pond outlet and wetland outlet). It is reported that like other SWMFs in southern Ontario, fine particles dominated the PSD, with 98% of particles smaller than 62 μm. (silt and clay). During the summer/fall, the average median particle sizes were 3.8 μm at the inlet (weighted average) compared to approximately 2.0 μm at the forebay, wet pond and wetland outlets. During dry weather, medium particle sizes at the Markham BMP ranged from 2.6 μm at inlet to 0.85 μm at the wet pond outlet. However, the median particle size increased by 0.65 μm from the wet pond to wetland indicating that resuspension of settled particle or certain smaller size particles that were not able to settle out.

Table 7 summarizes TSS concentrations and particle size mass fraction for find sand, silt and clay groups. Similar to Harding Park, in Markham facility 97.7 % of inlet mass constitute particle sizes less than 62 μm and 100% of outlet mass constitute particle sizes less than 62 μm. The particle size of 3.7 μm or less comprises of 28.4 % of inlet mass and 61.7 % of outlet mass. This data indicates that the PSD of TSS in stormwater runoff from urbanized catchments are mostly finer and less than 100 μm.

Table 3-5: Particle size class mass, mass proportion and performance

Particle size class	Size Range (μm)	Wet weather average TSS Concentration (mg/L)			Particle size mass fractions (%)		
		Inlet	Wet pond outlet	Wetland	Inlet	Wet pond outlet	Wetland Outlet
Fine to coarse sand	62 –999	6.9	0.02	0	2.3	0.04	0
Silt	3.7 – 62	210.1	6.9	8.8	69.3	47.9	38.3
Clay	1.69 – 3.7	86.2	14.3	14.2	28.4	52.0	61.7
Total		303.2	21.2	23.0	100	100	100

Laboratory measurement of TSS concentrations only included size fractions greater than 1.5 to 2 μm; therefore masses could not be calculated for the 0.17 to 1.69 μm size fraction

3.1.3 PSD of Construction Sediments

Schueler and Lugbill (1990) studied the performance of sediment basins and traps at different construction sites in Maryland. They reported that the PSD of incoming sediments to control devices was extremely fine-grained, primarily consisting of fine silts, clays and colloidal materials. They observed that 50% of all incoming sediments are less than 10 μm in size.

3.2 Particle Settling Velocities

The quality control performance in terms of removal of suspended solids in a SWM facility requires knowledge of the settling velocities of the particles comprising of TSS load. The principal factors affecting the settling velocity of a solid particle are particle size, specific gravity (or density), shape of the particles, the viscocity and density of the medium (i.e., water), and other factors such as temperature. Typically solids in stormwater runoff from urbanized catchments are dominated by particles with relatively high specific gravities; thus, if large enough are readily settleable in the SWM facilities. The typical range of specific gravities of stormwater solids is between 1.5 and 2.5 (Pitt, 2000). Generally, particles larger than 10 μm and with specific gravities greater than 1.0 are considered settleable (Nix et al., 1987) which indicates that stormwater treatment can be achieved through sedimentation process.

Generally, the estimation of settling velocities of runoff solids are based on sizes, specific gravities and fluid properties and these estimations are limited to a few idealized shapes (i.e., spheres). The settling velocity of discrete particles is primarily based on Stoke's and Newton's relationships. As 90% of stormwater particulates fall within 1 to 100 μm range, corresponding laminar condition suggest use of Stoke's law. Typically settling velocities for urban runoff solids are determined by settling column tests in a laboratory environments. The settling velocities and time required to settle one meter under laboratory condition for a wide range of sediment particles (i.e., sand, silt and clay) are provided in Table 8.

Table 3-6: Particle size and settling velocities of sediments

Particle size Classification	Particle Diameter (m)	Settling Velocity (m/hr)
Very coarse sand	1000 – 2000	39.0144
Coarse sand	500 – 1000	19.812
Medium sand	250 – 500	10.363
Fine sand	125 – 500	4.877
Very fine sand	62 – 125	1.829
Coarse silt	31 – 62	0.427
Medium silt	16 – 31	0.122
Fine silt	8 – 16	0.0305*
Very fine silt	4 – 8	0.0061*
Clay	< 4	0.0168*

* Discrete particles in still water
Source: Schueler and Lugbill (1990)

It may be noted that particles between 62-125 μm size range can theoretically settle nearly 60 times faster than particles between 8-16 μm size range.

The U.S. EPA has documented the typical setting velocities for runoff solids, which was obtained during EPA's Nationwide Urban Runoff Program. A total 46 settling tests from seven sites were used to provide an overall picture of settleability of stormwater solids. Based on U.S. and Canadian data MOE SWM BMP Manual (1994) group the settling velocities of stormwater solids into six distinctive size fractions for the SWM facility design criteria which is presented in Table 9.

Table 3-7: TSS settling velocity distribution of urban runoff solids

Size Fraction	Particle Size Range	Fraction of Total Mass Contained in Size Fraction	Average Settling Velocity (m/hr)
1	$x \leq 20\ \mu m$	20%	0.00914
2	$20\ \mu m < x \leq 40\ \mu m$	10%	0.0468
3	$40\ \mu m < x \leq 60\ \mu m$	10%	0.0914
4	$60\ \mu m < x \leq 130\ \mu m$	20%	0.457
5	$130\ \mu m < x \leq 400\ \mu m$	20%	2.13
6	$400\ \mu m < x \leq 4000\ \mu m$	20%	19.8

The settling of particles occurs two ways. First, the coarser particles settle out as discrete individual particles. The smaller particles on the other hand tend to agglomerate with time into larger particles and their settling velocities then accelerate. As a result, simple settling estimates using Type 1 settling theory may not reveal the actual mechanism of removal; only it can approximate the complex settling process. Moreover, Type I settling theory assumes quiescent flow condition which may be more applicable for the condition between the runoff events when sediment facilities are relatively static and calm. However, during runoff events facilities may experience multi-layered flow, turbulences, eddies, circulation of currents, short-circuiting, dead spaces and diffusion at inlets and outlets (Schueler and Holland, 2000). These factors lessen the removal capability of the facility, particularly with respect to the very finer particles (i.e., silt and clay) that often dominates urban runoff solids including construction site runoff.

3.3 Summary of PSD of Stormwater Runoff TSS

It is noted that the PSD data presented previously are representative only of the sampling sites from which they were taken. They may or may not be representative of other urban sites. However, we may believe that the data from literature and current studies in Ontario may provide the reasonable trends found in urban stormwater runoff. From the literature and available field data, the following general conclusions can be drawn:

- The prediction of long-term suspended solids removal performance of stormwater detention facilities is depended upon the particle size distribution of solids and their settling characteristics.

- It is observed from the recent studies that the suspended solids particle size distribution for urban stormwater runoff has become highly positively skewed, tending towards FINER particle ranges (i.e., silt and clay).

- Most of the solid particles found in runoff are less than the 100 μm size.

- From stabilized catchments around 50% of TSS load comes from the particle size smaller than 10 μm. This observation is attributed to less energy is usually required to detach, entrain and transport smaller particles in the overland flow.

- The design particle size is a convenient representation of the entire range of incoming sediment particles to the treatment facility. The current design criteria of SWM facilities (MOE, 1994) assumes that more than 50% particles have a particle size more than 100 μm which appear to be on the coarser particle size range compared to what is observed in the runoff (i.e., finer particle size range). Therefore, it is possible that the estimation of removal efficiency based on existing criteria may not reflect the actual field condition.

- Finer particles tend to behave as non-settleable solids because of their size. The electrostatic force generated by their extremely small size tends to impede settling. They posses high cat-ion exchange capacity and large surface to weight ratio (SWAMP Study, Markham and Richmond Hill, 2002). Thus, it may be very difficult to effectively remove most particles less than 10 μm in size by sedimentation alone (Schueler and Holland, 2000).

- The finer PSD requires longer detention time for their effective removal from runoff. Finer-sized particles have slower settling velocities and tend to remain suspended within the facility. This was exemplified in the Harding Park and Markham facilities, as the median particle size from the wetland is greater than wet ponds, which is located before the wetland in the treatment-train.

- Theoretically, a longer detention time will provide greater removal efficiencies. However, field and laboratory data have shown that most settling occurs within the first few hours and settling decreases with additional increasing detention time. As much as 60% of total removal is accomplished within the first six hours (Schueler and Lugbill, 1990).

4 Modelling Construction Sediment Control Ponds

This section describes the approach that will be adopted for modeling a construction sediment control pond. The objective of the modeling exercise is to develop improved technical criteria for sizing construction sediment control ponds. It has been proposed that the current ongoing runoff quantity and quality monitoring data from Ballymore pond will be employed for the development of a continuous simulation model for construction sediment control pond.

Clarifica Inc. (2002) evaluated the modeling tools that are suitable for simulating the physical conditions of a construction site and accompanied sediment control device (i.e., sediment control pond). It was suggested that a continuous simulation model should be developed which would integrate runoff, erosion, sediment transport and sediment accumulation. Several models were evaluated including HSPF, WASP, SWMM and QUALHYMO.

4.1 Development of Analysis Methodology

In order to develop improved sizing criteria for designing construction sediment control ponds/SWM facilities the following steps are planned:

- *Evaluation of physical processes*: This step identifies the influencing factors of pertinent physical processes involved in the analysis and most of the factors are presented in Section 2.

- *Evaluation of modeling methodology*: In this step a suitable continuous simulation model will be identified which is capable of simulating the physical processes identified in the previous step. It is proposed that the US EPA SWMM model will be used to develop the continuous simulation model of Ballymore Pond and its contributing catchment.

- *Calibration and verification of the simulation model*: The meteorological, hydrological, and catchment condition along with the construction site condition data for the Ballymore pond will be used to calibrate and verify the simulation model. The calibration and verification will be conducted in two steps:

    - Simulation of runoff volume and erosion processes; and

    - Simulation of sediment control pond.

- *Performance analysis*: The calibrated model of sediment control pond will be used for performance analysis where the model will be executed for a range of scenarios with varying physical characteristics (e.g., different construction phases) and different climatic conditions which will provide the entire rage of possible values of design parameters. Using the Storage-Treatment block of U.S. EPA's SWMM, isoquants of percent removal of suspended solids will be developed for various range of storage volume and outflow rates. From the values of design parameters a design envelop can be constructed (i.e., design parameter vs. treatment efficiency).

- *Development of theoretical receiving water quality approach*: The relationship between design criteria (i.e., treatment level) and receiving water impacts, particularly in terms of assimilative capacity of the stream, will be developed.

4.1.1 Selection of Model for Analysis

It is proposed that U.S EPA's SWMM model will be used for the analysis of construction sediment control pond. The preference of the SWMM is due to the following reasons:

- SWMM is a public domain software whose source code is readily available;
- Professional engineers of Southern Ontario are familiar with SWMM;
- The erosion simulation processes is simpler to use;
- The current design criteria (MOE 1994) for SWM facilities was developed with SWMM;
- Greater modeling flexibility.

4.2 Techniques for Predicting Long-term Performance

The techniques for predicting long-term TSS removal (or the removal of any other pollutant) in the SWM ponds/sediment control ponds can be classified into three groups:

1. Empirical estimation

2. Statistical models

3. Deterministic models

Empirical estimation technique uses a spectrum of data from a number of systems to relate long-term removal to simple system parameters. For example, development of removal efficiency curves based on storage-outflow relationships, and development of relationships between flow and concentration data with system design parameters. The treatment efficiency is estimated based on percentage of inflow and outflow TSS concentration or inflow and outflow load.

The statistical techniques rely on statistical representation of rainfall characteristics and relatively simple representation of physical systems (Howard, 1976, Hydroscience Inc, 1979, Li, 1991, Behera et al., 1999, Adams and Papa, 2001). These techniques are based on simplified representation of physical systems. They typically generate probability distribution of output variables (i.e., runoff volume, runoff load) instead of generating the output time series of flow and concentrations to the input responses. They require little computational efforts compared to the deterministic models, thus are recommended for planning and design level analysis.

A number of deterministic models have been developed to simulate hydrology and SWM facility performance over extended periods of time [STORM – Hydrologic Engineering Centre, (1977), SWMM – Huber and Dickinson, (1988)]. However, most of these models are not very sophisticated in their formulations of various pollution removal processes. Their approach is to mostly ‘book keeping’ i.e., keeping track of system inputs and outputs and developing performance statistics (Nix, 1987). The major advantages of these models over empirical and statistical techniques are that they have the ability to handle a wide range of conditions and pond configuration and to simulate over time. However, these advantages are in lieu of significant computational burden.

4.2.1 Review of Erosion and Sediment Generation Modules of SWMM

A continuous simulation model for the Ballymore pond and its contributing catchment will be developed using the RUNOFF block of SWMM. The quality module of RUNOFF block will be used to simulate the soil erosion and to depict the construction site scenarios over time. The basic computational algorithm of modeling urban erosion employed in SWMM is the Universal Soil Loss Equation (USLE). The USLE was derived from the statistical analysis of soil loss and associated data obtained in 40 years of research by Agricultural Research Service (ARS), U.S. The data include more than 250,000 runoff events at 48 research stations in 26 states, representing about 10,000 plot-years of erosion studies under natural rain.

It was developed by Wischmeier and Smith (1958) to estimate average annual soil erosion from rainstorms for given upland area, L, expressed as the average annual soil loss per unit area, (tons per acre per year):

$$L = R \cdot K \cdot LS \cdot C \cdot P \qquad (1)$$

Where

R = the rain factor,

K = the soil erodibility factor,

LS = the slope length gradient ratio

C = the cropping management factor or cover index factor, and

P = the erosion control practice factor.

This model represents a comprehensive attempt at relating the major factors in soil erosion. It is used in SWMM to predict the average soil loss for a given storm or time period. It is recognized that the USLE was not developed for making predictions based on specific rainfall events. There are many random variables, which tend to cancel out when predicting individual storm yields. For example, the initial soil moisture condition, or antecedent moisture condition, is a parameter that cannot routinely be determined directly and used reliably.

Input Parameters

Erosion Simulation: In SWMM erosion simulation falls under water quality component of RUNOFF module. Erosion is treated as an additional water quality constituent, so that one of fewer pollutants can be simulated. In addition, it is required that at least one quality constituent must be simulated (e.g., TSS). No particular soil characteristics (e.g., particle size distribution) are assigned to the erosion parameter, and its title is “Erosion” with units of mg/L, in the output.

To simulate soil erosion in SWMM, the parameter IROS in data-group J1 is to be indicated. Erosion may be added to another constituent, e.g., suspended solids, if desired using parameter IROSAD in-group J1. However, the Erosion parameter will also always be maintained as an individual parameter throughout the RUNOFF Module.

Other input parameters are:

1. The maximum 30-minute rainfall intensity of the storm (single event) or of simulation period (continuous), RAINIT, (group J1);

2. The area of each subcatchment subject to erosion, ERODAR, (group K1);

3. The flow distance in feet from the point of origin of overland flow over the erodible area to the point at which runoff enters the gutter (link) or inlet (node), ERLEN, (group K1);

4. The soil factor K, SOILF, group K1)

5. The cropping management factor C, CROPMF, (group K1) and

6. The control practice factor P, CONTPF, (group K1).

4.2.2 Review of Storage and Treatment Modules of SWMM

The Storage/Treatment Block of SWMM model provides the capability of simulating wet-weather simulation of a SWM facility (Huber and Dickinson, 1988 and Nix, 1987) including:

- The ability to model a wide range of SWM pond geometries and outlet structures;
- The ability to characterize pollutants by particle size and specific gravity or settling velocity distributions and to simulate particle settling;
- Provision for two modes of pond modelling – plug flow or completely mixed reactors;
- Provision of number of different types of equations to represent the pollutant removal process in the plug flow mode;
- The modelling of pollutants as first order reactants in the completely mixed mode.

A Ballymore sediment control pond model will be developed using the Storage-Treatment block of SWMM to simulate the long-term TSS removal by the pond. The hydrologic model which will provide time series of flow and suspended solids concentration from the contributing catchment will be linked with the storage-treatment pond model. The Pond model will be calibrated and verified with the monitored runoff quality data, especially particle size distribution of solids, and TSS concentration. After the calibration and verification, the catchment will be subjected to different construction phases and the performance of the pond will be evaluated for each scenario.

In addition to continuous simulation, the calibrated model will be run for design events to assess the removal efficiency for single event scenarios.

5 Summary and Conclusions

It is evident that construction activities in the urbanizing watersheds can contribute significantly to stormwater pollution problems and can have adverse impacts on our receiving waters and aquatic resources. To address this problem there is a need to develop efficient erosion and sediment control practices and its implementation procedures. A number of initiatives that are undertaken by TRCA are documented in this report.

A literature review on influencing factors that affect soil erosion in construction sites and performance of sediment control facilities has been described. Based on the finding of literature review, it is observed that particle size distribution of stormwater runoff solids and their settling characteristics have a major influence on the long-term suspended solids removal performance of SWM facilities and construction sediment control ponds. It is observed from the recent studies that the suspended solids particle size distribution for urban stormwater runoff has become highly positively skewed, tending towards FINER particle ranges (i.e., silt and clay). Most of the runoff particulates are less than the 100 μm size. The current design criteria of SWM facilities (MOE, 1994) assumes that more than 50% particles have a particle size more than 100 μm which appear to be on the coarser particle size range compared to what is observed in the runoff (i.e., finer particle size range). Therefore, it is possible that the estimation of removal efficiency based on existing criteria may not reflect the actual field condition; thus, there is a need to re-examine SWM facility/sediment basin design theory and application by focusing on the increased removal of smaller particles. Some steps towards this goal include the following:

1. Selection of smaller design particles, more in the line of silt and clay dominated runoff;
2. Provide more storage yielding longer detention time which will improve the pond performance during small, frequent storms;
3. Provide permanent pool for sediment control ponds for large construction sites;
4. Decrease the incoming amount of sediment loads by implementing effective erosion and sediment control practices for urbanizing watersheds and by implementing source controls for urbanized catchments;
5. Develop effective erosion and sediment control practices and its planning and implementing processes.

These first two recommendations will be verified in the modeling exercise of construction sediment control pond. A continuous simulation model of the Ballymore construction sediment control pond will be developed to understand the performance of the facility and associated catchment construction activities. The adequacy of the current design criteria of construction sediment ponds will be verified. The recommendations for revised design criteria, which will improve the sediment removal efficiency to protect receiving waters, will be obtained.

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