Winter operation of an on-stream stormwater management pond

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Abstract The winter operation of an on-stream stormwater management pond in Kingston, Canada is characterised. The pond froze over in late November. Ice thickness varied from 0.2 to 0.5 m, and initially, was well described by Stefan’s formula. The measured and modelled velocity field indicated a fast flow region, a small dead zone and a large recirculating zone. During a snowmelt event, near-bottom velocities reached 0.05 m·s⁻¹, but were not sufficient to scour the bottom sediment. Pond water temperature increased with depth, from 0.5°C to 3.5°C. The dissolved oxygen (DO) levels observed in the pond (6–13 mg L⁻¹) indicated stable aerobic conditions at the sediment-water interface. In one brief episode, DO fell to zero after a long cold spell. Reduction in DO readings from inlet to outlet indicated an oxygen consumption of about 1.7 kg·day⁻¹. pH ranged from 7.1 to 8.9. Conductivity readings indicated large quantities of total dissolved solids, representing mostly chloride from de-icing agents. During baseflow, conductivity increased with depth (total dissolved solids concentrations up to 1,200 mg L⁻¹ near the bottom), indicating density stratification. Average trace metal concentrations were mostly below detection limits.

Keywords Dynamics; stormwater pond; water quality; winter operation

Introduction

Stormwater management ponds were introduced as a common practice into urban drainage systems about 30 years ago to mitigate various impacts of stormwater discharges on receiving waters. A wealth of experience with their operation has been collected, but mostly in moderate or warm climates, and/or seasons without snow and ice (Marsalek and Larkin, 1998). Thus, there is a lack of information for design and operation of stormwater ponds in cold or alpine climates, with specific concerns about runoff/snowmelt quality (Oberts et al., 2000), public safety (Marsalek, 1997), the sizing of stormwater management facilities (Caraco and Claytor, 1997), and the impacts on receiving waters (Oberts et al., 2000).

Urban snowpacks accumulate large quantities of solids and contaminants (Viklander, 1997), which originate from airborne fallout, vehicular deposition, de-icing and anti-skid agents, pavement abrasion and litter. Such materials may be quickly released from snowpacks during snowmelt and, consequently, urban snowmelt and winter runoff may contain high concentrations of solids, chlorides, trace metals and hydrocarbons degrading receiving water quality (Novotny et al., 1999). Eventually, poor water quality in water bodies receiving urban snowmelt leads to a loss of biodiversity (Environment Canada and Health Canada, 2001). Such impacts were best documented for road salts, whose inclusion on the list of toxic substances controlled under the Canadian Environmental Protection Act is under consideration (Environment Canada and Health Canada, 2001).

In cold weather, the performance of stormwater ponds in mitigation of runoff pollution may be seriously impeded with respect to pollutant removal and/or release (Marsalek and Larkin, 1998; Oberts, 2000). For example, ice cover may adversely impact on solids settling, oxygen regime, and contaminant release from bottom sediment, and prevent reaeration of pond water (Marsalek, 1997), with implications for releases of chemicals from bottom sediment (Striegl, 1987). Other factors affecting chemical release from bottom
sediment include changes in pH, or ionic concentrations at the sediment-water interface (Novotny et al., 1999; Striegl, 1987). Some of these changes are exacerbated by chemical density stratification caused by the influx of chlorides originating from winter road maintenance (Judd, 1970; Kjensmo, 1997). Finally, frozen ponds are attractive for recreational activities and to ensure public safety, proper attention has to be paid to the ice thickness (Marsalek, 1997). Insulating properties of snow cover and heat influx from pond inflows may reduce ice thickness, which for public safety should be checked periodically.

To elucidate some potential impacts of winter urban drainage and stormwater management on the environment, the winter operation of the Kingston Stormwater Pond was studied with respect to both physical and water quality aspects (Marsalek, 1997). The physical aspects have been discussed elsewhere (Marsalek et al., 2000), but are summarised here, as is the basic characterisation of the pond water chemistry, with respect to water temperature, dissolved oxygen (DO), pH, conductivity and major ions, and the risk of release of trace metals from bottom sediment.

Methods
Facility studied
The Kingston Stormwater Pond (referred to as the Kingston Pond), located in Kingston, Ontario, Canada (latitude 44°15′N), is an on-stream stormwater management facility that receives runoff from a shopping plaza (A = 12.6 ha) and streamflow from the west branch of the Little Cataraqui Creek. The 4,500 ha creek catchment has mixed urban land use, with low imperviousness and the presence of a major multi-lane highway with limited access and two regional roads. The pond (Figure 1) consists of a wet cell (approximately 60 m wide, 90 m long, and 1.2–1.4 m deep, with a surface area of 0.56 ha), and a dry cell of a comparable size. The dry pond floods when the water level in the wet pond is 0.2 m above normal water level (Van Buren, 1994). Field investigations of the winter operation of the Kingston Pond included measurements of air temperature, ice thickness, velocity and four water quality parameters (water temperature, DO, pH and conductivity). In addition, pond water samples were collected and analysed for selected ions and trace metals.

Air temperature
Air temperature was monitored at the site during the entire study period from April 1995 to February 1997 by means of a VAISALA HMP 35A Humidity and Temperature Probe (sensor accuracy ±0.1°C), which was incorporated into an on-site meteorological station located 2.5 m above ground. A Campbell Scientific data logger recorded sensor readings.

Figure 1 Pond layout and sampling grid

Parking Lot
Runoff Weir

Meteorological
Station

Dry Pond

Creek Weir

Creek

Outlet Weir E D C B A

0 25 m

Downloaded from https://iwaponline.com/wst/article-pdf/48/9/133/423782/133.pdf by guest
Ice thickness

Ice thickness was measured by a measuring tape inside the holes drilled in the ice. Measurements were taken during two current metering surveys (February 20 and March 8, 1996) at 14 and 15 stations, respectively, and additional measurements were taken from February 7 to 20, 1996.

Flow velocity

Flow velocities were measured underneath the ice cover on two separate days, February 20 and March 8, 1996, using an Acoustic Doppler Velocimeter made by SonTek Inc. and capable of measuring velocity components in three directions to a resolution of 0.1 mm·s⁻¹. The first current meterings were conducted during a rare winter rain-on-snow event, which caused unseasonably high flows (0.07–0.25 m³·s⁻¹). The second survey was performed during baseflow conditions. In both surveys, velocities were measured at selected nodes of a 15 m × 15 m grid (Figure 1), at five or more depths.

Water quality

Four water quality parameters (temperature, DO, pH and conductivity) were measured using the water quality probe Hydrolab H₂O. Two water quality probes were used: a stationary probe near the centre of the pond, located approximately 0.5 m below the water surface, and a portable unit deployed at three depths at each of four sampling stations selected to capture spatial variation. Three stations were selected along the main streamline at locations B3 (close to the inlet; an inlet sediment delta prevented the use of station A3 by the inlet – shallow water), C3 (close to the pond centre) and E1 (close to the pond outlet), and the last station, C1, was located in the recirculating zone, south of the main streamline (see Figure 1). Three depths were selected: 0.4, 0.8 and 1.0–1.2 m below the ice. The water quality surveys were conducted eight times, on February 7, 10, 12, 13, 14, 15, 19, and 20, 1996. The following uncertainties in probe measurements were estimated: temperature ± 0.15°C, DO ± 0.3 mg·L⁻¹, pH ± 0.1, and conductivity ± 0.1 mS·cm⁻¹.

Results and discussion

Dynamics summary

Among the physical processes important for winter pond operation, ice formation and break-up appear to be the most significant. Ice formation changes pond operation with respect to flow trajectory (low flows pass as pressurised flow below the ice cover, high flows may pass partly over the ice cover) and oxygen regime (risk of oxygen depletion in an ice covered pond). Ice formation depends on several factors including air temperature, water temperature and pond heat budget, and the presence of dissolved solids to support nucleation of ice crystals. Winter air temperature and pond water temperatures were monitored to characterise the conditions under which ice formation and break-up occur in the pond. Ice break-up reverts the pond operation to free flow conditions.

Air temperature

Air temperature is an important factor in two aspects of pond ice regime: ice cover formation and ablation, and snowmelt in the catchment draining into the pond. In this particular case of a shallow pond with limited inflow in winter months, air temperature can be used to predict the temperature of pond water, and eventually, pond freeze-up and ice cover thickness.
Sinusoidal models were developed to describe the central tendency of measured values of both daily air temperature and daily pond water temperature (Eq. (1)).

\[ T(t) = \overline{T} + A \cos \left[ \frac{2\pi}{365} (t - \theta) \right] \]  

(1)

Here \( T \) denotes daily temperature (air or water), \( \overline{T} \) is the series mean, and \( A \) is the amplitude, all in °C; \( t \) is the Julian date, and \( \theta \) is the phase shift (Julian date number). Marsalek et al. (2000) describe the fitting methodology and give optimum parameter values; important findings are as follows: (a) pond water temperature lags air temperature by 3–4 days, (b) the amplitude for water temperature is 4.4°C lower than that for air temperature, because of thermal inertia, and (c) the fluctuations in daily water temperature about its sinusoidal model are about a third of the fluctuations in daily air temperature about its sinusoid.

**Ice cover formation and break-up**

Border ice starts to form along the pond shore in late November and then spreads out towards the pond centre. Ice cover growth is slowed by the inflow of creek water, which keeps an open path in the ice cover until late December. Once the pond surface is covered, the ice thickens as the freezing point penetrates deeper into the pond. Snowfall after this point provides thermal insulation and hence reduces ice thickness. Occasional snow clearing for skating removes this insulation. The creek influx of marginally warmer water reduces the growth in ice thickness.

On February 20, 1996, ice thickness varied from 0.22 to 0.45 m (mean and standard deviation of 14 measurements = 0.31 and 0.075 m, respectively). In general, the lowest values of ice thickness were found close to the inlet and outlet and along the main streamline because of higher velocities and warmer creek water. In a second survey on March 8, 1997, the ice thickness was significantly lower with a mean and standard deviation of 0.23 and 0.012 m, respectively. Unseasonably warm weather led to warm inflow, which contributed to the reduction in ice thickness. Stefan’s equation (Davar et al., 1996) was used to calculate the ice thickness for the winter of 1995/96.

\[ h_i = \alpha (D_f)^{0.5} \]  

(2)

Here \( D_f \) is the cumulative sum of degree-days (°C), \( \alpha \) is a coefficient of ice growth (mm·°C0.5·d0.5), and \( d \) = day. Comparison of the best-fit value of \( \alpha \) (12.4 mm·°C0.5·d0.5) with values tabulated in Davar et al. (1996) indicates that with respect to ice thickness, a shallow on-stream pond behaves more like a river than a lake. However, the equation overestimates the ice thickness for the later phases of winter because of the sudden reduction of ice thickness around day 40, when a one-day thaw occurred. During this period when inflows were high, the weaker ice in the pond centre was lifted and broke, allowing water to flow overtop of the ice. The ice remained anchored to the shore. Following this sudden thaw, sub-zero temperatures returned and the ice cover consolidated. The water that spilled onto the ice surface also froze, increasing the ice cover thickness.

Davar et al. (1996) classify ice cover break-up as either premature dynamic/mechanical, or over-mature/thermal, which occurred in the Kingston Pond. Warmer runoff entering the pond in March weakens the ice cover, which is still attached to the shore. The formation and break-up of ice cover in the Kingston Pond does not seem to cause any problems by flow blockage or erosion of pond sediment. This follows from the characteristics of on-stream ponds – flow through weakens the ice cover along the main streamline and then causes the break-up during rapid snowmelt events. During very high inflows, ice cover will break and excessive water flows over the ice rather than causing pressurised flow under the ice and scouring of bottom sediments.
Pond stratification and inflow hydraulics

Measurements of pond velocities and ambient water quality, particularly total dissolved solids (TDS), revealed that winter flow conditions in the pond are very complex. Strong density stratification and the confining boundaries (the ice cover and pond sides and bottom) affect flow patterns. Two sources of density stratification were observed: thermal stratification (temperature variation 0 to 2.4°C) and chemical stratification caused by dissolved solids, particularly chloride. Thus, the pond water is stably stratified, with chemical stratification clearly dominating. The stability of pond stratification was described by the meromictic stability \( S = 882 \text{ g·cm·cm}^{-2} \), which is relatively small and would not significantly delay pond destratification in late spring. For a deeper lake with high chloride inputs, Judd (1970) reported \( S \) values ranging from 2,100 to 18,000 g·cm·cm\(^{-2}\).

Two possibilities are envisaged regarding the form of creek inflow, which will affect the pond flow pattern. The first one is a gravity underflow, if high concentrations of total dissolved solids (TDS) and particularly chlorides are released from the upstream creek catchment in the early phase of snowmelt, as observed, e.g. by Westerstrom (1995), with early snowmelt concentrations exceeding average concentrations in the parental snowpack by 5–15 times. This type of inflow will contribute to density stratification in the pond. The second form is a buoyant jet when TDS concentrations in the inflow are low, such as in the later phases of snowmelt events. The buoyant jet spreads laterally, entrains pond water, moves in a relatively thin layer underneath the ice cover through the pond, and exits over the outlet weir. Thus, the buoyant jet associated with baseflow does not seem to interfere with the chloride/TDS accumulation and storage in the pond.

Velocity field in the ice covered pond

The current survey of March 8, 1996 covered true baseflow conditions with pond inflow of about 0.060 m\(^3\).s\(^{-1}\). Among the 84 velocity vectors measured, 74 (88%) had magnitudes \( \leq 2 \text{ mm·s}^{-1} \); the remaining 10 were between 2 and 4 mm·s\(^{-1}\). The lowest velocities were generally observed near the bottom and did not pose any risk of sediment washout.

The survey of February 20, 1996 covered a period of rising inflow caused by a sudden thaw and snowmelt. Flow ranged from about 0.07 to 0.25 m\(^3\).s\(^{-1}\). In spite of this flow variation over the 5–6 h survey, the run was completed because the resulting data offered some insight into the pond current circulation. Figure 2 displays horizontal components of velocity vectors in three horizontal planes. The velocity vectors seem to indicate a definite flow circulation pattern, with a region of direct flow from inlet toward the outflow weir, a dead zone north of this path, and a recirculating zone south of the path. This circulation pattern is similar to that simulated with the PHOENICS model (Shaw et al., 1997). In the bottom layer, average velocities were just 2.2 mm·s\(^{-1}\), except for Station B3 located at the downstream end of the sandy delta by the pond inlet. Even at this location, the measured velocity of 49 mm·s\(^{-1}\) was too low to initiate the movement of sandy bottom sediment (\( D = 0.425 \text{ mm} \)) using the critical shear stress criterion (French, 1985). Thus, even for this event, there was no risk of scouring bottom sediment.

A comparison of the velocity fields under open water (Shaw et al., 1997) and ice cover conditions indicated that during baseflow, mean velocities in an ice-covered pond are an
order of magnitude lower than those without an ice cover, when pond circulation is driven by wind shear stress. Moreover, circulation in the ice-covered pond is somewhat dampened by friction along the lower ice boundary and by the presence of density stratification which tends to reduce vertical mixing (French, 1985).

Water quality summary

The average values of each of the four parameters over the eight discrete water quality surveys are presented in Table 1. Parameter values were analysed for spatial variation (in the horizontal and vertical planes) and temporal variation. Within the limits of these surveys, the four water quality parameters in the ice-covered pond did not vary significantly in the horizontal plane. In the vertical plane, some obvious trends were noted in the data, as discussed in subsequent sections.

Water temperature

Under the ice cover a vertical temperature gradient was observed during most surveys with temperatures being lowest just beneath the ice cover and gradually increasing towards the pond bottom, with differences as high as 3°C. On one occasion (February 20), during a rain-on-snow event following a cold day, no thermal gradient was observed and water temperatures ranged from 0.6 to 0.8°C throughout the pond depth. High inflow to the pond caused thorough mixing of water in the pond and destroyed thermal stratification (see Table 1 for average values at each location/depth). With one exception, there were no significant water temperature variations in the horizontal plane.

Dissolved oxygen (DO)

The time-averaged data (Table 1) indicate a small decrease in DO (0.4 to 0.6 mg·L⁻¹) between inlet and outlet at all three depths. These differences are statistically significant at depths of 0.4 and 0.8 m, but not at 1.2 m. This decrease (for identical temperatures, similar chloride concentrations and the least depth of 0.4 m, close to the outlet) can be explained by oxygen consumption in the pond, which was estimated at 1.7 kg·day⁻¹ (Marsalek, 1997).

Variations in DO along the vertical, about 1.6 mg·L⁻¹ on average, were more significant than those in the horizontal plane, with lower DO values found close to the bottom, in warmer water containing higher concentrations of chlorides. Nevertheless, all data indicated high oxygen saturation ranging from 84% (depth of 1.1 m, near the outlet) to 94% (depth of 0.4 m, near the inlet).

The stationary Hydrolab data revealed that DO concentrations declined from about 10 mg·L⁻¹ on December 17, 1995 to zero on January 16, 1996, indicating that the pond oxy-

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Depth (m)</th>
<th>B3 Mean</th>
<th>C3 Mean</th>
<th>Location</th>
<th>C1 Mean</th>
<th>E1 Mean</th>
<th>Max. S.E.</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>0.4</td>
<td>7.62</td>
<td>7.60</td>
<td>7.60</td>
<td>7.59</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>7.57</td>
<td>7.57</td>
<td>7.55</td>
<td>7.57</td>
<td>0.07</td>
<td></td>
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<tr>
<td></td>
<td>1.2</td>
<td>7.50</td>
<td>7.52</td>
<td>7.48</td>
<td>7.52</td>
<td>0.09</td>
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</tr>
<tr>
<td>Dissolved</td>
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<td>13.4</td>
<td>13.0</td>
<td>13.2</td>
<td>13.0</td>
<td>0.41</td>
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</tr>
<tr>
<td>Oxygen</td>
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<td>12.1</td>
<td>12.1</td>
<td>12.0</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td>[mg·L⁻¹]</td>
<td>1.2</td>
<td>11.9</td>
<td>11.6</td>
<td>11.2</td>
<td>11.5</td>
<td>0.52</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>0.4</td>
<td>1.21</td>
<td>1.08</td>
<td>0.64</td>
<td>1.22</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>[°C]</td>
<td>0.8</td>
<td>2.17</td>
<td>2.18</td>
<td>2.15</td>
<td>2.22</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>2.36</td>
<td>2.38</td>
<td>2.41</td>
<td>2.47</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td>Conductivity</td>
<td>0.4</td>
<td>1.14</td>
<td>1.22</td>
<td>1.22</td>
<td>1.18</td>
<td>0.065</td>
<td></td>
</tr>
<tr>
<td>[mS·cm⁻¹]</td>
<td>0.8</td>
<td>1.51</td>
<td>1.52</td>
<td>1.51</td>
<td>1.45</td>
<td>0.103</td>
<td></td>
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<td></td>
<td>1.2</td>
<td>1.79</td>
<td>1.85</td>
<td>2.09</td>
<td>1.78</td>
<td>0.203</td>
<td></td>
</tr>
</tbody>
</table>
gen was not being replenished. Exceptionally cold weather leading to this episode suggested that the entire creek/pond system was ice covered and oxygen was depleted from the pond and the creek water. After January 16, 1996, air temperatures climbed to 5°C, which caused ice break-up on the creek, and reaeration of the pond water in several days.

**pH**

Inflow pH data were not available, but one could expect some difference between both inflow sources – shopping plaza runoff and the creek. Plaza runoff would be neutral to slightly acidic, considering the slightly acidic nature of rainfall and limited buffering of runoff on impervious surfaces and in a short concrete sewer system. Creek streamflow is neutral to alkaline, as a result of the limestone geology of the creek drainage area. The values of pH recorded in the discrete surveys in the pond ranged from 7.1 to 7.8, indicating more or less neutral to slightly alkaline conditions. Mean values of pH, obtained by averaging the readings from eight surveys (Table 1), were approximately constant in horizontal planes, and varied slightly along the vertical, decreasing with depth (by about 0.1 pH unit). With respect to temporal variations during the two-week period of discrete surveys, spatially averaged data (i.e. means of data from four locations) indicated only moderate variations.

pH values recorded by the stationary probe over four seasons ranged from 7.4 to 8.9, and were in compliance with the Canadian Water Quality Guidelines for protection of aquatic life (CCME, 1999) specified as $\text{pH} = 6.5 – 9.0$. Some relatively weak seasonal variations were discernible in this record. During summer and fall, pH was more or less constant (about 7.9), with minor variations ($\leq 0.2$ pH units). During the winter months, there was a gradual increase in pH (by about 0.5 pH unit), which was followed by a comparable gradual decrease in pH during the spring. This seasonal variation coincided with winter runoff/snowmelt and subsequent pond flushing in the spring.

**Conductivity and inferred total dissolved solids (TDS)**

Conductivity measurements can be used to estimate total dissolved solids, TDS, from the following equation (Hydrolab Corporation, 1994):

$$ \text{TDS}_{\text{calc}}/\text{conductivity} = 640 $$

(3)

where TDS and conductivity are expressed in mg·L$^{-1}$ and mS·cm$^{-1}$, respectively.

Average values of conductivity over the eight surveys (Table 1) were approximately constant in the horizontal planes, but varied significantly in the vertical plane with lowest values just below the ice cover and highest values near the pond bottom. Road salting, which resulted in chloride-laden runoff, caused this type of densimetric stratification.

Winter TDS concentrations are much larger than the mean value of TDS in the pond during the field season, 450 mg·L$^{-1}$ (Van Buren, 1994). Thus, additional dissolved solids are stored in the pond during winter (originating mostly from road salt) and then released in the spring. This process of TDS accumulation/release explains an apparent chloride “production” in stormwater ponds during typical field seasons from May to October reported by Van Buren (1994). The cycling of TDS in the pond was further confirmed by the data from the stationary Hydrolab, which indicated a gradual increase in conductivity during the winter and a relatively quick decrease in the spring.

With the arrival of cold weather in late November 1995, conductivity readings rose rapidly from warm weather readings of 0.30–0.85 mS·cm$^{-1}$. In the winter of 1995/96, the highest winter reading (2.94 mS·cm$^{-1}$, TDS $= 1,880$ mg·L$^{-1}$) occurred on January 15, 1996; in the winter of 1996/97, the highest recorded reading was 4.93 mS·cm$^{-1}$ (TDS $= 3,160$ mg·L$^{-1}$).
mg·L–1) on February 5, the last date for which conductivity data were available. This high reading compares well with that presented later for interstitial water in pond sediment (4.79 mS·cm–1, TDS = 3,070 mg·L–1) and indicates high accumulation of TDS in the pond during the winter.

Conductivity readings fluctuated strongly during the winter season, depending on the discharge through the pond. From Julian date 350, 1995 to date 16, 1996, conductivity readings increased steadily, reaching a maximum at 2.94 mS·cm–1, and then suddenly dropped to 0.27 mS·cm–1 on day 19. This sudden drop coincided with a rainfall/snowmelt event (37 mm of rain in 4 days from January 16 to 19 with a rise in average daily temperature of 5°C) that caused high inflows, which destratified the pond and flushed out the stored water of high conductivity. A similar phenomenon was observed in one of the portable Hydrolab surveys conducted on February 20, 1996, when 32 mm of rain fell and temperatures rose to 7°C. Conductivity readings at all three depths converged to one value indicating that densimetric stratification was eliminated by the inflow.

**Major ions and total dissolved solids (TDS)**

TDS readings are sometimes used to verify analyses of major ions using the following expression (APHA, 1998):

\[
\text{TDS} = 0.6 \cdot \text{alkalinity} + \text{Na}^+ + \text{K}^+ + \text{Ca}^{2+} + \text{Mg}^{2+} + \text{Cl}^- + \text{SO}_4^{2-} + \text{SiO}_3^{2-} + (\text{NO}_3^{--N}) + \text{F}^- \tag{4}
\]

where alkalinity is water’s acid neutralising capacity expressed as an aggregated property in equivalent mg·L–1 of CaCO3, and all other concentrations are also expressed in mg·L–1.

Contributions of individual terms (except SiO3, for which no analytical support was available) in Eq. (4) to TDS were determined from water samples collected throughout the pond (14 stations, up to four depths at each station) and from samples of interstitial water collected at three stations, one near the outfall and two close to the centre. The results of interstitial and pond water analyses are presented in Table 2. The interstitial water contained high TDS concentrations, about 2,500 mg·L–1, or three times those in pond water, and high chloride concentrations, about 1,300 mg·L–1, or almost four times those in pond water. These concentrations reflect high concentrations of chloride and TDS occurring in the pond during the winter season. Multiplying the interstitial water volume by chloride concentration indicated that the pond bottom sediment contained about 1,300 kg of chlorides. Through molecular diffusion, there will be some slow exchange of chlorides between the bottom sediment and the overlying water. Thus, during most of the year, there will be some release of chloride from the sediment into the water column, either by sediment disturbance or molecular diffusion, and this will contribute to chloride

**Table 2** Selected major ions in Kingston Pond, February 1997 (mg·L–1, conductivity in mS·cm–1)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Interstitial water</th>
<th>3B</th>
<th>3C</th>
<th>1C</th>
<th>1E</th>
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<tbody>
<tr>
<td>Ca</td>
<td>180</td>
<td>105</td>
<td>105</td>
<td>105</td>
<td>104</td>
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<tr>
<td>Mg</td>
<td>32</td>
<td>16</td>
<td>16</td>
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<tr>
<td>Na</td>
<td>613</td>
<td>143</td>
<td>144</td>
<td>145</td>
<td>142</td>
</tr>
<tr>
<td>Chloride</td>
<td>1,290</td>
<td>341</td>
<td>338</td>
<td>344</td>
<td>338</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>472</td>
<td>173</td>
<td>176</td>
<td>178</td>
<td>176</td>
</tr>
<tr>
<td>SO4</td>
<td>1</td>
<td>52</td>
<td>51</td>
<td>51</td>
<td>52</td>
</tr>
<tr>
<td>Conductivity</td>
<td>4.79</td>
<td>1.44</td>
<td>1.45</td>
<td>1.45</td>
<td>1.43</td>
</tr>
<tr>
<td>TDS</td>
<td>2,470</td>
<td>832</td>
<td>837</td>
<td>833</td>
<td>823</td>
</tr>
</tbody>
</table>
“production” in the pond. Additional chloride may escape into the groundwater, as suggested by Judd (1970).

In horizontal planes within the pond, there was practically no variation in TDS. The observed TDS concentrations (about 830 mg·L⁻¹) exceeded significantly the average values reported by Van Buren (1994) for baseflow (TDS = 499 mg·L⁻¹), creek events (TDS = 347 mg·L⁻¹) and parking lot events (TDS = 183 mg·L⁻¹). Chloride represented about 40% of the observed TDS concentrations. The ratio of Na⁺ to Cl⁻ concentrations in these samples (1:2.4) indicated that chloride originated not only from rock salt (NaCl, with a ratio of atomic weights of 1:1.5), but also from other sources (e.g. CaCl₂). Chloride is obviously a major contributor to TDS, but because all terms in Eq. (4) may vary somewhat independently of chloride concentrations, the changes in pond water conductivity cannot be explained just by changes in chloride concentrations. Also, depending on the source of the chloride ion (i.e. NaCl or CaCl₂) an increase in chloride concentrations would be accompanied by a concomitant increase in concentrations of cations.

High chloride concentrations in the interstitial water indicate that during some periods in late winter, chloride concentrations in the pond water attain the levels comparable to those observed in the interstitial water (1,300 mg·L⁻¹). Indeed, on March 5, 1996, chloride concentrations measured at a depth of 1.1 m reached almost 1,000 mg·L⁻¹.

**Dissolved and total trace metals**

Four pond water samples and three samples of pond bottom sediment interstitial water, collected during the major ion survey on February 26, 1997, were also analysed for total and dissolved trace metals. Average trace metal concentrations in the pond water were lower than the mean concentrations reported by Van Buren (1994) for creek baseflow and event runoff, plaza event runoff and pond outflow, during both baseflow and events. Total trace metal concentrations for iron and zinc in the ice-covered pond met the Canadian Water Quality Guidelines (CWQG) for protection of aquatic life (CCME, 1999) and PWQO (MOEE, 1994) (also for chromium, in the case of PWQO). For the remaining metals, almost all concentrations were below the detection limits, which generally exceeded the limiting values in guidelines and objectives; hence, no assessment was possible.

The concentrations of trace metals found in the Kingston Pond do not indicate enhanced release of trace metals from the bottom sediment during the winter period, and this finding is consistent with conclusions drawn from the water quality data presented earlier. The quality of interstitial water was similar to that of the pond water, with respect to trace metals. The only exception was an elevated concentration of total iron (450 µg·L⁻¹), exceeding both the PWQO and CWQG (300 µg·L⁻¹). Considering the strong bond of interstitial water to fine sediment, this excess does not pose a serious concern, unless the bottom sediment would be disturbed. However, even during sediment disturbance (e.g. when maintaining the pond by sediment removal), the interstitial water would be diluted more than 10 times by the pond water and this would bring the total iron concentrations below the PWQO and CWQG limits.

**General observations on winter pond operation**

Pond observations over two winter seasons revealed two types of problems – (a) accumulation of chloride and a low risk of oxygen depletion when the entire creek/pond system is ice covered. Chloride accumulation could be prevented by installing a controlled bottom outlet and operating it to release regularly pond bottom waters, which are laden with chloride. The second problem is more difficult to solve. Fluctuating water depths in the pond could reduce the risk of creek/pond freeze up, but this would also endanger winter recreational activities on the pond and in the surrounding park. In any case, it is believed
that both types of problems are less serious in on-stream ponds than in off-line ponds (Oberts et al., 2000).

Conclusions
Investigations of winter operation of an on-stream stormwater pond produced unique data with respect to both physical and chemical pond processes. Pond water temperature lagged air temperatures by several days, and the pond froze over in late November. The ice thickness initially grew proportionally to cumulative degree-days, reaching 0.3–0.5 m. The ice covered pond was densimetrically stratified. During baseflow, the measured velocities in the ice-covered pond were much smaller than in the ice-free pond. For a snowmelt event, the measured velocity field indicated a fast flow region, a small dead zone and a large recirculating zone. The highest near-bottom velocity of 0.05 m·s⁻¹ was not sufficient to scour the bottom sandy sediment. Pond water temperature increased with depth, from 0.5°C to 2.5°C. The DO levels (6 –13 mg·L⁻¹), generally observed throughout the pond, indicated stable aerobic conditions at the sediment-water interface. In one brief episode, DO fell to zero after a long cold spell. Reduction in DO readings from inlet to outlet indicated an oxygen consumption of about 1.7 kg·day⁻¹. The values of pH ranged from 7.1 to 8.9, which is acceptable for protection of aquatic life. Conductivity readings indicated large quantities of total dissolved solids, representing mostly chloride from de-icing agents. During baseflow, conductivity increased with depth, indicating strong density stratification. Average trace metal concentrations were mostly below detection limits. Thermal ice break-up occurred in March.

References
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