The influence of city water consumption on the water balance and quality of drinking water supply with implications for altered operating rules

T. Pedusaar, E. Loigu, A. Pyrh and M. Pihlak

ABSTRACT

In the period 1990–2006, the decrease in water consumption of Tallinn, the capital of Estonia, determined both the input and output of the water balance of Lake Ülemiste, the drinking water reservoir of the city as well as its hydraulic retention time (HRT). In 2006, the city’s water consumption accounted for only a quarter of that in 1990. The role of regulated inflow in the water balance decreased and that of catchment run-off increased. Lake HRT increased four-fold. Before the 1990s, Lake Ülemiste resembled a river, now it is more lake-like. Changes in the water regime were correlated with the decline in concentrations of organic matter and chloride suggesting a likely causal relationship between them. Managerial challenges turned on finding new functions for upstream reservoirs and on the opportunity to refill the lake with better quality raw water.

Key words | city water consumption, drinking water reservoir, hydraulic retention time, operating rules, water balance, water quality

NOMENCLATURE

Ca\(^{2+}\) (mg l\(^{-1}\)) calcium ions
CDOC coloured dissolved organic matter
Cl\(^{-}\) (mg l\(^{-1}\)) chloride ions
COD\(_{\text{Mn}}\) (mg l\(^{-1}\)) potassium permanganate consumption
DOC dissolved organic matter
EMHI Estonian Hydrological and Meteorological Institute
HCO\(_{3}^{-}\) (mg-eqv l\(^{-1}\)) bicarbonate ions
HRT hydraulic retention time
SO\(_{4}^{2-}\) (mg-eqv l\(^{-1}\)) sulfate ions
THM trihalomethanes
WTP water treatment plant

INTRODUCTION

The decrease in drinking water consumption in cities is not a new phenomenon; it has been reported in both old and new member states of the European Union (Bogdanowicz et al. 2001; Rajala & Katko 2004). Both an increase and a decrease in water consumption provide new challenges to water works and resource managers. Uncertainties relate to predicting future water requirement in the light of human population pressures and climate change, as well as to the ecological consequences of changing water regimes. City water consumption has a particular influence on the water supply regime, and this is seen as an important factor in the functioning of lake and reservoir ecosystems affecting conservation values (Coops et al. 2003).

Lake Ülemiste represents one of the most intensively exploited lakes in Estonia as it has supplied the city of Tallinn, the capital of Estonia, with water since the 14th century. However, water treatment started only in 1927. Currently, Tallinn Water Ltd treats approximately 63,000 m\(^3\) d\(^{-1}\) of water originating primarily from Lake Ülemiste to supply more than 0.4 million customers, principally in Tallinn. The current water treatment technology

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consists of microfiltration, ozonation, coagulation/flocculation, clarification in sludge blanket clarifiers, filtration through two-layer anthracite or activated carbon filters and final disinfection with chlorine. From the beginning of the 1990s, and particularly after Estonia regained its independence (1991), the city water consumption declined rapidly.

The objective of the present paper is to show the extent of changes in the water balance and HRT of the lake as well as changes in water quality accompanying the decline in water consumption in the period 1990–2006. The implications of altered operating rules are also discussed.

LAKE ÕULEMISTE AND CATCHMENT AREA

Lake Õlemiste (59°24′1″ and 24°45′48″) is a natural lake bordered from north by the city of Tallinn (Figure 1).

In times past it had multiple uses, in the period 1990–2006, its prime function was to serve as a source of water supply to the city of Tallinn. The main characteristics of the lake are recorded in Table 1.

Public activities such as fishing, swimming, and boating, are prohibited in the lake. The lake is polymictic and shallow with hard water (Erm et al. 2001). It usually has a stable ice-cover for approximately 141 days a year. The lake has a gently sloping littoral zone. The shoreline is regular with a few sheltered bays and floodplains. There are man-made shorelines in the northern, north-eastern and southern sectors of the lake. The bottom of the lake is mainly covered with soft sediments (mud) but there is also some sand and gravel. Accelerated eutrophication has been identified since the second half of the 1960s (Pork et al. 1980).

The water level of the lake is regulated via the man-made Pirita-Õlemiste Canal from Vaskjala hydropoint (Figure 1).

Figure 1 | Map of Lake Õlemiste with scheme of catchment area.
There is also an unregulated inflow from the Kurna Canal (Figure 1), which waters previously discharged directly into the lake. In order to protect the lake, the natural Kurna wetland was reconstructed and the water from the canal was directed through marshes before reaching the lake (Pedusaar & Järvet 2004). The water treatment plant is the only outflow except for an emergency outlet. Agricultural areas (47%) with forest and semi-natural areas (38%) cover 85% of Lake Ülemiste natural catchment area including the Pirita-Ülemiste Canal drainage basin. Urban areas (ca 10%) are situated in the northern part of the lake but spread also to the southern part after 1991 due to the suburbanization process around Tallinn (Tammaru 2002).

The natural catchment area of Lake Ülemiste (70 km²) was enlarged by factor of ca 23 in the period 1922–1987 to meet the increasing water demand of the city of Tallinn. Currently the catchment area extracts water from four rivers (Pirita, Jägala, Soodla and Pärnu) by means of a network of interlinked reservoirs, rivers and canals covering 1,865 km², i.e. approximately 4.5% of the Estonian territory (Figure 1). Besides Lake Ülemiste, only the Paunküla and Soodla reservoirs have storage capacity. Vaskjala, the main linking point between the lake and catchment, is fed by two sources, the natural inflow of the Pirita River, and the artificial supply of the Jägala-Pirita Canal, which itself is fed by releases from the Kaunissaare hydropoint.

### MATERIAL AND METHODS

The water balance was calculated by the formula:

\[ I + P - E - O - \text{EXF} \pm \Delta \text{STOR} = 0, \]

where

- **I** input (regulated inflow from the Vaskjala hydropoint into the Pirita-Ülemiste Canal and run-off from the lake catchment area)
- **P** precipitation on the lake surface
- **E** evaporation
- **O** output (abstraction for drinking water treatment and flow through the emergency outlet)
- **EXF** groundwater outflow (0.17 m³ s⁻¹; Tepaks 1946)
- **ΔSTOR** change in lake volume

Regulated inflow released into the Pirita-Ülemiste Canal was gauged manually in the period 1990–1999. Automatic flow gauging systems were installed in 2000. Whenever the canal was closed, only the run-off from the canal catchment area (28.7 km²) was taken into account using the hydrological analogy method. Calculations were based on the daily run-off data of the nearby River Leivajõgi (gauging station Pajupea, catchment area 96.2 km²) measured by EMHI. In addition, the inflow from the Kurna Canal was calculated using the analogy method and data from the River Leivajõgi. Precipitation data were obtained from the EMHI’s database. Evaporation was calculated using the formula (selected by EMHI):

\[ E = 0.14n (e_0 - e_2) (1 + 0.72w_2), \]

where

- **n** number of days in month
- **e₀** saturated vapour pressure at surface water temperature
- **e₂** air vapour pressure at a height of 2 m
- **w₂** wind velocity at a height of 2 m

Water balance calculations were made on a monthly basis but the results are shown on an annual basis. The HRT was calculated by dividing total output by the lake volume. We used the long-term water quality data for

### Table 1

<table>
<thead>
<tr>
<th>Main characteristics of Lake Ülemiste at normal pool level (36.62 meters above the sea level (m.a.s.l.) according to the Baltic system) and its main physical characteristics for operating as a water reservoir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface area (km²)</td>
</tr>
<tr>
<td>Minimum pool level (m a.s.l.)</td>
</tr>
<tr>
<td>Pool level during design flood (m a.s.l.)</td>
</tr>
<tr>
<td>Critical maximum level (m a.s.l.)</td>
</tr>
<tr>
<td>Optimal lake level during ice-free period (m a.s.l.)</td>
</tr>
<tr>
<td>Optimal lake level during ice-cover period (m a.s.l.)</td>
</tr>
<tr>
<td>Maximum level observed in the period of 1879–2005 (m a.s.l.)</td>
</tr>
<tr>
<td>Minimum level observed in the period of 1879–2005 (m a.s.l.)</td>
</tr>
<tr>
<td>Catchment area (km²)</td>
</tr>
</tbody>
</table>
Lake Ülemiste, collected to monitor raw water quality for the proper operation of the WTP. Samples were taken at least once a month and analysed according to ISO standards. Paerson correlations were calculated using SYSTAT version 8.0. Multivariate Mann-Kendall tests were carried out by the program developed by Libiseller & Grimvall (2002).

RESULTS AND DISCUSSION

City water consumption as the major component of the output of the water balance of Lake Ülemiste

The city’s demand for water has decreased steadily since the beginning of the 1990s (Figure 2).

In 2006, the city’s water consumption was only 26% of that in 1990, close to that of 1962. As the city’s water consumption controlled the output of the water balance, comprising over 80% of the total output in 1990–1996, the role of other components, such as evaporation, groundwater outflow and outflow through the emergency outlet, was small (Figure 3). But as water consumption gradually decreased and from 1997 onwards, the proportion of evaporation and groundwater outflow, in particular, increased.

Changes in the input of the water balance and longer HRT of the lake

There was considerable correlation between regulated inflow and city water consumption for the period 1990–2006 ($R = 0.72$; $p = 0.001$; $n = 204$). Regulated inflow was the major component (average 68%) of input in 1990–1997 (Figure 4).

From 1998, the role of regulated inflow decreased, the average being only 39% including the exceptional year of 2004. The latter was an extreme year because of high amount of precipitation (more than 900 mm y$^{-1}$) that resulted in high run-off from the natural catchment area with very little need for additional water. There was a small but significant correlation between precipitation and runoff ($R = 0.21$; $p = 0.002$; $n = 204$), and a medium negative relationship between regulated inflow and run-off from the lake catchment area ($R = -0.32$; $p = 0.001$; $n = 204$). Run-off from lake catchment varied between 14 and 29 Mm$^3$ y$^{-1}$ with the exception of 34.5 Mm$^3$ y$^{-1}$ in 2004. In 2006, the total hydraulic loading to the lake was 25% of that in 1990.

Decreased outflow from the lake caused a decrease in inflow and as a result the HRT increased four times: from 0.36 y to 1.4 y over the observed time scale (Figure 2).
Long-term trends in water quality of the lake

The water colour, \( \text{COD}_{\text{Mn}} \), \( \text{Cl}^- \) and permanent hardness in the lake showed significant downward trends in 1990–2006 (Table 2). At the same time, other water quality parameters did not show any significant trends.

There is a strong correlation between \( \text{COD}_{\text{Mn}} \) and water colour in Lake Ülemiste \( (R = 0.63, \ p = 0.001, \ n = 200) \). Also, Reinart & Pedusaar (2008) showed that water colour is a good indicator of the amount of CDOC in the lake. Significant decreases in both proxies of organic matter, such as colour and \( \text{COD}_{\text{Mn}} \) in the lake coincided with the decline in input. Regulated inflow correlated strongly both to colour \( (R = 0.6; \ p = 0.000; \ n = 201) \) and \( \text{COD}_{\text{Mn}} \) \( (R = 0.5; \ p = 0.000; \ n = 203) \). Catchment-derived water is, in general, more coloured than the water in Lake Ülemiste. There is a ‘colour surge’ into Lake Ülemiste typically during periods of high flow (Faulkner et al. 2003). It is likely that the concentration of organic matter in the lake was affected not only by a drop in external water loading but also by the longer HRT. A long lake HRT allows more time for internal processes such as oxidation by microbes, photobleaching of CDOC, as well as photooxidation of DOC in general (Kalff 2002). In addition, in 2004, biomanipulation of Lake Ülemiste was initiated as an in-lake restoration measure and the first effects of fish removal on nutrient concentration and plankton were detectable (Pedusaar et al. 2008; Pedusaar et al. 2010).

Water colour and \( \text{COD}_{\text{Mn}} \) are considered to be important parameters because of the formation of THM, carcinogenic compounds that are produced when water with a high DOC concentration is disinfected with chlorine. Both water quality indicators are used by WTP to determine the necessary coagulant dosages in the ensuing treatment process. The coagulant is the biggest single cost in the annual operating budget (Faulkner et al. 2003). Better water quality in the lake, due to decreased concentrations of water colour and \( \text{COD}_{\text{Mn}} \), has reduced the cost of and improved the efficiency of drinking water treatment.

A strong correlation between \( \text{Cl}^- \) and permanent hardness \( (R = 0.5; \ p = 0.001; \ n = 200) \) is an indication that the \( \text{Cl}^- \) ions play a role in the formation of the lake water’s permanent hardness. Also there was a medium but significant correlation between chloride ions and regulated inflow \( (r = 0.4; \ p = 0.000; \ n = 203) \). Chloride is one of the major anions reflecting human activity, and its decline is often associated with altered hydrology in the catchment area, improved industrial practices and wastewater treatment, and a decrease in fertilizer-derived \( \text{Cl}^- \). A decrease in the use of fertilizers and livestock production, as well as modernisation of industrial production with the construction of new wastewater treatment plants and the improvement of existing ones, have been extensive since 1991 in Estonia (Iital et al. 2005).

### Table 2 | Mann-Kendall test results of long-term (1990–2006) water quality parameters of Lake Ülemiste with medians (25%, 75% quantiles) in 1990 and 2006 for parameters showing trends

<table>
<thead>
<tr>
<th>Water quality parameter</th>
<th>MK stat</th>
<th>( p )</th>
<th>1990</th>
<th>2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{COD}_{\text{Mn}} ) (mg\text{l}^{-1})</td>
<td>-3.18</td>
<td>0.001</td>
<td>12.9 (11.7; 13.2)</td>
<td>9 (8.6; 9.9)</td>
</tr>
<tr>
<td>Colour (mg Pt\text{l}^{-1})</td>
<td>-3.88</td>
<td>0.001</td>
<td>70 (59; 91)</td>
<td>45 (41; 47)</td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
<td>-0.76</td>
<td>0.440</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{SO}_4^{2-} ) (mg\text{l}^{-1})</td>
<td>0.12</td>
<td>0.900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{Ca}^{2+} ) (mg\text{l}^{-1})</td>
<td>0.01</td>
<td>0.990</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{HCO}_3^- ) (mg\text{l}^{-1})</td>
<td>-0.58</td>
<td>0.560</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{Cl}^- ) (mg\text{l}^{-1})</td>
<td>-3.14</td>
<td>0.002</td>
<td>14.5 (13; 15.5)</td>
<td>10 (9.9; 10.3)</td>
</tr>
<tr>
<td>Alkalinity (mg-equiv\text{l}^{-1})</td>
<td>-0.33</td>
<td>0.740</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{pH} )</td>
<td>2.05</td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temporary hardness (mg-equiv\text{l}^{-1})</td>
<td>-0.13</td>
<td>0.890</td>
<td>1.08 (0.88; 1.45)</td>
<td>0.92 (0.71; 1.07)</td>
</tr>
<tr>
<td>Permanent hardness (mg-equiv\text{l}^{-1})</td>
<td>-2.56</td>
<td>0.01</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Altered operating rules for the lake and catchment management in relation to the decline in city water consumption

The decline in the city's demand for water can be attributed to the following: the collapse of industry as water usage by industry in Tallinn decreased from 46 to 9 Mm$^3$ y$^{-1}$ in the period 1990–2006; the installation of water meters, which resulted in a more sustainable use of water, both industrial and domestic; more economical sanitation devices; and fewer leakages in the water distribution system. Leakage level was below 18% in 2005, which is 50% lower than in 2000 (Annual Report 2005). However, the main reason for the decreased water consumption was the rise in the cost of water: household tariffs increased steadily from €0.013 m$^3$ in 1992 to €1.48 m$^3$ in 2006.

The fourfold drop in the Tallinn’s water consumption entailed changes in the hydrological regime of the lake. Before the 1990s, Lake Ülemiste resembled a river, now it is more lake-like. These new conditions generated the need and provided the opportunity to pay more attention on lake and catchment management.

Currently, the annual city water consumption (23 Mm$^3$ in 2006) is higher than the usable storage capacity of Lake Ülemiste (16 Mm$^3$) but smaller than the lake’s total capacity (32 Mm$^3$). In wet years (annual precipitation greater than 750 mm), the run-off from the lake’s catchment area is equal to or higher than water consumption, and therefore a supply of raw water is guaranteed. In the case of the common mean annual precipitation, which ranges from 550 to 750 mm in Estonia (Kont et al. 2002; Reihan 2008), and on the current levels of water demand (approximately 23 Mm$^3$ y$^{-1}$), the regulated inflow requirement may range between 25% and 50% of total input. The increase in the emergency outlet’s open period combined with the decline in intra-annual amplitudes of lake level as well as a higher mean annual water level since the 1990s (Treì & Pedusaar 2006), suggest that the yield is adequate for the current levels of water demand. However it should be noted that the regulated catchwater requirement depends on intra-annual fluctuations of rainfall as well. Although the climate of Estonia is humid, there are often droughts in summer (Kont et al. 2002). Extreme dry or wet periods in Estonia have become more frequent in the last decades (Tammets 2007).

Therefore, the catchment system established in the past to guarantee raw water for the city, has partly lost its role. There has been discussion of abandoning some upstream water sources, but everyday practice has shown that a dry year (< 500 mm y$^{-1}$) or dry summer may affect long-term reliability. Moreover, in the event of climate change and the possibility of expanding the local market for water, it seems sensible to keep the storage capacity. Upstream reservoirs have taken on functions in addition to water supply, such as recreation, hydropower production or fisheries.

Another change in operating rules was the timing of the lake’s replenishment with regulated catchwater. The summer recharge of the lake increased significantly in the period 1990–2006 (MK stat $= 2.88; p = 0.003$), but the spring (MK stat $= -1.81; p = 0.06$) and winter (MK stat $= -1.85; p = 0.06$) recharges showed a downward trend. It is well recorded that during high water periods and winter, nutrients and organic matter concentrations are higher and water run-off from rivers can be more turbid. The substantial decrease in city water consumption made it possible to avoid or reduce the need to refill Lake Ülemiste with raw water during these periods.

Finally, it should be remembered, that in the period under consideration (1990–2006), the lake was subject to four, probably synergistic, processes: a decrease in hydraulic loading due to the drop in Tallinn’s drinking water consumption; the opportunity to choose better quality raw water for delivery into the lake; and an increase in in-lake processes due to a longer HRT. The fourth factor, as mentioned above, is the remarkable decrease in pollution due to the collapse of Soviet-type agriculture and industry since the beginning of the 1990s (Iital et al. 2005).

CONCLUSIONS

Human needs have modified the functioning of Lake Ülemiste ecosystem. Before the 1990s, the lake served as a regulating waterbody for river run-off and a guaranteed raw water supply for the city of Tallinn. In the period 1990–2006, the lake became more lentic as a result of the four-fold reduction in external hydraulic loading and the four-fold increase in the HRT. The change in the lake’s water regime brought about alterations to operating...
rules and was likely one of the main factors causing the reduction in levels of organic matter (CODMn and colour) and chloride concentrations in the water supply. We can therefore conclude that the decrease in water consumption offers an opportunity for a more rational and sustainable approach to water resources management.

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