Planning and Design of Combined Sewer Overflow Treatment

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A newly produced (2004) Combined Sewer Overflow (CSO) Treatment Technologies Manual provides an overview of practices in, and guidance for, planning, design and implementation of CSO treatment. Towards this end, the manual first addresses CSO abatement program planning in order to provide an overall framework within which the application and design of CSO treatment facilities may be considered. Following the establishment of a planning framework, guidance is provided for CSO treatment facility preliminary design, which encompasses such steps as the development of CSO control and treatment objectives, assessment of design flows, development of a treatment process train, site-specific considerations, and costs and operating and maintenance (O&M) factors. Finally, preliminary design considerations are developed in more detail for CSO retention treatment basins (RTBs), which are commonly applied to control and treat CSOs in the Great Lakes municipalities. Well-designed RTBs can meet the Ontario requirements for CSO pollution abatement and thereby contribute to the remedial action in the Great Lakes Areas of Concern.

Key words: combined sewer overflows (CSOs), abatement planning, treatment, retention treatment basins, design

Introduction

The older parts of many Canadian municipalities are served by combined sewers, which in dry weather collect wastewater and transport it directly to a wastewater treatment plant (WWTP). However, in wet weather, inflows of stormwater or snowmelt can exceed the hydraulic capacity of the collection system. The excess flow is released as combined sewer overflows (CSOs), in order to prevent basement flooding and damage to downstream pumping and treatment facilities.

Even though construction of new combined sewer systems was abandoned about half a century ago, the environmental problems associated with CSOs from these systems persist to this day. The Great Lakes region of both Canada and the United States in particular has been impacted by CSO discharges resulting in beach closures as well as impacts on water, sediment and aesthetic quality. Ten of the original seventeen Canadian Great Lakes Areas of Concern (AOCs), identified by the International Joint Commission (IJC) as requiring remedial action, receive CSOs (Weatherbe and Sherbin 1994).

Over the last 30 years a broad array of CSO abatement technologies has been applied in these AOCs, including:

- Full or partial sewer separation whereby new sewers are installed to fully or partially separate runoff from sanitary wastewater.
- Tank storage facilities to retain CSO flows until sewer and/or WWTP capacity becomes available following storm events.
- Tunnels, which serve to store and transport CSO to the WWTP.
- Increased central wastewater treatment plant capacity to treat captured CSO.
- Real-time control applied to optimize the operation of storage, treatment and collection system components.

Increasingly though, municipal wastewater authorities in the Great Lakes region and throughout Canada are exploring new and innovative treatment technologies specifically designed for CSOs. These technologies, when applied as part of an overall wastewater management strategy, can produce efficient and cost-effective solutions for CSO control. However, like all technologies they require systematic design and proper operation. In many cases the basic information needed by municipal decision makers and their engineers to evaluate, select and design CSO treatment technologies has been difficult to assemble.

The Government of Canada’s Great Lakes Sustainability Fund (GLSF) has supported and directed research and remedial action designed to abate CSOs virtually since its inception in the early 1990s. The GLSF has supported a number of studies defining the wet-weather pollution challenges in the AOCs and co-funded demonstration projects featuring advanced CSO control technology, including high-rate physical and physical-chemical CSO treatment. In keeping with this historic role and sustainability objec-
tives, the GLSF commissioned the preparation of a Combined Sewer Overflow Treatment Technologies Manual (XCG Consultants Ltd., In press) in partnership with the Region of Niagara and the City of Welland. This manual has been completed and serves to provide information about physical and physical-chemical CSO treatment technologies, and at the same time to assist local governments and other interested parties with the selection, preliminary design, and application of CSO treatment technologies.

The manual consists of two parts. Part I, Planning and Regulation, provides the planning framework underlying the CSO abatement program development, including an overall program context, within which the decision to apply CSO treatment can be made. Part I also presents the CSO regulatory requirements across Canada and for the Great Lakes region of the United States. Part II, Design and Implementation Concepts and Treatment Technologies, reviews the preliminary design and implementation of CSO treatment facilities and presents up-to-date information regarding CSO water quality. The bulk of Part II deals with information on 10 treatment technologies, including preliminary treatment (screening, degritting), physical or physical-chemical treatment (retention treatment basins [RTBs], chemically enhanced high-rate sedimentation, continuous deflective separation, vortex separators, dissolved air flotation, fuzzy filters), and disinfection (chlorination/dechlorination, ultraviolet irradiation).

This paper is excerpted from the Manual (XCG Consultants Ltd., In press). It begins by presenting an overall framework for CSO program planning, which is followed by an overview of the steps associated with the preliminary design of CSO treatment facilities illustrated using a RTB design.

**CSO Abatement Program Planning**

CSO abatement program development should be a systematic, staged process. Figure 1 presents an overview of the three major components involved in the preparation of a CSO program.

The initial phase, Phase I – the State-of-the-System Assessment, begins with a definition of the study area, as well as the collection of baseline data pertaining to the collection system, treatment facilities and the area receiving waters. Various modelling and analytical tools are developed in this phase. Through the assessment activities of Phase I, the status of the land-based facilities (i.e., collection system and treatment plants) is evaluated in terms of overflow frequency, volume and loadings, among other factors. At the same time, the Phase I assessment addresses current receiving water quality, as well as the impact of existing CSO loadings. The initial phase also addresses the development of CSO control and treatment objectives and the development and initiation of a consultation program.

The second study phase, Phase II – Formulation and Evaluation of Alternatives, builds on the information and insights developed during Phase I. In this study phase, a framework and specific criteria are prepared to facilitate the systematic development and evaluation of alternative strategies. The alternative strategies are then assembled and through the evaluation process, a preferred strategy is obtained.

The final study phase, Phase III – Implementation Plan Development, completes the preparation of the CSO abatement program. In this phase, the details of the implementation plan are prepared. These address the sequence and timing of proposed works, regulatory approvals, cash flow requirements and post-implementation monitoring and evaluation.

**CSO Treatment Facility Preliminary Design**

There is no single correct approach to the development of a CSO treatment facility preliminary design. Individual designers apply their unique knowledge and background in each case, and call on the manufacturers of wastewater process equipment to provide input to the design of specific unit processes. The preliminary design of CSO treatment facilities involves all the considerations associated with any wastewater treatment plant design plus those arising from the rather unique aspects of an intermittent and highly variable influent. A second uncommon aspect pertinent particularly to satellite CSO treatment facilities is that they are “green field” developments involving locating a facility where none had been previously present. Special attention must therefore be paid to siting issues and the potential operating impacts such as odours that may be associated with a satellite facility.

Figure 2 presents an overview of the logical steps involved in developing a CSO RTB preliminary design, including: Step 1 – Development of CSO treatment objectives; Step 2 – The determination of design flows; Step 3 – The treatment process development ; Step 4 – The determination and consideration of location-specific issues generally associated with siting and integration of facilities; and (e) Step 5 – Evaluation of costs and operating and maintenance (O&M) impacts for the proposed preliminary design.

The procedure shown is iterative and culminates in the development of a preliminary design which then forms the basis for a final detailed design, complete with plans and specifications.

Steps 1 through 4 are taken together to prepare a draft preliminary design. This draft preliminary design is checked to ascertain whether the CSO treatment and control objectives will likely be achieved. If objectives do not appear likely to be achieved, then an additional iteration will be required. The capital, operating and life cycle costs are then estimated for the draft preliminary design, as are
the projected O&M impacts. If the costs and O&M considerations are found to be unacceptable, then additional iterations may be needed. Otherwise, the preliminary design may now be taken to the final detailed design stage.

**Step 1 – CSO Control and Treatment Objectives**

The development of CSO control and treatment objectives is the critical first step in the preparation of a facility preliminary design.

**CSO control objectives.** CSO control objectives are specific statements regarding the desired level of CSO control. Such objectives flow from the water quality objectives or end-of-pipe objectives or both. Water quality derived CSO control objectives are determined through water quality modelling of CSO impacts. End-of-pipe CSO control objectives address frequency, level of volumetric control (i.e., fraction of wet-weather flow volume captured and treated) or level of loading control.

**CSO treatment objectives.** CSO treatment objectives are specific statements regarding the level of treatment needed to meet the CSO control objectives and in turn any water body objectives. The CSO treatment objectives can be specified as effluent concentration limits, effluent
loading limits or percentage removal requirements. The averaging period used to assess compliance with CSO treatment objectives varies depending upon local circumstances and ranges from a given duration maximum to per event, seasonal or annual averaging. The treatment objectives are based on water quality objectives or end-of-pipe requirements or both. Table 1 gives some typical examples of both control and treatment objectives.

Considered jointly, the CSO control and treatment objectives should specify the following:

- **The Pollutants of Concern (POC).** In general for the Great Lakes (Ontario and U.S. border states) and many other jurisdictions, CSO treatment performance requirements are based upon the concept of “primary equivalent” treatment. The measured performance parameters used to establish “primary equivalent” treatment are CBOD$_5$ and TSS. Other pollutants of concern most often addressed by regulatory requirements are floatable materials (gross debris) and bacteria, which require specific treatment train components. Hence, the POC listing used to develop CSO treatment objectives is usually restricted to these four parameters. Other parameters derived from water quality assessments may be included but these may require application of unconventional or previously untested control/treatment technologies.

- **The Level of CSO Control.** The level of CSO control follows directly from the CSO control objectives. It is generally expressed as a frequency of overflow, a percentage volumetric control or a percentage loading control. Using Ontario regulations as an example, the required level of volumetric control is 90% capture of all sanitary flows during wet weather periods. The level of control in turn dictates, along with the CSO characteristics, the treated effluent requirements and the nature of the process train and the sizing of the facility.

- **The Treated Effluent Requirements.** These requirements are not always specified by all jurisdictions and the selection of process trains may be predicated on whatever technology requirements (e.g., primary treatment equivalent) exist in a given locale. Continuing with an Ontario regulatory example, the Ontario CSO treated effluent requirements are expressed as percentage removal requirements for CBOD$_5$ and TSS, and effluent concentration limits for TSS and E. coli. Treated effluent requirements may also be determined from receiving water modelling.

When applied to a specific treatment technology such as an RTB, the “primary equivalent” treatment requirements for TSS and CBOD$_5$ can be specified as percentage removal requirements and effluent concentration limits. The averaging period for TSS and CBOD$_5$ treatment objectives can range from individual storm events to monthly or seasonal averages.

As noted, other water quality parameters typically considered in CSO treatment objectives include floatable materials (gross debris) and bacteria, which require specific treatment train components. Hence, the POC listing used to develop CSO treatment objectives is usually restricted to these four parameters. Other parameters derived from water quality assessments may be included but these may require application of unconventional or previously untested control/treatment technologies.

![Fig. 2. Overview of retention treatment basin facility preliminary design.](image-url)

### TABLE 1. Examples of CSO control and treatment objectives

<table>
<thead>
<tr>
<th>Objective</th>
<th>Typical example</th>
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<tbody>
<tr>
<td>CSO control objectives</td>
<td>• Reduce the frequency of CSOs per recreation season to 3 events or less.</td>
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<tr>
<td></td>
<td>• Meet the volumetric control level of 90% for all overflows discharging to the receiving water during the recreation season.</td>
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<tr>
<td>CSO treatment objectives</td>
<td>• Reduce CSO total suspended solids (TSS) concentrations by 50% (seasonal average).</td>
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<td></td>
<td>• Seasonally averaged TSS concentration in the treated CSO effluent should not exceed 90 mg/L.</td>
</tr>
<tr>
<td></td>
<td>• Reduce CBOD$_5$ concentrations by 30% (seasonal average).</td>
</tr>
<tr>
<td></td>
<td>• Geometric mean of E. coli counts in the treated effluent should not exceed 1000 cfu/100 mL, on a per event basis. This objective applies where there is a potential for recreational water impacts (e.g., beaches).</td>
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bles and indicator bacteria (*E. coli*). Treatment objectives for floatables are specified by objectives such as removing gross debris and floatable materials greater than a certain size (e.g., 5 mm) in any dimension from all treated CSOs. Treatment objectives for bacteria are typically given as the geometric mean of effluent *E. coli* densities. The target densities are usually specified as not to exceed a limit based upon the geometric mean for a storm event. While it is possible to remove other particulate associated pollutants, such as selected heavy metals and phosphorus, these parameters are not normally included explicitly in RTB treatment objectives.

Finally, it is also worthwhile to remember that the RTB will need to be sized to meet any volumetric- or frequency-based CSO control objective such as 90% volumetric control and the process retention time requirements for any in-tank disinfection. This means that there will be a number of control and treatment objectives, the most stringent of which will dictate basin sizing.

**Step 2 – Design Flow**

The sizing of CSO treatment facilities is dependent upon the flow characteristics of the overflows to be treated. Two approaches have been used historically to define the anticipated CSO flows: individual design storms and a seasonal or annual overflow time series. Both approaches have their place in the sizing of CSO treatment facilities in general and RTBs in particular. In Ontario and in some Canadian municipalities in other provinces the CSO control requirements are expressed as either frequency of overflow or percentage volumetric control derived from a “typical” year rainfall time series input. The latter is called “continuous analysis” involving the modelling of the behaviour of the facilities during wet and dry weather over the entire study period. This continuous analysis approach is also consistent with federal CSO guidance in the United States (U.S. EPA 1995).

The use of the continuous analysis provides a more realistic evaluation of the facility operation over the long term. Firstly, continuous analysis allows update of catchment and facility conditions in the inter-event period. This permits the depiction of more rational initial conditions for wet-weather event analysis. Continuous analysis also allows examination of operating requirements and the estimation of consumables (e.g., coagulant) usage and effluent statistics. Moreover, if it is required to assess compliance with water body goals by means of receiving water modelling, then continuous analysis is essential. Water body goals are typically based on a percentage compliance with a water quality standard thus necessitating the time-based statistics produced by continuous analysis.

In contrast, the use of design events provides limited information. Design events by their nature are artificial constructs using the statistics of extreme rainfall assembled into a synthetic time distribution. Consequently, it is difficult if not impossible to assess the long-term performance of a facility and its attendant water quality benefits using design events. Nonetheless, because of their historical and present usage for drainage design and for CSO control design as practised in British Columbia, their use continues (XCG Consultants Ltd., In press).

The preliminary design of CSO treatment facilities including RTBs using single design storms is discouraged. However, the analysis of facility hydraulic behaviour under extreme peak flows is a useful application of design events. Once the facility process selection, layout and sizing is completed, the designer should evaluate the hydraulic behaviour of the control structures and the facility, including any bypass provisions, using one or more design events of varying return frequency and time base. This type of analysis can highlight hydraulic design weaknesses.

The continuous analysis approach to RTB preliminary design develops a volume balance for CSO flows arriving at a regulator as shown in Fig. 3. The distribution of CSO flows for any RTB falls into one of the following components: (a) captured by the collection system and conveyed for treatment at the wastewater treatment plant or “intercepted” (not shown in Fig. 3); (b) captured by the storage volume of the RTB treatment units and any other additional storage-only facilities and returned to the interceptor for treatment at the WWTP; (c) treated within the RTB treatment train and discharged to the receiving water; or (d) untreated CSO discharged to the receiving water.

The untreated CSO refers to flows not entering the RTB treatment train, i.e., diverted to a bypass channel provided for flows exceeding the peak design flow of the RTB. The volume of allowable untreated CSO is given by the CSO control objectives. For example, if the allowable bypass volume is 10%, then a CSO volumetric control level of 90%, based on the annual or seasonal time series, is required.

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**Fig. 3.** CSO hydrograph distribution.
The sizing of the RTB then needs to use the annual flow time series to determine both the requirements of the CSO control objective, i.e., to meet the volumetric control target and to meet the surface overflow rate (SOR) requirements consistent with the CSO treatment objectives—the desired percentage removal and/or desired effluent concentration. The latter aspect is discussed in the next section which deals with the RTB treatment process.

**Step 3 – Treatment Process**

**General considerations.** Retention treatment basins can be used as satellite facilities, stand-alone facilities at a WWTP, or integrated facilities at a WWTP. Figure 4 shows a satellite RTB with pre-treatment by screens, optional coagulant addition and disinfection within the basin. Figure 5 shows an alternative RTB configuration located at a WWTP. In this case the RTB is part of an integrated treatment train with common pre-treatment and disinfection. In both instances the RTB will serve as a storage facility to capture smaller overflow events with flow volumes smaller than the RTB volume or to capture portions of larger events.

RTBs typically consist of several compartments to allow smaller overflow events to be captured and/or treated without the utilization of the entire facility. Dividing the storage volume of the RTB into separate compartments also allows different portions of the tank to be used for other unit operations (e.g., disinfection). Smaller storm events and portions of larger events are captured within the storage volume afforded by a RTB. In this case, captured flows are transferred to a central wastewater treatment plant when capacity allows.

RTBs can be designed as simple gravity sedimentation basins or they can be augmented to enhance settling with coagulant addition or through inserts such as plate settlers. Positively buoyant materials are usually removed by some type of baffle or skimmer arrangement. Screens may be added to the RTB to ensure removal of positively buoyant and neutral density floatable materials. RTBs can also be employed as disinfection vessels usually through the addition of chlorine solution. Designs typically incorporate dechlorination as a final process step. Both chlorination and dechlorination require good mixing usually provided through a mixing device located in the RTB. It is also possible to add a disinfection step in a separate vessel following the RTB. In this case either chemical disinfection or disinfection by ultraviolet (UV) light irradiation can be considered.

**CSO quality considerations.** The next step in the RTB preliminary design is the characterization of CSOs to establish settling characteristics of solids and the concentrations of TSS, CBOD₅ and any other parameters of concern such as bacteria. If disinfection is required then appropriate process parameters such as UV transmittance or chlorine demand should also be evaluated at this time. It is recommended that CSO characterization should be based on data from 5 to 7 storm events. If coagulant addition and in-tank or add-on chlorination are considered likely adjuncts to the RTB then treatability testing should also be carried out at the same time. The treatability testing involves jar testing for coagulant selection and dosage and retention time determination for solids removal. The in-tank or add-on chlorination evaluation would require determination of the chlorine demand and the CT product (i.e., chlorine concentration x the contact time) to achieve the CSO treatment objective. If add-on UV disinfection is being considered, then UV treatability testing will also need to be carried out.

CSO characteristics required to evaluate process capability to meet “primary equivalent” treatment include TSS concentration (required to determine the RTB size needed to meet effluent target concentrations),
total CBOD$_5$ concentration and its dissolved fraction (required to estimate the particulate CBOD$_5$ fraction that could be removed by settling), and settling characteristics of CSO solids in the form of a settling velocity distribution. Examples of CSO settling velocity distribution curves are shown in Fig. 6.

The settling curves provide information about the design surface overflow rate (SOR) of the basin, which consequently determines the basin size and the dimensions. If the settling curves, characterization data and treatability data indicate that CSO treatment objectives will likely not be achieved, then consideration should be given to a RTB design with coagulant addition or to alternative technologies. The addition of coagulants, such as alum or ferric chloride and/or polymers, can significantly increase SORs and correspondingly reduce RTB footprint and tankage requirements. Depending upon the nature of the particulates found in the CSOs, it may be necessary in any event to employ coagulant assisted settling to meet CSO treatment objectives.

Even though CBOD$_5$ removal requirements may be specified in CSO treatment objectives, RTBs are usually not designed on this basis. Rather, the CSO soluble and particulate CBOD$_5$ fractions are measured during the characterization phase of the process design and the overall removal of CBOD$_5$ is then estimated from predicted TSS removal efficiency and the soluble CBOD$_5$ fraction. Hence, the SOR may need to be adjusted to increase solids capture to effect the corresponding regulatory CBOD$_5$ removal.

The decision to employ in-tank chlorination and dechlorination adds yet another aspect to RTB sizing. In this case, the CT product required determines the necessary retention time of the RTB at peak design flow. The basin dimensions meeting this retention time need to be calculated and compared with dimensions determined from the SOR analysis. Finally, as noted above, the RTB preliminary design also needs to meet the requirements of the CSO control objective(s) with respect to frequency, volumetric control or loading control. The basin should be sized for the largest of the three dimensions, depending on which control objective is the most critical.

**RTB sizing and dimensioning.** Specific criteria for RTB SOR and tank depth do not exist in North America. In contrast, Germany has had a standard for RTBs for some time, which specifies a fixed design SOR of 10 m/h with a tank length-to-width ratio of at least two for rectangular tanks. This standard has been applied in the design of thousands of CSO retention/treatment facilities ranging in size from 50 to 20,000 m$^3$.

More recently, RTB performance data with and without coagulant addition in CSO applications have been compiled from studies in the United States and Canada. For example, recent studies in the City of Windsor and the City of Toronto have demonstrated the feasibility of high SOR (>20 m/h) RTB operation using polymer addition as the coagulant (Li et al. 2003, 2004; Marsalek et al. 2003).

The North American results are summarized in Fig. 7 (XCG Consultants Ltd., In press). This figure may be used to obtain an initial estimate of design SOR which should be then refined through modelling or pilot testing. A numerical simulation model such as the Storage/Treatment Planning and Design of CSO Treatment

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**Fig. 6.** Select Ontario particle settling velocity distribution curves.
block of the Stormwater Management Model (SWMM) or GPS-X (Schraa et al. 2003) can be used to conduct detailed evaluations of average RTB performance for plain settling. In addition, more complex computational fluid dynamics (CFD) modelling or physical modelling (He et al. 2004; Stovin and Saul 2000; Schmitt et al. 2002) can also be employed to finalize the RTB layout. The prediction of performance with coagulant addition will require piloting at range of dosage and SOR conditions.

**Location-Specific Factors**

**Siting**

The need to find a good location for the satellite RTB facilities must balance siting in proximity to the overflow point with the availability of suitable property and community concerns. In virtually all cases satellite facilities are located close to a water body, in areas that are often among the most prized urban properties from an environmental viewpoint and from the potential for recreation or development. A broad range of practical, social and technical factors needs to be assessed and addressed in siting decisions. They include: community concerns, land availability, geotechnical suitability, site contamination, facility flood protection, facility environmental impact, access and utility availability. Additional details regarding each of these issues may be found in the CSO Technologies Manual (XCG Consultants Ltd., In press).

Siting at WWTP locations can be equally challenging primarily due to space limitations and the need to integrate the RTB with the existing processes. This aspect of RTB preliminary design is discussed in more detail in the next section.

**Integration**

Integration of RTB facilities refers to a range of technical issues associated with the linking of the facility to a satel-}

![Fig. 7. RTB suspended solids removal efficiency.](image-url)
Costs

Design and construction costs. The cost of design and construction of RTBs and CSO storage facilities in general can be substantial. Some of the factors that influence the construction costs include location of the facility, groundwater and geotechnical conditions, requirement for facility cover, requirement for facility ventilation and odour control, requirement for facility cleaning, pumping requirements, as well as the basin size.

Walker et al. (1993) developed a capital cost curve for CSO storage tanks, based on studies that assembled information on CSO control costs, and included the construction costs of structures and associated equipment. Costs of pumping were included in some cases, while the costs for land acquisition and engineering were excluded. The capital cost curve is presented in Fig. 8. Additional data presenting case study specific costs may be found in the CSO Technologies Manual (XCG Consultants Ltd., In press).

Operation and maintenance costs. Walker et al. (1993) also developed curves to estimate the annual O&M costs of RTBs for CSO control. These curves are shown in Fig. 9 for different design flows. Additional data presenting case study specific costs may be found in the CSO Technologies Manual (XCG Consultants Ltd., In press).

In addition to the specific capital and O&M costs, life cycle costs for the project should be developed and evaluated as part of the cost assessment.

Summary

A newly produced (2004) Combined Sewer Overflow Treatment Technologies Manual provides guidance for planning, preliminary design and implementation of CSO treatment. Towards this end, the manual addresses CSO abatement program planning, by focussing on program objectives reflecting regulatory requirements and addressing collection-treatment system impacts, and environmental, public health and community concerns. Following the establishment of planning objectives, guidance is provided for CSO treatment facility preliminary design, which encompasses such steps as development of CSO control and treatment objectives, design flows, treatment process trains, site-specific considerations and costs. Such considerations were developed in more detail for CSO retention treatment basins (RTBs), which are commonly applied to control and treat CSOs in the Great Lakes municipalities. Well-designed RTBs can meet the Ontario requirements for CSO pollution abatement and thereby contribute to the remedial action in the Great Lakes Areas of Concern.

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