Off flavours in large waterbodies: physics, chemistry and biology in synchrony


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Abstract The Laurentian Great Lakes of North America are a drinking water source for millions of Canadian and US consumers. These waterbodies have undergone extensive change over the past century as a result of widespread degradation and remediation. Many of the Lakes are prone to taste and odour (T&O), and although these outbreaks have been poorly monitored, evidence suggests that they are increasing in frequency. Tracing and controlling T&O in such large systems presents a challenging task, due to their physical size and complexity. This paper presents an overview of recent investigative and management approaches to T&O in Lake Ontario and its outflow, the St. Lawrence River. We have identified three distinct patterns of T&O in these source-waters, caused by geosmin and 2-methylisoborneol and differing in their planktonic and benthic sources, and temporal and spatial dynamics. Each pattern has required a different approach by scientists and management, in partnership with the water industry. We have shown these T&O outbreaks are caused and moderated by physical, chemical and biological mechanisms over a spectrum of spatial and temporal scales. Canadian municipalities affected by these outbreaks have been key to the investigation of the links between T&O and ecosystem processes with the aim to develop more proactive water treatment and long-term management.

Keywords Geosmin; Great Lakes; Lake Ontario; 2-methylisoborneol; proactive management; taste and odour

Introduction: taste and odour in the North American Great Lakes

Aquatic off flavours are most commonly associated with moderate-to-small sized source-waters, but significant taste and odour (T&O) outbreaks also occur in large waterbodies, and can have extensive socio-economic impacts, affecting millions of consumers and other stakeholders. Tracing and controlling these events can be particularly challenging, and require a multi-level approach. T&O in large lakes is often produced by events that are linked across a wide continuum of spatial and temporal levels (Davies et al., 2004). Thus, factors which affect the production and transport of odour compounds at the micro-scale (cell) interact with processes at the population, community and ecosystem levels and ultimately, with broad heterogeneity in climate, watershed, basin, diffuse/point-source loading and lake circulation. Large-scale physical processes play an important role in the transport and distribution of material, biota and energy in large lakes, and can profoundly influence the final distribution and impact of T&O. The same waterbody can...
thereby produce both localised outbreaks which affect a small proximal zone, and widespread events which occur across a substantial area.

The Laurentian Great Lakes of North America hold approximately 20% of global fresh water and this water provides drinking water to over 15 million Canadian and US consumers (http://www.epa.gov/glnpo/p2/bns.html). Historical and current reports indicate that many areas of the Lakes are prone to odour outbreaks and that these are increasing in frequency (e.g. Anderson and Quartermaine, 1998; Watson and Ridal, 2004; Moore and Watson, 2007). Until recently there have been few direct measures of T&O and/or consumer complaints, and little monitoring or assessment of this impairment. This is largely because of the size, spatial/jurisdictional complexity, and history of these waterbodies, which evolved ~5,000 years ago as oligotrophic ecosystems. In the last two centuries, the exponential increase in human settlement accompanied basin development, dredging, diversion and damming, erosion and a major lake-wide ocean-linked shipping route (Mac Millan, 1987). Climate change has modified ice cover, hydrological and thermal energy budgets. Agricultural, industrial and urban liquid wastes resulted in eutrophication, algal blooms and rising levels of anthropogenic pollutants, toxins and pathogens (IJC, 1980). Ballast water and other human vectors introduced invasive species, favoured by the disrupted resilience of the system (e.g. Maclsaac and Grigorovich, 1999). Above all, this accelerating degradation has been difficult to reverse, as a result of a widespread complacency about the Lakes.

By the latter part of the last century, however, their deterioration initiated an international remediation effort, under the Canada-US Great Lakes Water Quality Agreement (GLWQA).

As part of this programme, the International Joint Commission (IJC) identified 42 areas of concern (AOCs) with one or more of fourteen major beneficial use impairments (BUIs), which included taste and odour (Figure 1). Remedial action plans (RAPS) were developed for each AOC to reduce impairments to “acceptable” target levels. Even though T&O was judged as an impairment in over a third of the AOCs, in most cases this was not based on direct measures (i.e. sensory and/or analytical) but rather on infrequent and subjective information from treated municipal drinking water (with no attention to small user groups, recreational areas and other sectors). In fact, most evaluations of

Figure 1 Areas of concern (AOCs) in the Great Lakes with: (i) T&O listed as an impairment (black circles): (ii) a history of T&O but no formal listing (grey circles) and (iii) no known T&O (crosses). BQ: Bay of Quinte; SLR: Saint Lawrence River
T&O in the Great Lakes have relied on incidental reports, ‘proxy measures’ (average nutrient levels and, algal biomass (usually measured as chlorophyll-a (chl-a)) or water treatment plant (WTP) chemical treatment doses, disinfection by-products, and sporadic consumer complaints (e.g. Stride, 2003). These same proxy measures have been used to define “acceptable” target levels of T&O – and gauge the success of RAPs in addressing the issue. Clearly, there are problems with this approach because none of these criteria is necessarily linked to the processes which initiate, drive and modify T&O production, or to the final odour levels at the tap or beach. It should also be noted that T&O outbreaks are reported from areas in the Great Lakes outside AOC boundaries, where their frequency and severity are unknown.

The RAP and other lake-wide and local restoration initiatives made considerable progress in lake-wide reduction of nutrients and algal blooms in the Great Lakes by the late 1980s (Charlton, 1997). Public concern with blooms, T&O, drinking water quality and safety played a key role, and continues to influence policy-makers and researchers in this multi-level remedial action programme. However, the state of flux induced by this ecosystem “recovery” has been offset by diffuse shoreline loading, urban runoff and exotic biota, which have modified inshore nutrient cycling, water transparency and food webs, resulting in significant changes in biochemical signals such as T&O. In this paper, we present a brief synopsis of three cases of T&O in the Lake Ontario, where management response to consumer feedback has initiated science-based approaches to this issue.

Case studies: Taste and odour in Lake Ontario

Regional differences in taste and odour issues

Based on phosphorus and chl-a levels, both Lake Ontario and its major outflow the upper St Lawrence River (SLR) would be considered oligo-mesotrophic (e.g. Vollenweider et al., 1980), and therefore unlikely to generate significant T&O problems. We have identified three T&O patterns in these systems over the past 5 years (Figure 2). The first occurs in the NW basin of Lake Ontario, where widespread T&O is caused by abrupt and severe geosmin outbreaks, which afflict major municipal supplies between Hamilton and Cobourg, serving over 5 million consumers in the most densely urbanised region of Canada (Figure 2). Geosmin peaks occur every year between late August – mid September over ~2 week period, but show considerable variation in severity, with maximum levels remaining below the odour threshold concentration (OTC) of ~4–10 ng/L in some...
years, or reaching 25–200 ng/L in other years. Planktonic chl \(a\) and algal biomass remain very low during these events and show much lower interannual variability (<2–7 \(\mu\)g/L; ~100–500 \(\mu\)g/L, respectively). This suggests significant geosmin production per unit algal biomass, and certainly not one that would be projected by traditional management models (e.g. Jüttner, 1984; Sugiura and Nakano, 2000; Jarvie et al., 2002).

The second case occurs in the NE end of the lake (Kingston basin) and upper SLR, where earthy-musty T&O is produced annually by both geosmin and 2-methylisoborneol (MIB), each ranging between 10–60 ng/L. These outbreaks also affect an extensive shoreline (~100 km) but persist over a more prolonged period from September–October/November. In different years, geosmin and MIB have co-occurred and/or peaked in succession over the season, and varied in relative and absolute abundances (Watson and Ridal, 2004, Ridal et al., 2006). Midstream pelagic chl \(a\) has remained low. A third earthy-musty T&O pattern is seen in the Bay of Quinte (BQ), a long, shallow embayment which drains an agricultural and urban area into E. Lake Ontario (Figure 1), with a history of eutrophication and cyanobacteria blooms (Minns et al., 1986; Nicholls, 1999a, b). Following nutrient reduction, this AOC reached meso-eutrophic conditions, but still develops annual blooms, with patchy mid-summer increases in geosmin and MIB and cyanotoxins (Watson et al., 1997, 2004). Even so, BQ shows less extensive odour impairment than the other two more ‘oligotrophic’ sites. Although these odour compounds can reach significant levels in some areas of the Bay (~30–50 ng/L), their effects are localised and have had little impact on the drinking water in municipal supplies (Keene, 2003; Watson et al., 2004; XCG Consultants, 2005).

Investigative approaches to regional differences in taste and odour

Each case has required different investigative approaches. In NW Lake Ontario, two particularly severe geosmin outbreaks in 1998 and 1999 (with increased publicity and consumer complaints) led to a general perception that the frequency and severity of these events were increasing, as were treatment costs. In response, the Ontario Water Works Research Consortium (OWWRC) was formed in 1999–2000, partnering the six large Canadian municipalities in this region with scientists and experts from federal, provincial and municipal governments (Moore and Watson, 2007). Over the past 5 years, this partnership has worked to determine the major causes of the T&O outbreaks, identify key predictors, and use this to optimise treatment and develop management strategies to mitigate their occurrences. The broad geographical impact of these T&O events has required a combination of both large- and small-scale research, and a cumulative budget exceeding several millions (made possible by the large consumer base and combined lab/research/organisational infrastructure). Researchers have used a multi disciplinary approach, which has combined i) analysis of historical and current water treatment plant (WTP) data; ii) fieldwork integrating lake-wide surveys with event-based or seasonal focussed sampling in the NW basin and two major inflows; iii) lab studies with suspected odour producers isolated from the system (actinomycetes and the cyanobacterium \(Anabaena lemmermannii\)); and iv) meteorological and satellite data. Since 1999, weekly or biweekly samples have been taken in late June–October each year at an inshore-offshore transect adjacent to a WTP concurrently collecting data. Lake water quality (WQ), nutrients, T&O and phytoplankton have been sampled and coordinated with T&O, water quality and customer complaint data from the WTPs. Moored instrumentation has been deployed to identify upwelling/downwelling events and major along-shore, and inshore–offshore water movements near a major WTP intake. Two major inflows, the Niagara and Credit Rivers, have been sampled for T&O and biota. Annual late-summer lakewide ship surveys have sampled WQ, phytoplankton and T&O, and combined this with shipboard incubations for odour production and algal
productivity (Brownlee et al., 2004). All lake samples have been monitored for cyanobacteria, notably the large colonial Anabaena lemmermanii, which has been isolated into culture and investigated for variability in morphology, growth and geosmin production under different light, temperature and nutrient levels. Research is currently underway to characterise key genetic sequences of these and other cyanobacterial odour producers. Actinomycetes have been isolated from the Credit River and NW basin of the lake, and characterised for odour production (Zaitlin et al., 2003). Benthic geosmin production has been measured using discreet water column depth sampling, sediment grabs and in situ surveys of the extensive beds of dreissenid mussels present along much of the shoreline of the lake.

T&O research in the East (St. Lawrence and Bay of Quinte) has been carried out on a more moderate financial and operational scale, also partially funded by the OWWRC, together with direct and/or in-kind support from other local stakeholders (Bay of Quinte Remedial Action Group, Department of Fisheries and Oceans, and the St. Lawrence River Institute of Environmental Sciences). Again, the work was initiated by industry and public concern with marked changes in the biota and odour production in these areas (Ridal et al., 1999) and the establishment of effective multidisciplinary partnerships among scientists, government agencies and the water industry. Researchers in the SLR have followed odour levels in this corridor since 1996; and combined this with: i) spatial surveys of major physical parameters, WQ (including nutrients), T&O and phytoplankton in surface water, both along and across the river at selected sites; ii) extensive surveys and mapping of inshore (littoral) water and biofilms for physical characteristics, substrate types, T&O, and algal/actinomycete/macrophyte abundance and species; iii) analysis of long-term changes in water levels, discharge and treatment options; iv) an assessment of the impacts and contribution to downstream T&O of a major pulp and paper mill (found to produce significant amounts of geosmin and MIB in the secondary treatment reactors); and v) work on control technologies with the Cornwall Water Purification Plant (Watson et al., 2003; Watson and Ridal, 2004; Ridal et al., 2003, 2007).

Taste and odour research in the Bay of Quinte was initiated relatively recently (2003), even though it was originally identified as a recognised impairment in. Historically, T&O was largely assessed and “monitored” using proxy data (nutrients, chl, treatment dosages/ by-products, sporadic complaints etc; see above), as with many other AOCs. Our research has included spatial surveys and seasonal site monitoring for most of the above parameters, combined with WTP data and RAP support. While there are few data on T&O, a valuable long-term database maintained by the Quinte RAP and associated Project Quinte programme (e.g. Minns et al., 1986) has provided insight into recent changes in water quality and biota within this waterbody. The major aims of our Quinte T&O study has been to elucidate the sources, severity and temporal spatial patterns of impairment and its potential links, if any, with cyanotoxin production, and to use these data to assess the current RAP T&O criteria and targets.

Causes and controls: Contrasting mechanisms in different regions
Our combined research has clearly demonstrated that different mechanisms produce and modify T&O in Lake Ontario and the SLR. In the NW basin, the timing and severity of the annual geosmin peaks in drinking water supplies are largely a function of the degree of synchrony between small and large scale processes. Geosmin is not carried in from rivers but produced within the lake by planktonic cyanobacteria (not actinomycetes) in the illuminated offshore surface layers. Offshore production peaks briefly each year in late summer but only reach nuisance levels in some years. Aerial odour is usually low or undetectable across the lake, and cell disruption by heat or other forms of release (or
water treatment processes) is needed to release cell bound geosmin (e.g. Marvin et al., 2006). Importantly, it requires a climate-driven event for this peak to be detected in drinking water supplies. Following the warm, calm period when offshore production increases, late-summer east wind causes the mass transport of offshore surface water and associated cells/geosmin towards the NW shore and downward to deep WTP intakes. The strength of the annual downwelling and associated T&O event varies among years with the duration and persistence of the east winds (Rao et al., 2003).

In contrast, in the East Basin and Saint Lawrence River, both MIB and geosmin are produced annually over a prolonged period (Sept–Nov) and are largely derived from the substrate and macrophyte biofilms in shoreline areas (both cyanobacteria and actinomycetes). Production is highly patchy. In the SLR, aerial odour is frequently evident along much of the shoreline, indicative of cell disruption and VOC release, possibly as a result of periodic desiccation with changing water levels, scouring or grazing (Watson and Ridal, 2004).

The Bay of Quinte shows more erratic odour both in the open water and inshore sites with heavy macrophyte growth and increased abundance of the cyanobacteria Gloeotrichia echinulata, which migrates from benthic to planktonic zones during its lifecycle (Watson, 2004). Large scale transport processes do not appear to play a significant role in the transport of T&O in this embayment. However, our preliminary data from moored instrumentation in the Bay of Quinte suggest that both wind and small scale turbulence may be important in the spatial distribution of cyanobacteria.

Conclusions: Progress and future directions
These distinct patterns of T&O in Lake Ontario and the SLR differ markedly in their dynamics, biological and spatial origins and environmental modifiers, but in particular demonstrate the importance of inshore–offshore and benthic–planktonic coupling. Despite the complexity of these waterbodies, we have made significant progress towards understanding the factors driving odour production, the spatial and biological origins and the small- and large scale processes moderating the final impact at the WTPs and consumer taps. However, we still are still not able to predict the interannual variation in the intensity of the events, and our ongoing research, for example using genetic and remote scanning tools, may allow us to resolve some of the unknown mechanisms underlying the unpredictability. On a positive note, T&O issues in the Great Lakes have served to initiate changes in the approach taken by the water industry and other stakeholders to source water issues, in part because T&O affects a large, increasingly informed and concerned consumer base, and is a key criterion used by this group to judge the acceptability and potential safety of drinking and recreational water. Canadian municipalities affected by these T&O outbreaks have played a leading role in the development of a science-based approach to treatment, management and source water protection, with the aim to not only identify sources, triggers and modifiers facilitating more proactive water treatment, but also to long-term management strategy and increase our understanding of this source water by investigating links between T&O and ecosystem structure and processes.

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