Chapter 6

Effective use of a Catchment Modeling Approach as a Diagnostic Tool for Integrated Water Management

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For the last ten years, the *Association québécoise des techniques de l'environnement (AQTE)* and *Ministère de l'environnement et de la faune (MEF)* have been involved in the definition and development of an integrated water resource management plan at the watershed level (AQTE, 1993). An integrated water management plan is currently being implemented in the semi-rural watershed of the Chaudière River by the *Comité régional du bassin de la Rivière Chaudière (COBARIC)*, (COBARIC, 1996). Similar plans for managing other watersheds (the Saint Charles and the Assomption River basins) are also being considered. In collaboration with the MEF and the Québec Urban Community (QUC), the Institut national de la recherche scientifique (INRS-Eau) is developing a framework for the integrated water management of Québec's urban areas (Vescovi and Villeneuve, 1996a). The main objectives of an integrated water management approach in the Québec City region are to develop support among community planners and water managers for an ecosystem-based approach to land use (see Figure 6.1); water planning and management criteria; and, tools to assess the health of critical streams within the Saint Charles River basin and the QUC.

The first step in a successful urban water management program is to maximize the knowledge of the dynamics between the rural and urbanized portions of a river basin and the principal sources of surface water contaminants (see Figure 6.2). Several diagnostic tools are available to accomplish this.

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Figure 6.1 Urban water management within an integrated planning approach.

Figure 6.2 Integrated water management phase for the Saint-Charles River watershed and the Quebec City region.

Probably, the most flexible means of water resources management are rapidly emerging software systems that integrate simulation models, geographical information systems and database management systems. An example of one such system is GIBSI (*Gestion Intégrée des Bassins à l'aide d'un Système Informatisé*), which is being developed at INRS-Eau. Work on establishing the needs of the system was carried out in 1995 and the first applications were carried out in 1996 (Villeneuve et al., 1996). These initial applications raised some questions as to the suitability of the model for diagnosing the water quality status of moderately urbanized river basins.

This chapter proposes an integrated watershed modeling approach to develop water management programs in urbanized river basins. This approach provides a means of delineating and incorporating urban areas as subwatershed units of a river basin, as well as a unique way of improving water management by initiating partnerships between users of water resources.

To determine their suitability, two operational simulation models (a hydrological model and a water quality model) were applied to the moderately urbanized 550-km² Saint Charles River basin. Because the main objective of this study was to use simulation models for diagnosing a past event, CEQUEAU (Morin et al., 1995) was calibrated against data available for a specific period and no further model validation was performed. Simulations with QUAL2E (Brown and Barnwell, 1987) were performed without calibration. The models were chosen because of their high robustness and user-friendliness. The proposed catchment modeling process makes the most effective use of the available data in the watershed.

6.1 The Study Area and the Environmental Issues

6.1.1. The Saint Charles River basin and the Quebec Urban Community

The Saint Charles River basin (figure 6.3) covers an area of 550 km². The northern part of the basin, which belongs to the Jacques Cartier Regional County Municipality (RCM), is mostly forest while the southern area (60% of the total basin surface area) lies within the QUC which has a medium to high degree of urbanization. The territory of the QUC amounts to 550 km² and encompasses thirteen municipalities (figure 6.3), eleven (312 km²) of which are included in the Saint Charles River basin. It is divided into two waste water drainage basins. The western basin serves 220,000 inhabitants and the eastern basin serves 250,000 inhabitants. Most of the sewer network is combined, with 80% of the population connected to a combined sewer network system. The waste water of the QUC is treated by two sewage treatment plants and the treated effluent is discharged into the Saint Lawrence River.

6.1.2. Environmental Issues

During the summer, combined sewer overflows (CSO) are the major cause of environmental problems affecting the Saint Charles watershed river bodies as well as the Saint Lawrence River (Lavallée *et al.* 1984; Lavallée *et al.*, 1988). This is particularly relevant for the Saint Charles River where water quality is directly affected by CSO. Recently, Hébert (1995) reported that the state of the Saint Charles river ranged from not polluted downstream of lake Saint Charles to

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Figure 6.3 The Saint Charles River basin and the Quebec Urban Community.

strongly polluted where the river meets the QUC, and that the Duberger and Lorette Rivers were also strongly affected by CSO. Only the water quality of the Jaune and Des Huron Rivers was satisfactory. The main water quality concerns in the QUC are (i) control of suspended solids, (ii) decrease of the settleable solids, (iii) decrease of particulate organic matter, (iv) decrease of bacteriological pollution, (v) control of floating material, oil and grease, and (vi) control of toxic chemicals. Solutions to these problems being considered are the control of combined sewer overflows by the construction of retention facilities (Côté, 1996) and the use of a real time control of CSO (Wilson *et al.*, 1988).

6.2 Strategy and Tools

Readily available data was used for the model simulations. The conceptually-based distributed hydrological model CEQUEAU simulated river flows and the physically-based water quality model QUAL2E was used to simulate fecal coliform concentration and biochemical oxygen demand (BOD). The choice of models was made after evaluating available models against the following

criteria: user-friendliness with an existing windows version; simplicity (i.e. number of parameters); adaptability to the Saint-Charles River basin; and availability.

The hydrological model CEQUEAU is a distributed conceptually-based reservoir model that has been used extensively on numerous watersheds in Canada, the United States, Europe and Africa. The Windows version of CEQUEAU is available on the internet (<http://www.inrs-eau.quebec.ca/cequeau>). In CEQUEAU, the watershed is discretized in “mesh squares” and “partial mesh squares”. CEQUEAU can estimate flows at gauging stations as well as at any point within the watershed. The model can simulate artificial reservoirs and can take into account the spatial and temporal variations in the physiographic characteristics of the watershed (for example, impermeable surfaces). The model consists of two main parts: the production function and the transfer function ; that describe water flow from rainfall to the watershed outlet. The production function deals with vertical water flow, taking into account rainfall, snowmelt, evapotranspiration, infiltration and water balance between surface and ground water. These processes are represented conceptually by three reservoirs: the soil reservoir (unsaturated zone), the groundwater reservoir (saturated zone) and the lakes and marshes reservoir. Water flow between reservoirs is simulated, on a daily basis, with mathematical relationships representing different mass transfers. A vertical balance is calculated for each mesh square. Therefore, a water volume within a mesh square is available for transfer to a river reach. Within CEQUEAU, this is done by the transfer function from one partial mesh square to another. The water volume available within a partial mesh square is a fraction of the water volume within an entire mesh square, depending on the percentage of overlap. This volume is added to other volumes entering a mesh square from one or more partial mesh squares directly upstream. The resulting volume becomes available for transfer to a mesh square directly downstream. This process is repeated from one partial mesh square to the next, down to the watershed outlet.

QUAL2E was developed by the US EPA (Brown and Barnwell, 1987). A windows version is available on the internet at http://www.epa.gov/docs/QUAL2E_WINDOWS/. This model describes the major interactions in the nutrient cycle, algae production, benthic and carbonaceous oxygen demand, and atmospheric reaeration, as well as their effect on the dissolved oxygen balance (Brown and Barnwell, 1987). The river’s physical domain is discretized into reaches according to the spatial increments of the finite difference formulation of the governing mass transport equations. For each computational element, a hydrologic balance in terms of flow, a heat balance in terms of temperature and a materials balance in terms of concentration are calculated. Advective and dispersive transport are considered in the materials balance. Mass can be gained or lost from the element by transport processes and external and/or internal sources and sinks. The model is applicable for steady flow and steady state conditions.

A wealth of data is available that describes the river system's hydrology and water quality (Figure 6.4 and Table 6.1). However, little of the hydrologic and water quality data were taken simultaneously, resulting in a shortage of data for model calibration.

Table 6.1 State of hydrological and water quality monitoring data of the Saint Charles basin in 1994.

River name	Monitoring station number and years of observation		
	Meteorology	Hydrology	Water Quality
Saint Charles	7016294	Quebec City	0509001 : 1967-1970
		airport	0509002 : 1973-1994
	7011309	Charlesbourg	0509003 : 1978-1994
	7012232	Quebec	05090016 : 1990, 92-93 05090017 : 1994
Lorette	same as above	050905: 73-76; 83-86 050910 : 1986-1989	05090014 : 1990, 92-93
Jaune	same as above	050906: 1983; 85-89	05090011 : 1990, 92-93
Duburger	same as above	050907: 1983-1989	05090015 : 1990, 92-93
Nelson	same as above	050908: 1983; 85-89	05090013 : 1990, 92-93
Des Hurons	same as above	050912 : 1994	05000012 : 1990, 92-93

For flow simulation, physiographic data (% forest, % water, % wetland in each mesh square, % surface of the partial mesh square, flow direction) and basin data (basin and the subbasin surface in km²) are required by CEQUEAU, as well as daily river flow and meteorological data. Physiographic data was estimated from 1:50000 topographic maps. The meteorological data were taken from the Environment Canada monitoring station located at the Quebec City Airport. The hydrological and water quality data come from the gauging station managed by the MEF.

Water quality concentrations required by QUAL2E come from the sampling station managed by the MEF. Hydrological data was obtained by CEQUEAU and hydrometric data, the physical characteristics of the river network required to use the trapezoidal channel option of QUAL2E, (Manning coefficient, bottom width) was supplied by the MEF (Boucher and Hubert, 1990) as well.

6.4 Results

6.4.1 Hydrological Modeling using CEQUEAU

The hydrology of the area is complex with both natural and artificial factors influencing the river flows (Figure 6.5), and a thorough understanding of the area hydrology is necessary for an accurate simulation with CEQUEAU. The natural input factors affecting the river's flow are precipitation, snow melt, Lake Saint-Charles, and the water table. The artificial input factors are Lake Saint-Charles during low water conditions and the CSO during wet, and to some extent dry, conditions. Evapotranspiration is the natural output factor. The major output

Figure 6.5 Natural and artificial factors influencing the Saint Charles river flows.

factors affecting the flows are artificial, consisting of water withdrawal for agriculture and drinking water purposes ($2.3 \text{ m}^3/\text{s}$ in the Saint Charles River). Figure 6.6 shows how the Saint Charles River basin has been discretized for flow simulation with CEQUEAU.

Model calibration was performed using 12 years (1982-1994) of recorded riverflows (mostly from gauging station 05904). For the same time period, data is missing for the other sampling stations (05905, 05906, 05907 and 05908). The calibration process was at first done by trial and error and then through the use of an optimization program on both a monthly and daily basis (Levite, 1995; Vescovi and Villeneuve, 1996b).

As shown in Figure 6.7 and Table 6.2, CEQUEAU did a good job of simulating the upstream hydrology of the watershed at station 050904. Nevertheless, due to a strong human influence on water management, the complexity of the flow processes in an urban environment, and lack of data, the results for the downstream simulation with CEQUEAU were poor. The same reasons can explain the limited accuracy of the results on a daily basis. Meanwhile, for the monitoring stations 05905 and 05906 (Table 6.2) daily simulations were better

Figure 6.6 Discretization of the watershed. (The arrows show the flow direction, “Ex” represents the location of the withdrawal for drinking water, “F”s and “R”s show the location of virtual and real sampling stations, and “M” is the meteorological station).

Table 6.2 Hydrological modeling results. Nash coefficient at the hydrological sampling station covering the Saint-Charles River basin.

	Nash coefficient stn. 050904 1982-1994	Nash coefficient stn. 050905 1982-1994	Nash coefficient stn. 050906 1982-1994	Nash coefficient stn. 050907 1982-1994	Nash coefficient stn. 050908 1982-1994
Interannual monthly mean flow	0.9875	0.2825	0.2273	0.8727	0.7283
Monthly mean flow	0.8897	0.2913	0.7023	0.8169	0.7472
Daily flow	0.8047	0.3987	0.7345	0.7374	0.5837

Figure 6.7 Monthly mean flow at station 050904

(for these station values of the Nash coefficient (Nash and Sutcliffe, 1970) were 0.3987 and 0.7345 respectively) than the monthly simulations (Nash coefficient values of 0.2825 and 0.2273 respectively).

6.4.2. Water Quality Modeling with QUAL2E

Water quality modeling of the Saint Charles River is closely related to the characterization of the CSO which affects its quality. The main issue is how to use QUAL2E, a steady-state model, to assess the impact of the CSO on the receiving water. Similar concerns have been pointed out in a recent study on the Charles River in Boston (Walton and Webb, 1994). The first simulations were run on the bacteriology. The objective was to understand the global effect on bacteriology and, if possible, on other water quality indicators. As a second variable, BOD, was also considered.

The discretization (Figure 6.8) for QUAL2E was done with regard to the location of the water quality sampling stations. Because of the lack of data, many simplifications of the Saint Charles River network were necessary. Only the Saint Charles River was discretized. Four reaches were identified and the main tributaries were considered as effluents. Simulations were done using the trapezoidal channel option. The water quality input data (BOD and coliform concentrations- C_1 to C_5) were those measured at the water quality sampling stations. The hydrological data required by QUAL2E (Q_1 to Q_4 and q_1 to q_4) were obtained from CEQUEAU's simulations.

Figure 6.8 Saint-Charles River discretization for QUAL2E (Brown and Barnwell, 1987).

The hydraulic data for each reach was established after calculating mean values of different Manning coefficients included in the reach (Boucher and Hubert, 1990). The river's bottom width was estimated by calculating the mean of the cross-section included in the reach. Because no data is available in the region to estimate the bacteriological decay rate, the median value within the range of parameters proposed in the QUAL2E manual was chosen. The simulation was run for 4 events in 1990, 4 events in 1992, and 4 events in 1993, all with the same set of model parameters. Figure 6.9 and 6.10 show the results obtained on 21st July 1993 for flow calculation and water quality (fecal coliforms and BOD) simulation, respectively. Figure 6.9 shows the large influence of drinking water withdrawal on the flow of the Saint-Charles River.

Estimation of predictive uncertainty associated with QUAL2E's input data (*i.e.* set of degradation parameters, fecal coliforms and BOD concentrations from point sources, and simulated river flows) involved 3000 Monte-Carlo simulations. A normal distribution, centred on the median value of the proposed range

Figure 6.9 Flow simulation with QUAL2E for the Saint-Charles River on June 21, 1993.

Figure 6.10 Bacteria and BOD simulations with QUAL2E on June 21, 1993.

of parameter values and the corresponding standard deviation, was used to generate random values of degradation parameters. Simulated river flows and concentrations of fecal coliforms and BOD from point sources were arbitrarily varied as well (plus or minus 20% variations). Simulation results (+ - standard deviation) were compared with the observed data. Figures 6.11 and 6.12 present the results for fecal coliforms at water quality stations 05090003 and 05090002, respectively.

The results from QUAL2E show the bacteriological contamination degradation caused in the Saint-Charles rivers by its tributaries especially the Lorette and Duberger Rivers. These results do not consider the bacteriological contamination caused by CSO's or sewer leaks at reaches 4, 3 and 2. Once contaminated,

Figure 6.11 Results of the Monte-Carlo sensitivity analysis (3000 simulations) for Fecal coliforms at 05090003 (upstream). Observed data (+/- 30%) available at 12 dates are compared with the base mean, the simulated mean, min, max and standard deviation.

the assimilative capacity (i.e. the natural bacteriological decay rate) in the Saint Charles River is not great enough for water quality to comply with the standard of 200 col./100ml. As can be seen in Figures 6.10 and 6.11, qualitative comparison with observed data shows that the upstream fecal coliforms simulations are a good representation of what is observed most of the time. The exception is 21st June 1993, which is also the date presented in Figure 6.10. Downstream simulation results are not in good agreement with observed data (Figures 6.10 and 6.12).

Figure 6.12 Results of the Monte-Carlo sensitivity analysis (3000 simulations) for Fecal coliforms at 05090002 (downstream). Observed data (+/- 30%) available at 12 dates are compared with the base mean, the simulated mean, min, max and standard deviation.

6.5 Discussion and Conclusion

Reasonably good hydrological results, with CEQUEAU, were obtained in the rural portion of the river basin (43% of the basin's surface area). However, in the urbanized subwatersheds of the river basin, the simulated river flows did not reproduce well the observed flows. Similarly, water quality results obtained by QUAL2E respected the order of magnitude of those observed in the rural portion of the river basin. However, in the urbanized portion of the Saint Charles River, the results differed by several orders of magnitude from the observed data. Although they were not relatively quantified, human impact, lack of observed data, and complex hydrological pathways probably accounted for the discrepancies.

The technology being developed for implementing an integrated water management plan in the QUC is being done to solve operational problems (e.g. integrated real time approach) and address concerns at the decision-making level (integrated urban planning, Saint Charles watershed management and modeling).

The diagnostic tools used for this study simplified, to a large extent, the complexity of the Saint Charles River Basin. Because of this, no claims can be made that the modeling work identified, without a reasonable doubt, the phenomena responsible for surface water degradation. However, the proposed method of estimating predictive uncertainty has developed a sound quantitative framework for conducting and elaborating integrated watershed management programs in urbanized river basins.

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