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Isabelle JALLIFFIER-VERNE[1], Mourad HENICHE[2], Robert LECONTE[3], Uriel F. HUARINGA ALVAREZ[3], Martine GALARNEAU[4], Anne-Sophie MADOUX-HUMERY[1], Michèle PREVOST[1] and Sarah DORNER[1]

[1] Department of Civil, Geological and Mining Engineering, École Polytechnique de Montréal, 2900, boul. Édouard-Montpetit, Montréal, QC, H3T 1J4, Canada
(E-mail: isabelle.jalliffier-verne@polymtl.ca ; sarah.dorner@polymtl.ca ; anne-sophie.madoux-humery@polymtl.ca ; michele.prevost@polymtl.ca)
[2] Department of Chemical Engineering, École Polytechnique de Montréal, 2900, boul. Édouard-Montpetit, Montréal, QC, H3T 1J4, Canada
(E-mail: mourad.heniche@polymtl.ca)
[3] Department of Civil Engineering, Faculty of Engineering, Université de Sherbrooke, 2500 Boulevard de l'Université, Sherbrooke, QC, Canada, J1K 2R1
(E-mail: robert.leconte@usherbrooke.ca)
[4] Engineering department, city of Laval, 1333, boulevard Chomedey Rez-de-chaussée, C.P. 422 Succ. Saint-Martin Laval (Qc) H7V 3Z4 (E-mail: m.galarneau@ville.laval.qc.ca)

Abstract

During precipitation events in regions with combined sewers, overflows can occur upstream of drinking water treatment plants. The purpose of the research was to model the transport and propagation of pathogens and pharmaceuticals in the Rivière Des Prairies during flood and low flow events. The water quality is quantified in terms of the behaviour of the river, the interactions of contaminants with the environment and the impacts of climate change. Hydrosim was used for hydrodynamic modeling; Dispersim was used to model the dispersion of contaminants. The impact of climate change was represented by the change of flow in the river. To do so, simulations were performed using Hydrotel, a hydrologic model applied to the Ottawa River. Thus, the impact of dispersion and diffusion of contaminants on the water quality were analyzed to determine the potential impact on raw water quality. Water quality will be affected by lower flows and heavy rains, which will change the frequency distributions of fecal contaminants upon which microbial risk models are based.

Keywords

Hydrodynamic; contamination; diffusion; water quality; climate change

INTRODUCTION

The potability of water is directly related to its environment. The protection of sources is taken into consideration in multi-barrier approaches to ensuring safe drinking water. Depending on the standards, water treatment obligations are based on raw water quality and, therefore, upstream contaminant loads. Therefore, it is important to characterize water quality based on known and potential sources of contamination. Peaks of chemical and biological contamination, observed during overflow events, correspond to periods of risk to human health. However, the impact of climate change on the quality and quantity of drinking water are seldom included in the development plans for the protection of water intakes, despite their potential effects on the quality of water. The characterization and prediction of upstream changes allow us to mitigate the potential impacts of sources of contamination on drinking water treatment. The behaviour of streams is related to climatic conditions which have an influence on the supply capacity of drinking water intakes, but also on the physico-chemical and biological characteristics of water. Water contamination has a direct impact on the operation and design of treatment facilities. The drinking water treatment depends on its quality. It is determined based on the annual average concentration in *Escherichia coli* (*E. coli*) in the raw water. This bacterium is a common host in the gut flora of mammals including humans. Its presence in water characterizes the existence of fecal contamination that could be potentially pathogenic. Therefore, *E. coli* was used as the indicator of fecal contamination of the water.

The Rivière des Prairies is a simple system which does not have a large number of contaminant sources relative to other local rivers. It has already been sampled and the results were published in conference proceedings (Madoux-Humery *et al.*, 2010a; Madoux-Humery *et al.*, 2010b; Madoux-Humery *et al.*, 2010c) and various manuscripts submitted for publication. The Rivière des Prairies, fed by the Ottawa River and main effluent of the Lake of Two Mountains, is directly influenced by the hydrology and water resources management in the Great Lakes and the Ottawa River. Water levels in the Great Lakes are managed by an agreement between Canada and the United States (Pietroniro *et al.*, 2007) by the International Joint Commission (IJC). The Ottawa River is governed by the Ottawa River Regulation Planning Board, which objectives are to protect people from flooding and protect the interests of users of the river (Ontario Power Generation and Hydro-Québec).

The probability of overflows depends on precipitation events and snowmelt. The work of Mailhot et al. (2007) suggests an increase in precipitation and therefore an increase in the frequency of overflows could be expected. Patz et al. (2008) suggest that the increase of the number of heavy rainfalls, causing a greater number of overflows, helps to increase the risk of waterborne diseases in the Great Lakes region. The impact of overflows is intensified by the fact that the discharge water is not treated and their location prevents a proper dilution. There have been observed episodes of fecal contamination in raw water filtration plants on the Rivière des Prairies (Madoux-Humery *et al.*, 2010c). Finally, the impact of the change in runoff water from the Rivière des Prairies on the water quality has not yet been estimated.

This paper presents a particular case (Rivière des Prairies) for the integration of climate change impacts in assessing the quality of drinking water in Quebec.

MATERIAL & METHODS

Site

The study site will be free of obstacles such as dams to ensure good modeling. The Centre d'Expertise Hydrique du Québec (CEHQ) has conducted a study on the river to determine the dimensions of flood recurrence over 20 and 100 year periods (CEHQ, 2006). Based on this document and a site visit, we can describe the location of our modeling.

The Rivière des Prairies takes its source in Lake of Two Mountains, fed by the Ottawa River. During floods, Rivière des Prairies is a major effluent for the lake which capacity can reach 35% of the flow of the Ottawa River. The Rivière des Prairies flows over a distance of 51 kilometers to the northeast until it empties into the St. Lawrence River. The portion that we study is a dozen kilometers long. There are several gauging stations operated by the CEHQ, Environment Canada and Hydro-Québec. Station 043301, located at the head of Cheval Blanc Rapids and managed by CEHQ, measures the flow of the river. It has been in operation since 1922.

The Rivière des Prairies is a major water resource in the Montreal area where population growth increases the demand for water. Three water treatment plants are located along the Rivière des Prairies serving approximately 380,000 people. The latter two treatment plants are downstream of overflows, located at the end of combined or mixed networks, which, during heavy rainfall, flow directly into the river without treatment. Thus, combined and sanitary sewer overflows present a major risk of fecal contamination upstream of drinking water treatment plant intakes. One of the water intakes is downstream of 53 overflows and the second intake is downstream of the first. It is under the influence of the releases mentioned above but also 37 additional overflows. The Rivière des Prairies also has many areas of wildlife interest in the vicinities of water intakes. The quality of water in many places has limited its use for recreational activities in the past. There have been over 180 events per year of sewer overflows. Sewer systems are predominantly combined, and overflows are the main cause of microbiological contamination.

Hydrodynamic Modeling

To characterize the levels of floods, the CEHQ chose to model the sector with models in two dimensions. The software used is Modeleur (Secretan *et al.*, 2000) and Hydrosim (Heniche *et al.*, 1999). They were developed by the Centre Eau Terre Environnement of National Institute of Scientific Research (INRS). These combine georeferenced data of hydraulic characteristics into a 2-dimensional model representing the solution to the Saint-Venant equations (CEHQ, 2006).

The Modeleur and Hydrosim software allow simulations of water levels. The input data is a digital terrain model, the distances between observation sites, the roughness coefficients, the downstream boundary conditions of the model, the hydrometric statements and the calibration of the hydrodynamic model. The bathymetry of the site was provided by the Canadian Hydrographic Service of Fisheries and Oceans Canada. The topography of the banks was measured by an aircraft equipped with a LIDAR system (light detection and ranging) in fall 2001. The data cover all sides of the river to a width of about 200 meters on each side of the river and the data points are spaced by about 3 meters. This model was used to simulate several events to calibrate hydrodynamic model adequately. To obtain a model closer to reality, we compared simulation results to actual events. Then, we used different observation sites. The Manning roughness coefficients allow us to better adjust the model to observations.

"The banks and the floodplain of the Rivière des Prairies are largely urbanized and, in some places, covered with grass or fields. The Manning coefficients corresponding to the bed, the banks and floodplain of the river varies from 0.018 to 0.100."(CEHQ, 2006).

The hydrometric statements were made by the CEHQ for 9 measurement campaigns: 2 in autumn 2001, 5 in spring 2002, one in spring 2003 and one in autumn 2003. For their analysis, the selected campaigns by the CEHQ are 22/04/2002, 01/05/2002 and 27/11/2003 (as seen in Table 1).

Table 1. Water levels of our studied portion of the Rivière des Prairies (CEHQ, 2006)

Site	22/04/2002	01/05/2002	27/11/2003
9.2	17,33	17,27	17,26
9.4	17,52	17,43	17,40
9.5	17,70	17,60	17,54
9.6	17,93	17,79	17,69
11	19,73	19,44	17,15
Measured flow rate (m^3s^{-1})	2356	2110	1923

Table 2. Results of calibration of the studied portion (22/04/2002) (CEHQ, 2006)

Site	Simulated level (m)	Observed level (m)	Difference (cm)
9.2	17,33	17,33	0
9.4	17,52	17,52	0
9.5	17,58	17,7	-12
9.6	18,03	17,93	10
11	19,66	19,73	-7

The model calibration was done with measures at high flow to prevent flooding. Differences in levels (as seen in Table 2) are satisfactory to the CEHQ.
Hydrosim model is a 2D finite element hydrodynamic model with drying-wetting capabilities. It takes into account wet areas, dry areas and transition zones that are characterized by a value of level positive or negative. This model allows for the study of both permanent and non-permanent flows.
In this model, there are two types of boundaries. A fixed boundary is used: it applies to the constraints of adhesion or friction. The moving boundaries are used to specify the type of flow. The finite element method is used to discretize the conservation equations and is solved by the Galerkin method in its weak form. It is stabilized by a diffusion operator that dissipates errors with mesh refinement. In addition, the authors use a triangle of 6 nodes as a finite element, which respects the Babuska-Brezzi condition (Babuska, 1971; Brezzi, 1974). The resolution of resulting matrices is carried out by a version of GMRES (Generalized Minimal Residual Method) using the factorization "Incomplete Lower-Upper" (ILU) as a starting point (Leclerc *et al.*, 1996; Saad *et al.*, 1986; Secretan, 1992).
This model cannot make any assumptions about the level of the water. The method can solve problems of steady and transient regimes. The continuity equations of conservation of motion in their discrete forms are retained throughout the simulation domain and allow the calculation of realistic velocity field in wetlands. However, it does not simulate a surge of water like in case of a dam failure (Heniche *et al.*, 2000a).

Contaminant modeling

Our model is based on the Dispersim module (Heniche *et al.*, 2000b) to simulate the spread of contaminants in the studied river. It can simulate: SS (suspended solids), DO (dissolved oxygen), BOD (biochemical oxygen demand), faecal coliforms, heavy metals and toxic organics. This is a two-dimensional model where averaged variables in the water column are calculated (Heniche *et al.*, 2000b) in triangular finite elements. The resolution is possible for stationary or transient flow.
It is based on the scalar equation of transport-diffusion in its non-conservative form as cited by Heniche *et al.* (2000b). On a closed boundary, the normal velocity is zero and we impose a condition of Neuman. In a boundary input, we impose a condition of Dirichlet or Cauchy. For the output, we assume that the concentration outside of the domain is the same as inside. Otherwise we can assume a Neuman condition.

Methods

The Hydrosim model provided by the CEHQ is calibrated during floods. The setting of the model in low flows is done by varying the Manning coefficient on the studied portion (upstream from the Hydro-Québec dam). This calibration is based on five measurement campaigns (3 in August 2011, 2 in August 2012) and five used observation points (some points were not chosen because outside of the mesh, inaccessible or distorted by the presence of site work) (presented in Table 3). Monitoring campaigns were carried to determine a calibration for low flow events.

Table 3. Measured water levels

Date		2011-08-23	2011-08-26	2011-08-31	2012-09-06	2012-09-10
Flow	(m^3/s)	689,5	702,4	687,1	502,4	540,4
Water level	(m)					
9.2		17,158	17,133	17,186	17,171	17,166
9.4		17,202	17,129	17,196	17,149	17,153
9.5		17,222	17,227	17,197	17,121	17,146
9.6		17,212	17,292	17,272	17,332	17,262
11.		17,601	17,598	17,605	17,3726	17,460

Water levels were measured with an accuracy of ± 5 cm.
For the calibration of a model, it is important to calibrate the boundary conditions. Upstream, there are 2 inputs for the flow where it is necessary to provide a level and a flow corresponding to the model. Downstream, there is an outlet where it is only necessary to provide the level.
The flow distribution between the north entrance and the south entrance is determined by a percentage (47% in the north, 53% of the flow in the south). These percentages are based on observations made during floods (standard deviation 1.07%). No other data allowed us to establish the distribution of flows. The water level has not been measured upstream during low water events; we determined the relationship level flow from the available data. The relationship between flows and water levels is established for each entry with the raw data.
North entrance: $Level_{north} = 0{,}0022\ Q_N + 20{,}908 ; R^2 = 0{,}9914$
South entrance: $Level_{south} = 0{,}0016 Q_S + 21{,}414 ; R^2 = 0{,}9820$
For the downstream boundary, data were collected during the five measurement campaigns. The flow rate was controlled upstream, by the Ottawa River Regulation Planning Board and the upstream level controlled by Hydro-Québec, it is difficult to pull out a stage-discharge relationship only with low-flow data (R^2 = 0.109). Taking into account the data during floods from the model Hydrosim on the Rivière des Prairies, we can highlight a relation:
$Level_{downstream} = 7 * 10^{-5} Q + 17{,}121 ; R^2 = 0{,}9466$
Using this relation, we obtain synthetic levels that induce a maximum error of 3.9 cm, the required accuracy is ± 5cm.

Table 4. Synthetic levels for the downstream boundary

Flow (m3/s)	Observed level (m)	Synthetic level (m)	Error (m)
502,4	17,171	17,156	0,015
540,4	17,166	17,159	0,007
687,1	17,186	17,169	0,017
689,5	17,158	17,169	-0,011
702,4	17,133	17,170	-0,037
1923	17,256	17,256	0,000
2110	17,27	17,269	0,001
2326,6	17,286	17,284	0,002
2356	17,325	17,286	0,039
3152	17,339	17,342	-0,003
3543,5	17,363	17,369	-0,006

The simulations are performed with the synthetic level from Table 4. For the preparation of scenarios observations, a frequency analysis was conducted in floods and during low flows. Calibration data for Dispersim in terms of contaminants will be taken from sampling campaigns conducted previously. In addition, data on intakes have been identified by the city of Montreal. The coefficient of degradation of *E. coli* was evaluated on the river by other works of our team.

Climate change

In future climate, flows are based on the work of Huaringa Alvarez *et al.* (2012). What follows is based on the report provided by his team to us. Climate projections are from the Canadian Regional Climate Model (CRCM) coupled to the Canadian global climate model CGCM. CRMC conducts simulations to fine scale of about 45 km with a time step of 15 minutes between each integration (ESCER). The screening was performed using data from 1960 to 1999 and takes place over the period from 2040 to 2070. It is composed of data of minimum and maximum temperatures and precipitations.
In this projection, the work was done for the Rivière des Mille-Îles and Rivière des Prairies, both mainly fed by the Ottawa River and connected with the Lake of Two Mountains. The

management of the watershed of the Ottawa River is not available; the team used a neural network to simulate basin management, created using the Matlab tool. The verification is performed on the flow value at Carillon. For the creation and evaluation of the performance of the neural network, they used the hydrological model Hydrotel.

Hydrotel model (Fortin *et al.*, 2001) was created by the National Institute of Scientific Research, Water, Earth and Environment (INRS-ETE) of Quebec. Hydrotel has the advantage that it can be used with a minimum of meteorological data. It adapts to the amount of available data. Therefore, it is possible to calculate contributions from the Lake of Two Mountains. Contributions are made by the flows at Carillon which are simulated by neural network, the flows of the North River which are simulated by Hydrotel and the lateral inflows from the lake which correspond to 2.49 times the flow of the North River.

River flows were simulated four times. The first three simulations correspond to learning throughout the period, learning during the cold period and learning during the warm period. The fourth simulation is the simulation using observed streamflow at Carillon, called "evaluation". This last simulation analyses the influence of neural network simulations on river flows.

Observed data are available from 1913 to 2008 for the Mille-Îles River and are available from 1923 to 2001 for the Rivière des Prairies. The analysis period of reference is considered from 1972 to 2000 and the future is seen from 2042 to 2070. CRCM predictions available for the reference period and for the future are 40 years (1961-2000) and 30 years (2041-2070) respectively. However, the analysis between the reference period and the future period was conducted for 29 years, respectively, to reflect the same number of years for debits.

RESULTS AND DISCUSSION

There are no differences between the model during floods and during low water period. The model for low water periods meets: ± 10 cm and a gap between inflow and outflow is less than 7%. The error of up to 13 cm in point 11 is assumed to be due to work near the site. In addition, we analyzed the results by comparing water levels from upstream, downstream and 5 points of observation. Some adjustments were made to the upstream conditions where the differences with the previously simulated discharges. These adjustments were made only on the level of water that could be measured and this allows us to model convergence near the borders of the model (no jump in value). Here are the results for two simulated water levels (Table 5).

Table 5. Results of 2 simulated water levels

			Observed	Simulated	Gap	Observed	Simulated	Gap
Flow	Downstream	(m^3/s)	687,1	710,437	-3,40%	502,4	516,503	2,81%
Upstream	North	(m^3/s)	322,937	343,076	-6,24%	236,128	251,018	6,31%
	South	(m^3/s)	364,163	383,118	-5,21%	266,272	280,252	5,25%
	Total	(m^3/s)	687,1	726,194	-5,69%	502,4	531,27	5,75%
Water level	9.2	(m)	17,186	17,169	0,017	17,1711	17,156	-0,015
	9.4	(m)	17,196	17,194	0,002	17,1492	17,1691	0,02
	9.5	(m)	17,197	17,2	-0,003	17,1207	17,1721	0,051
	9.6	(m)	17,272	17,322	-0,05	17,332	17,2397	-0,092
	11.	(m)	17,605	17,728	-0,123	17,3726	17,4793	0,107
Upstream	North	(m)	21,545	21,545	0	21,2327	21,2323	0
	South	(m)	21,49	21,491	-0,001	21,2574	21,2562	-0,001

For the creation of scenarios, we conducted frequency analyses. The flood frequency analysis was made by the CEHQ. During floods, the Rivière des Prairies follows the Gamma law (Maximum Likelihood). During low flow periods, we follow the same process as the CEHQ. We obtain that the law is the generalized extreme value law (GEV) (Maximum Likelihood). The statistical study of the low water period was conducted over the same period as the study of floods (1923-1976 and 1978-2002). The study has been extended until 2010. It is considered as the average daily low flow, the lowest in a year. Table 6 shows us the results of the frequency analysis.

Table 6. Flows for several return periods in actual climate

Return periods (year)	Flood (CEHQ) (m^3/s)	Low water flow (m^3/s)
2	2326,6	595,7
5	2728,2	517,22
10	2955,4	483,86
20	3152	459,35
50	3383,4	434,39
100	3543,5	419,29
1000	4018,3	381,52

It also notes that the minimum flow of water to a catchment and supply optimum water intake (Q2, 7) is 499 m^3/s. However, during low water, this flow is not necessarily achieved, which can cause problems with water quality downstream. We can assume some problems in the quality of water in case of a decrease of flows.

Initial results from *E. coli* contamination have been analyzed and a relationship was established between flow and concentration of *E. coli* in the river (Figure 1). The trend highlighted is that the higher the flow, the higher the concentration of *E. coli* in water, excluding winter. Variability in data during spring could be explained by washoff and transport during floods. Our points of interest in this work are the critical values (i.e. the highest).

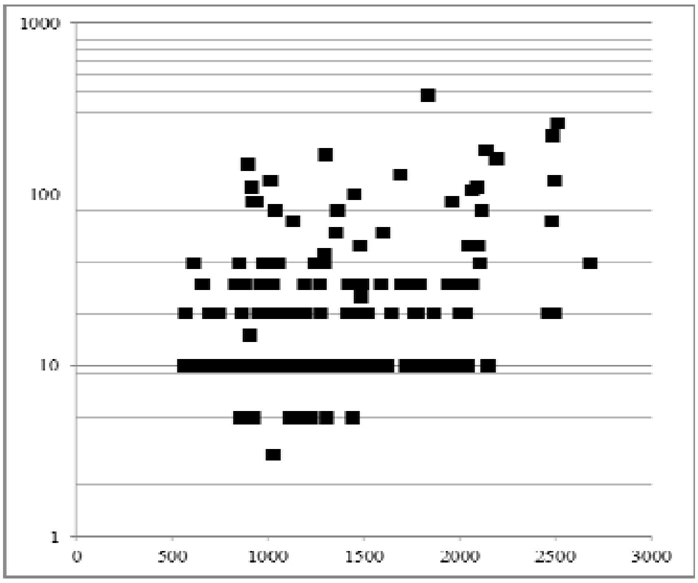

Figure 1. Flow versus E. coli concentrations during spring only

We can also assume that the increase of heavy precipitations should have an impact on the contaminant concentration. Others analyses will be done to quantify the impact of an increase or a decrease of flows (not only high flow or low flow). It will highlight the impact of resuspension, one of the processes who impact the water quality. At this time, we are working on relationships between several factors like flows and *E. coli* concentrations to obtain a better modelling system.

Climate change

Climate projections show a clear trend in annual temperature and seasonal temperature increase in future periods. Annual precipitation, spring precipitation and winter precipitation will increase, but the summer-fall precipitation shows no significant increase.

Neural network performance was evaluated by comparing four neural networks created from four different learning. Nash coefficients were obtained very good for each of them. The offset of the spring flood and low flows, lower in future periods, are the most notable impacts of climate change on Rivière des Mille-Îles and Rivière des Prairies. With the data from these studies, we can do a quick comparison (Table 7) between the current value and projected floods and low flows.

Table 7. Change in flows

	Flood				Low water			
Return period (years)	Current climate flow (CEHQ) (m^3/s)	Future climate flow (m^3/s)	Gap (m^3/s)	Gap (%)	Current climate flow (CEHQ) (m^3/s)	Future climate flow (m^3/s)	Gap (m^3/s)	Gap (%)
2	2326,6	2117,9	-208,7	-9,00%	595,7	619,9	24,2	4,10%
5	2728,2	2409,9	-318,3	-11,70%	517,22	579,3	62,1	12,00%
10	2955,4	2546	-409,4	-13,90%	483,86	562	78,2	16,20%
20	3152	2650,9	-501,1	-15,90%	459,35	549,4	90	19,60%
50	3383,4	2761,6	-621,8	-18,40%	434,39	536,5	102,1	23,50%
100	3543,5	2831,5	-712	-20,10%	419,29	528,6	109,3	26,10%
1000	4018,3	3013,2	-1005,1	-25,00%	381,52	509,1	127,6	33,40%

During flooding, there is a decrease of 25% of the flow for a return period of 1,000 years. All rates are falling. In low water, the rate of recurrence of 1,000 years increased by 33%. All rates are rising. These findings may be explained by a smaller flood peak, an earlier snowmelt and rainy summers.

Several scenarios for the future can be created after this observation in order to have a better management of treatment under climate change.

CONCLUSIONS

The hydrodynamic model of the river is now calibrated and is ready to be used for simulations during low water and high water periods for the diffusion and dispersion of contaminants. A first brief analysis of the fate of contaminants could be determined from the existing data. The possible relation between flow rates and concentrations could be further studied by analyzing the impact of an increase in the flow rate on concentration.

The quality of water is expected to be impacted by the changes in flows and by the increase of heavy rains. It can also be expected that the pollutant concentrations will increase and affect the class of treatment required. The magnitude of the impact will be quantified by this work and will assist with better management and decision making to reduce risks of fecal contamination in drinking water sources.

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