The evolution from watershed hydrological science to integrated watershed management

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Abstract Contemporary hydrology, as it is currently practiced, is essentially based on mathematical modelling. Over the past 40 years, with the emergence of information technology, increasingly complex hydrological models have been developed. More recently, water quality models have been integrated into those models. Prior to this, some elementary tools for analysis and decision making at the watershed level had been available. More recently, with the development of geographic information systems and the availability of satellite data, the heterogeneity of watersheds can be accounted for. Models integrating these new tools are well adapted to evaluate development scenarios in the context of integrated watershed management. The GIBSI model, used in Quebec, demonstrates the efficiency of integrated management concepts and illustrates the importance of implementing this management philosophy.

Keywords hydrology evolution; integrated watershed management; GIBSI; hydrological models; water quality

INTRODUCTION

Modern hydrology rapidly advanced with the arrival of scientific calculators, followed by personal computers which spurred the development and application of increasingly complex mathematical models that are able to represent hydrological processes at a watershed scale. From the moment when complex models were able to aggregate the links between different processes (physical, chemical, biological) at a relatively fine scale across the watershed, integrated watershed management became possible. These models, once adjusted to best represent the behaviour dynamic of the watershed, allow one to verify the effects of a modification to the watershed and to predict the repercussions in space and time. When coupled with a water quality model, water health and its fate in terms of quantity and quality can be evaluated.

As a result, in the 1980s and early 1990s, new versions of models and new models geared specifically to integrated watershed management were developed. Water became the indicator of natural and anthropogenic effects in a watershed. As a result, the framework offered by integrated management and the mathematical tools we now possess became integral to water resources management and the evaluation of anthropogenic effects at a watershed scale.
In the following section, we will provide a brief summary of the evolution of hydrology across the ages up to the modelling of hydrological processes at a watershed scale. This will be followed by the historical evolution of models that can simulate water quality. We will provide several examples of hydrological and water quality models that demonstrate the evolution towards useable integrated watershed management tools. We will only describe deterministic models because they consider physical processes and therefore relationships between watershed characteristics and flow (quantity and quality) can also be determined. We will then provide several examples of models specifically developed to facilitate the application of integrated management. Finally, after highlighting the inherent principles of integrated management, we will provide several examples of its application to the Chaudière River watershed in Quebec.

THE EVOLUTION OF HYDROLOGY

Reflections about the Earth’s water cycle, according to Eagleson (1970), date back to the 6th century B.C. Eagleson notes that these reflections were made by philosophers, first Thales, followed two centuries later by Aristotle (circa. 330 B.C.). It is the Roman philosophers who began to understand the water cycle and its relationship to the world’s oceans, in the first centuries B.C./A.D., that initiated our understanding of hydrology. Lucretius (circa 100 B.C.) proposed the existence of a relationship between evaporation, condensation and the formation of rain, yet without linking river flows however. Vitruve (circa 100 B.C.) set out what appears to be a preliminary understanding of the water cycle. He understood that mountains receive rain and snow, and that this water circulated through the rocks to the foot of the mountain giving birth to rivers. As of that moment, the base concepts of hydrological cycles were formed. Little new knowledge on the topic was added before the Middle Ages. Da Vinci, in the 15th century, was really the first to provide a good description of the water cycle (Eagleson, 1970).

In the 16th century, Bernard Palissy further refined the description. Nonetheless, it was only accepted 250 years later during the 19th century. Quantitative experiments to test these new ideas were initiated by French and English physicists during the 17th and 18th century commencing with rainfall, flow, evaporation and capillarity measurements. Among the most notable physicists were Perrault, Mariotte and Halley. In particular, Perrault was the first to determine the water balance for a watershed, that of the Seine in France (Perrault, 1674). Perrault is attributed as the father of quantitative hydrology. The first publications in the domain of hydrology were published during the mid-1800’s. These first publications described the experiments undertaken by researchers such as Francis, Herschel and Manning.

Before the 18th century, descriptive hydrology seemed to satisfy society’s needs. During the 18th century, and even more so during the 19th century, population growth and industrial development lead to a much greater use of water resources. As water needs grew along with its use for a multitude of purposes, quantitative hydrology became necessary. As highlighted by Réménéiras (1965) in his book Hydrologie de l’ingénieur, “the construction of hydro-electric plants, water distribution systems, flood protection works, drainage and irrigation systems in addition to a network of navigation canals, necessitates advanced hydrological study.” Advanced hydrological measures to address the inventory of surface water and groundwater resources is a necessary part of development planning. Since the middle of the 18th century, pushed by need for the resource, hydrological research progressed considerably. It is during the 19th century that the first attempts at hydrological modelling occurred. Simple models that associated river flow to precipitation were put forward by Mulvaney in 1851 and by Imbeault in 1892. In the United States, the golden age of hydrology is considered to have begun in 1930 with a second wave in 1960 following the application of acquired hydrological knowledge to solve water resources problems (Eagleson,
In addition, Wisler and Brater (1967) also recognized that the first golden age corresponded to the dawn of hydrological sciences and that this was marked by two important milestones. The first milestone, in 1932, was the development of the unit-hydrograph concept, which is credited to Sherman (1932). The second, in 1933, was the development of the theory of infiltration; one of the numerous contributions by Horton (1933). Wisler and Brater (1967) also suggest that the period since 1930 could be considered the dawn of hydrological sciences.

**NUMERICAL SIMULATION MODELS**

**Hydrological Models**

It wasn’t until the 1960s that the equations describing water flow within a watershed were grouped together to form a mathematical model. In fact, it is only with the arrival of computers that the first hydrological models capable of simulating a group of hydrological processes were developed (Stanford Watershed Model: Crawford and Lindsey, 1966). Since then, an impressive number of models with varying degrees of complexity have been developed. Here, we will only name a few of them. The first models were essential global models representing watersheds as a whole (Dawdey and O’Donnell, 1965; Mandeville et al., 1970; SRM: Martinec, 1975; SSAR: Corps of Engineers, 1956, 1987). Several additional global and semi-distributed models (e.g., HBV: Bergström and Forsman, 1973) were developed thereafter, coming into competition with different distributed models, better adapted to include the spatial variability of hydrological processes and land use at the watershed scale (Girard: Girard et al., 1971; CEQUEAU: Morin et al., 1975, 1981; MC: Girard et al., 1981; Deschènes et al., 1985a,b). Physics-based models also began to appear such as the European Hydrological System SHE (Abbott et al., 1986a, b). These were often difficult to apply due to the large quantity of detailed information required to run the model. We also note the development of other models, such as TOPMODEL (Beven and Kirkby, 1979), requiring less data but developed for specific purposes using non-forested watersheds in humid and temperate regions (Beven et al., 1984). None of these models were developed with the goal to incorporate geographical information systems (GIS), although it may be possible (Fortin et al., 1979, 1983; Abbott et al., 1986 a,b). In addition, standard data sets are generally not adequate to provide all of the necessary information to simulate variable hydrological processes both in time and space concurrently.

Once teledetection and GIS data became more prevalent and accessible, it became imperative to develop a new generation of models or determine a way to adopt the existing models such that they could process this new type of information. Thus distributed models were born, better adapted to the spatial distribution of this new type of data (Peck et al., 1981; Rango, 1985). Then, hydrological models with a spatial structure based on Digital Elevations Models (DEM) were developed (Moore et al., 1988; Palacios-Vélez et Cuevas-Renaud, 1992; Vieux et Gaur, 1994) and models such as SHE and TOPMODEL were adapted for this new type of data (Quinn et al., 1991; Robson et al., 1993). At the same time, new models compatible with teledection and GIS data began to emerge (Fortin et al., 1985, 1990; Leavesley et Stannard, 1990; Schultz, 1990; Wigmosta et al., 1994; Tarboton et al., 1995; Julien et al., 1995; Desconnetts et al., 1996; Dupont et al., 1996; Olivera & Maidment, 1999). Finally, by evolving from a global model structure to a distributed model to simulate hydrological processes within a watershed, the hydrological models that, in the beginning, were used by employing large calculations, were adapted to micro-computers (i.e., personal computers). The model interfaces initially developed to be used by experts also evolved to become more user-friendly and intuitive.
Quality models

Concurrent to the development of the hydrological models, was the development of water quality models. The first of these models was likely Streeter-Phelps, developed in 1925. This model simulates the spatial and temporal evolution of dissolved oxygen concentrations as a function of point releases of organic matter in a River. The original model (Streeter and Phelps, 1925) can be resolved analytically for a permanent regimen with constant releases and simple watercourse geometries. The arrival of computers in the 1960’s rendered the creation of more complex versions of the Streeter-Phelps model possible. The river could hereafter be split into discrete homogeneous sections and the differential equations, also discrete, could be resolved numerically. While dissolved oxygen was the base of the modelling (Chapra, 1997), the numerical resolution of the models allowed more complex geometric systems to be considered, integrating non linear kinetics to analyse the non permanent regimen. The two most important individuals associated with this period were O’Connor (O’Connor and Dobbins, 1958) and Thomann (1963). During this same period, O’Connor (1962) also integrated bacteriological models to water quality models. Biodimensional models were also being developed at this time.

Around 1970, public interest in water quality transferred from dissolved oxygen to eutrophication of rivers. As a result the relationship between nutrients (nitrogen and phosphorus), primary producers (phytoplankton and/or algae), and dissolved oxygen were introduced into water quality models (Chen, 1970; Chen and Orlob, 1975; Di Toro et al., 1971; Canale et al., 1974, 1976).

Until the 1980’s, modelling efforts focused on simulating water quality in lakes and rivers (Thomann, 1998). The evaluation of contamination sources was conducted outside of the models: only point sources, not non-point sources, could be integrated, because the link between land use and water quality were not represented in the models. These models were used primarily to evaluate the impact of point source releases (municipal and industrial) on water quality in rivers, while non-point sources were considered as background contamination.

During the 1970’s and 1980’s, following considerable investment in water treatment facilities, the majority of urban effluent in the United States and in several European countries received secondary treatment. The principle point sources were now treated in industrialized countries, thus attention turned to non-point sources of contamination because the relative contribution of non-point pollution compared to point-sources had now increased. According to Thomann (1998), as of 1980 until about 1995, models became increasingly complex due to: (a) an increase in the number of attribute variables; (b) the integration of hydrodynamic models in several dimensions; (c) the integration of sedimentological processes; and (d) a linkage between watershed models whereby non-point sources could be related to inflow. It was during this period that models simulating water quality in lakes or watercourses with point source pollution evolved towards models that integrated hydrological process at the watershed level (e.g., SWAT: Arnold et al., 1995).

Concurrently, a representation of the relationships between the food chain in the water column, sediments and benthic fauna were integrated into certain models. These advances were motivated in particular by the emergence of concern with toxic contaminants and a new understanding of the predominant role of suspended solids in the transport and fate of these contaminants (Chapra, 1997). Indeed, certain potentially toxic contaminants (e.g., metals, pesticides) fix to sediments and suspended matter in the aquatic environment. The deposition and the re-suspension of sediments represent important mechanisms that control the transport and fate of toxic contaminants in freshwater. Similarly the ingestion of small organic particles, such as phytoplankton, by a higher trophic level organism, is an important transmission vector and point of contaminant
concentration.

In addition, in some sectors, the importance of atmospheric inputs of chemical products (organic elements, metals, and nitrates) and the impact of these inputs on water quality were becoming better understood. According to Thomann (1998), new models should integrate air quality modelling and water quality modelling to consider both the atmospheric deposition of these contaminants, not only directly on the water’s surface but also throughout the watershed (both land and water).

That said, one must recognize that, in the context of integrated management of water resources at the watershed scale, models simulating water quality are used to compare the impact of various intervention scenarios on water quality. Thus, these models do not need the ability to provide a detailed and precise representation of the concentration of specific elements in the watercourses, but rather provide a general estimation of the component concentrations that are good water quality indicators (e.g., dissolved oxygen, BOD, suspended solids, nitrogen compounds, phosphorus, certain representative metals, etc.). The representation of specific processes, such as those related to transfers in the food chain for example, are not necessary in most cases for integrated management models.

**Commentary on parameter estimation**

The models, regardless of type, still present certain problems associated with calibration. The models are strongly non-linear and often the parameters are correlated to each other. To achieve a satisfactory calibration, one must have a comprehensive understanding of the model and of the processes being modelled. Each calibration constitutes a particular case linked to the watershed being modelled. To achieve a good calibration, one can limit the number of parameters using one of two methods. To begin, those linked to physical laws can be determined *a priori* based on field observations. Then, a sensitivity analysis can be conducted to determine which parameters least influence the results and those parameters can be set *a priori*. With a good understanding of the model, one can calibrate using trial and error. An automatic calibration can also be done by optimization from an objective function. The result depends on the type of the function used and the quality of the data (Sorooshian et Gupta, 1995). It is not a simple nor direct process.

Calibration becomes more and more difficult as the complexity of the model increases, involving a greater number of parameters and more data. Calibration, a major difficulty of modelling, must be completed by individuals with a comprehensive understanding of the model used. This difficulty remains despite the numerous automatic algorithms that have been developed in recent years to calibrate watershed models. In general, automatic methods are used in conjunction with manual calibration that draws upon the judgement and experience of the modeller.

**SOME EXAMPLES OF HYDROLOGICAL MODELS**

In this section, we have distinguished between three classes of models and for each class, representative models are described. The classification used in based primarily on the spatial representation of the processes and their link in space. Time was not a factor because all of the examples use a daily or shorter time step which is amply suitable for the purposes of integrated management. The first class represents global models; models that consider the watershed as a whole and that transform rain within the watershed to flow at the outlet of this same watershed while considering the global nature of hydrological process. The second class of models consists of semi-distributed models that subdivide the watershed into several sub-watersheds. Each sub-
watershed is treated as a global model. The final results consist of the hydrological budget between the sub-watersheds. The third class consists of distributed models that divide the watershed into smaller units. Distributed models seek to represent, at the small scale of these units, the full set of hydrological processes within each unit in order to establish the physical link between the processes.

In the next section, we have provided examples for each of these model classes. We have briefly described the models without detailing the equations and supporting mathematics for each as they have all been very well documented in existing literature (e.g., Singh and Fervert, 2002a,b; Singh, 1995). In our opinion, the models exemplified best demonstrate the evolution of hydrological modelling based on the models we know.

A. Global models

Global models use mathematical relationships to describe physical processes but do not consider the spatial distribution of these relationships on a watershed scale. They also do not consider the variability of parameters that govern physical processes at the watershed scale. This type of model was used principally from 1950 to 1970. Several examples are provided.

The rational method. This is one of the first models, if not the first model, to relate surface runoff to rain intensity and to the area of the watershed. The rational method is defined as:

\[ Q_p = c i A \]  

where \( Q_p \) represents the maximum runoff at the outflow of the watershed; \( c \), the runoff coefficient; \( i \), rain intensity (mm/h) for a rain event whereby the length of the event was equal to the concentration time of the watershed; and \( A \), the area of the watershed.

This method simulates the outflow of a watershed by assuming that precipitation is uniformly distributed across the watershed and that all sub-basins contribute equally to the flow at the outlet. This formula is widely used, particularly in small watersheds and for the development of storm sewers in urban settings. This relationship has been used to evaluate flood flows, notably by Fuller (1914), Horton (1914) and Foresaith (1949).

It was quickly realized that the rational method could not produce accurate results for large (or varied) watersheds, because in those cases, one must consider the variability of precipitation across the area, the drainage network, infiltration and storage capacity, to obtain a good estimation of flow.

Unit-hydrograph. Sherman, in 1932, put forth the unit-hydrograph (unit-graph) method. This method is based on the hydrograph that results from runoff generated by a uniform rainfall of one inch (or unit height) over the entire watershed for a given period. Using watershed-scale observations constituted, while still broad, a better overall representation of the hydrological process that occurs at the watershed level.

Stanford Watershed Model. The objective sought during the development of this model was to establish a continuous link between the various components of the water cycle (Crawford and Linsley, 1966). This was rendered possible by using numerical calculators. The model considers precipitation, evapotranspiration, runoff and soil humidity. The model simulates the behaviour of the watershed at a daily or hourly time step. The principal advantage of this model is that is can calculate runoff and evapotranspiration continuously from meteorological data. It was the first
model that could do that. The processes simulated by the model (using the daily time step) are interception, infiltration, surface runoff, groundwater flow, evapotranspiration, river flow, flood control and snow melt. Within the watershed, the river is subdivided into reaches. Each reach corresponds to the surface area of the watershed that contributes to the river’s flow at the point of segmentation. Each segmentation point is located at an overflow response time, calculated based on flow that does not vary over time (Figure 1). It is often considered, and rightly so, to be the first deterministic model that integrated all of the hydrological processes.

**Figure 1** Flow diagram of the Stanford Watershed Model (adapted from Crawford and Linsley, 1966).

**SSARR.** According to Speers (1995), the SSARR model was initially developed by the U.S. Corp of Army Engineers to provide mathematic hydrological simulations required for the planning, design, and operation of water control works on the Columbia River. In 1987, a user manual was produced that described the theoretical aspects of the model in addition on how to use the software. It is a global model made up of two modules. The first module simulates water circulation in the watershed (Figure 2), and the second, simulates river flow using a reservoir model (Figure 3). In the first module, snow melt, interception, ground infiltration and the flow transfer between different components of the river system are simulated (Figure 2). SSARR has been used for several years to simulate a variety of hydrological regimens. It has also been used to make long term predictions. These predictions, based on historical meteorological data, are used to conduct statistical analyses of discharge rates. .
Figure 2 Diagram of the production and circulation of water towards the river in the SSARR model (adapted from Speers, 1995)

**GR Models.** The Génie Rural models were developed by the Cemagref in the early 1980s. These conceptual and empirical models deserve mention because they emanate from a desire for a more simple approach. From the CREC model (Cormary and Guilbot, 1973), a simple two reservoir model with one parameter was developed. When it was applied to the Orgeval bassin, two GR2 parameters were used. The model was modified in 1991 (Edijatno, 1991), by improving the production function and adding a third parameter (GR3). Tests were conducted on 110 French watersheds. The results were judged to be comparable to more complex models. A fourth parameter was added by Nascimento (1991) to include groundwater exchanges. The GR4 model was applied to 120 watersheds and provided better results than the GR3 model. Ma (1991) added a third reservoir to improved low water level simulations and to allow the model to be coupled to a produce and nitrate transfer model (GR5).

**SRM.** The SRM model was developed by Martinec (1975) for small European watersheds (Martinec and Rango, 1986). It is one of the first hydrological models that simulates snowmelt. It was developed to determine the flows (daily) at the outlet of small mountainous watersheds in which snowmelt is the principal component. The SRM model is a degree-day model that requires data entry of snow cover obtained by teledetection (NOAA images). Thanks to the improvements to snow cover teledetection, SRM has been applied over the years to larger and larger watersheds. The model parameters are estimated from temperature, precipitation and snow
Figure 3 An illustration of river flow in the SSARR model (adapted from Speers, 1995).

Cover observations. These parameters can be calculated from measurements or estimated using expert judgement by considering certain watershed characteristics (forest area, soil conditions, previous precipitations and flow. SRM is composed of empirical and theoretical relationships. One of the big advantages of this model is that it uses minimum terrestrial information, which is very useful in the developing world. Instead of using data from meteorological station, SRM uses satellite data and data from geo-referenced areas. It is the first hydrological model to depend so directly on data from teletection. The model was successful during several World Meteorological Organization (WMO) tests of overflow simulations and flow prediction in real time. This model could be considered a deterministic model in which the parameters can be evaluated directly (i.e., evaluated on the basis of their physical significance).

TOPMODEL. TOPMODEL is a global deterministic model where the modelling is intended to be more representative of the processes (Beven and Kirkby, 1979; Beven et al., 1984). It is a conceptual model that considers the effect of a watershed’s topography on its hydrological exchanges. It is based on simple approximations of hydrological concepts. This model predicts, for each time step, the spatial distribution of the water content in each array of the numeric terrain model of the watershed being considered. The water content is calculated as a function of the distribution of a hydrological similarity indicator and from the deficit of mean water level for the watershed. TOPMODEL calculates the flow exiting the watershed and the spatial distribution of water on the ground from temporal precipitation and evaporation series and topographic data. The structure of the model, which is relatively simple, can be easily adapted to particular watershed behaviours (Figure 4). The model contains minimal parameters, established with the objective of being physically interpretable. The value of these parameters is determined based on the flows at the outlet. This model is an attempt to establish a tool with a global approach, few parameters and able to fit a semi-distributed model.
B. Semi-distributed models

In semi-distributed models, the watershed is subdivided into sub-basins where processes are simulated globally and where the physical characteristics of the sub-basin are globalized or weighted. Generally, there is no direct link between the processes of one sub-basin to another except those that allow the hydrological balance to be respected right to the outflow. The examples that follow can be classified as semi-distributed models.

HBV. This conceptual model is a second generation model characterized by an attempt to represent all of the hydrological processes using the simplest and most robust model structure possible. It subdivides the watershed into sub-basins in which the elevation and land use are determined. This subdivision into sub-basins is used for climatological and geographically heterogeneous watersheds or where a large lake is present in the watershed (Figure 5).

Developed in 1972 (Bergström and Forsman, 1973), an algorithm was added in 1975 to take the snow and snowmelt processes into account. It became the standard flow simulation in Nordic countries and was also tested by the WMO (WMO, 1986). It is a deterministic model that does not require a lot of data (it uses standard climate data). A minimal number of parameters need to be used for calibration. This model is made up of three principal components: snow accumulation and snow melt; soil humidity; and river flow calculations. Certain model parameters are obtained using calibration, while others describing the watershed characteristics remain fixed values during the calibration.

In 1985, it was used to evaluate the short-term variability of water acidity and, in 1990, to model the transport of non-point source pollution. The HBV model was also used in Norway and in Finland in 1991 to verify climate change effects on water resources. HBV is the base model for PULSE, a more appropriate model for hydro-chemical simulations (Bergström, 1995).

According to Irvine et al. (2005), HBV is one of the best performing semi-distributed models.
HEC-1. The first version of the HEC-1 model was published in October 1968. The model has been revised several times since then with a major revision in 1973. It is a rain-flow model that integrates infiltration losses. This hydrological model can be applied in small or large basins.

The hydrological basins modelled by HEC-1 can be relatively complex; for example include several sub-basins, various river reaches and reservoirs. This model is considered to be a global model where precipitation and infiltration are evaluated as uniform across the sub-basin. This inconvenience can be compensated by using numerous small basins in which parameters would be considered uniform. Figure 6 illustrates the basin components of the model.
C. Distributed models

**SHE.** The SHE model was developed during the 1970’s by a collaborative of three organizations: the Danish Hydraulic Institute, the Institut of Hydrology in the United Kingdom and SOGREAH in France.

To evaluate the impact of human activities in a particular territory, one must be able to represent them at a watershed scale. Only a distributed model that uses a physical base can take spatial variability among the characteristics of the watershed as well as the distribution of human activity into consideration. It is this principle that guided the model developers (Abbott et al., 1986b). They also wanted a flexible operating structure that would allow the use a little or a lot of data for the simulations. This model can incorporate topography, vegetation and soil property data.

The hydrological processes that are modelled individually are: snow melt, interception, evapotranspiration, drainage towards saturated and unsaturated zones, overflow and river flow. The model assumes that flow in unsaturated zones is vertical and horizontal in saturated zones. It also assumes that overflow reaches the river over the ground surface and from the saturated zone only. A pilot manages the interrelations between the various process models. The spatial distribution of the basin parameters, precipitation and hydrological behaviour is obtained by dividing the basin using an orthogonal grid. On each grid, a column of horizontal layers represents each of the processes being modelled (Figure 7).

In SHE, the hydrological processes are modelled using an analog finite difference scheme for the
mass balance, movement quantity and energy equations. The scheme is completed by several empirical equations (Abbott et al., 1986a). This approach necessitates knowledge of the initial conditions and the boundary conditions, which can be difficult to determine a priori. The quantity of information in space and time that is necessary is directly linked to the level of discretization, rendering application more difficult. Nevertheless, according to the developers, the flexibility of SHE allows even small amounts of information to be used.

The developers assert that because the model is physically based, it requires no calibration. This in our opinion is impossible in practice. The model’s capacity to account for the spatial variability of processes and the hydrological and physical characteristics makes this model useful for integrated watershed management.

![Diagram of the discretization of the SHE model (adapted from Abbott et al., 1986a).](image)

**Figure 7** Diagram of the discretization of the SHE model (adapted from Abbott et al., 1986a).

**CEQUEAU.** The CEQUEAU hydrological model (Morin, 2002; Morin et al., 1995), first developed in the mid-1970’s, is a deterministic model that takes into account the physical characteristics of a watershed as well as the variation within these characteristics in space and in time. This conceptual, water balance-type model uses distributed parameters. To do so, the basin is divided into squares (Figure 8). The spatial division allows the evolution, in time and space, of the represented processes to be tracked. It also allows the user to verify the impact of modifications in the watershed. This subdivision provides a high-level of flexibility to represent the heterogeneity of the hydrological and physical characteristics of the basin.
Figure 8 Watershed division in squares of the CEQUEAU model (From Morin, 2002).

Figure 9 Production function: Reservoir diagram of the CEQUEAU model (from Morin, 2002).
In the model, the hydrological processes are represented conceptually with the help of two functions: the production function that represents the vertical balance, and the transfer function, that transports the water across the watershed to the outflow. The production function is applied to every square and simulates the vertical water balance depicted by different reservoirs (Figure 9). The transfer function directs water from partial square to partial square towards the closest river component. To do this, each square is further subdivided into partial squares according to the drainage dividing lines within the square (Figure 10).

![Diagram of water circulation in the CEQUEAU model](image)

**Figure 10** Transfer Function: Diagram of water circulation in the CEQUEAU model (from Morin, 2002).

This model has been applied in varying geographical contexts including North and South America,
Europe and Africa. In Quebec, the model has been used in over 60 watersheds to determine maximum probable flood levels. It has also been used in Quebec by different organizations to conduct flow predictions in real time.

The model has been compared with other models in two separate studies (WMO, 1986, 1992). The concluding results attest to quality and precision of the model predictions. Its ability to consider modifications within the basin provides a hydrological model suited to integrated watershed management.

The WATFLOOD model (Kouwen, 2006). WATFLOOD consists of a group of programs that can predict flood flows and conduct long term hydrological simulations for a watershed with varying response times. It is a distributed model because it subdivides the watershed into rectangular elements, then regroups them into sub-units known a Grouped Response Unit (GRU) (Figure 11). The objective of this model is to optimize the use of remote sensed data. Radar data, land use data from LANDSAT or SPOT and land cover data can be directly introduced into this hydrological model.

Grouped response units are used to account for the basin heterogeneity

Figure 11 Grouped response units and flow diagram for the WATFLOOD (adapted from Donald, 1992).

The SPL9 model (a component of WATFLOOD) is a deterministic model that represents the hydrological budget of the watershed. It was developed for long term hydrological simulations by
using distributed precipitation data, obtained from radars and numerical temperature models. The processes represented are interception, infiltration, evaporation, snow accumulation, snowmelt, surface flow, recharge, base flow in addition to overflow and river flow (Kouwen et al., 1993; Kouwen, 2000).

The size of each GRU is determined based on LANDSAT or NOAA images. Each image pixel is georeferenced and classified into an appropriate hydrological response group, for example: dense forest, open forest, agriculture, bare ground, urban land, wetland or glacier. A group of pixels in a rectangle with the same spectral qualities indicating a particular type of land use are grouped together as a GRU. The pixels do not need to be contiguous. The number of pixels in each GRU is then used to determine the percentage of GRU surface area that is hydrologically pertinent to each sub-basin. The hydrological response for each land use class is calculated as if the class covered the entire area being modelled, but its response (flow) is weighted based on the percentage of the surface area covered by that class.

HYDROTEL. (Fortin and Royer, 2004; Fortin et al., 2001). Developed, from the beginning, to ensure compatibility with teledetection and GIS data, the objective of the HYDROTEL model is to simulate flows in each water course within a watershed as well as to simulate the spatial distribution of the various water cycle processes. The drainage structure of the watershed is evaluated by PHYSITEL, a GIS-based program specialized for use in hydrological models (Figure 12).

The model can be used to estimate impacts to hydrology resulting from modifications to the physical characteristics of the watershed (e.g., forest clearcuts, crop rotation, damming, etc.). It can predict river flows in real time using meteorological forecasts. It can also simulate the maximum probable flood using critical meteorological conditions for snow melt and/or precipitation.

![Figure 12](image-url) An illustration of the cells that make up a watershed derived from the cell identified as the basin outlet in the HYDROTEL model (Taken from Fortin and Royer, 2004).
PHYSITEL (Turcotte et al., 2001; Royer et al., 2006) prepares the data from a watershed for HYDROTEL, which then conducts the hydrological simulations. Thus, PHYSITEL works to determine and map the drainage structure of a watershed from a digital elevation model (DEM) and a digital hydrographic network (necessary to identify the lakes/reservoirs and meandering rivers). It also works to structure and map the land use data as well as the soil type data. HYDROTEL simulates and evaluates the following hydrological processes: interpolation of meteorological data, accumulation and melt of snow cover, potential and actual evapotranspiration, vertical water budget, surface and sub-surface runoff and river routing. It can display (mapping) and archive variables associated with the aforementioned processes. The model produces a hydrogram at various points within the drainage network.

After the cells that make up the watershed are determined, and thus the direction of flow from cell to cell, the watershed is divided into very small sub-basin in which the physical, hydrological and hydraulic characteristics are considered to be a relatively homogeneous hydrological unit (RHHU). The discretization into RHHU from small cells (normally 10 to 100 m per side) is more advantageous than discretization based on larger cells. Compared to the total area of the basin, the RHHU conserves the internal hydrological structure of the units. Each one of these units is linked to the drainage network, thus reconstituting the entire basin. The vertical water budget model (Figure 13) is applied to each RHHU. Water that is available for drainage is directed into the river reach associated with that RHHU based on a delay function calculated using a geomorphological hydrograph specific to that RHHU. It is then directed within the network according to two river routing simulations.

The HYDROTEL model contains technical characteristics that make it a highly flexible application. It can use simulation algorithms based on physical processes. Algorithms can also be selected based on available data. It is compatible with teledetection and GIS data (Landsat and NOAA images). From the outset, the model was designed so that it could be modified, relatively easily, by changing or adding modules.

![Figure 13](https://example.com/figure13.png)

**Figure 13** Division of the vertical water budget into three layers, part of the water budget model within HYDROTEL (Taken from Fortin and Royer, 2004).
This model can spatially and temporally simulate hydrological processes at a watershed-scale. It also allows the modeller to increase the dimension of the sub-basins (RHHU) to group them based on different levels of homogeneity. Inversely, if one wants to account for a high level heterogeneity within the physical and hydrological characteristics of the basin, the modeller can reduce the size of the RHHU. It is a particularly useful model for integrated watershed management.

This model has been applied in various geographical contexts. Applications of the model have been made in North and South America, Europe and Africa. In Quebec, it has been used by various organizations to prediction flow in real time.

D. Conclusion

These examples of deterministic models, selected from many, are a good illustration of the evolution of hydrological modelling at a watershed-scale over the last 50 years. Two factors explain the overall evolution of these models. The first is linked to the development of computers, to their computational capacity and their availability. The second is associated to the availability of teledetection data which facilitates the acquisition of field data (elevation, land use, etc.). Hydrological modelling, during the 1990s, achieved a level where it was sufficiently precise and distributed to simulate the impact of development and land use on the hydrology of a watershed. The maturity of hydrological models is an essential step towards a smart approach to integrated
management.

HYDROLOGICAL AND WATER QUALITY MODELS AT THE WATERSHED-SCALE

ANSWERS. This model was developed to evaluate the behaviour of watersheds within which agriculture is primary land use. Its main objective is to examine strategies that can be used to control non-point source pollution emanating from intensively cultivated areas (Beasley and Huggins, 1982). The principal characteristic of this model is the use of a distributed parameter concept in order to integrate the spatial variation of parameters such as topography, soil type and land use.

ANSWERS is a deterministic model based on the hypothesis that relationships exist between flow and the hydrological processes that govern it (rain, infiltration, topography and soil type.). In addition, flow can be used in relation to other processes to model other phenomenon such as soil erosion and chemical reactions within the watershed. During application, the watershed is divided into sufficiently small grid cells to be hydrologically homogeneous (Figure 15). The modelling characterizes water production and the evolution of pollutants within these small cells. Water circulation within the basin occurs through the transfer of production from one cell to another. The same transfer mechanism is also used for pollutants carried in the water. All of the hydrological processes are integrated into the model (precipitation, overflow, infiltration, river flow, etc.) For the water quality modelling portion, soil erosion and transport towards watercourses and sediment transport in rivers are modelled. This model, first conceived in 1966, was concretely established in a doctoral thesis published in 1977 and is one of the first distributed parameter hydrology-quality models (Beasley, 1977).

SHE/SHESED. SHE/SHESED is a deterministic spatially distributed model that models flow and sediment transport at the water/catchment scale (Bathurst et al., 1995). This model was developed in the Civil Engineering Department at the University of New Castle (U.K.). The main reason for its development was to evaluate the behaviour of the system in function of its land use. The principal processes that must be considered are water circulation, sediment transport and the propagation of contaminants.

The SHESED model is based on the following processes: soil erosion through raindrop impact, leaf drip (Figure 16), sheet overland flow (without rilling), the transport of the eroded material by overland flow, riverbed erosion and river flow. These processes are fed by flows provided by the SHE model (see the preceeding section). The transport of sediment by overland flow is represented by a two-dimensional total sediment load conservation equation. For river transport, the total load is represented by a one-dimensional mass conservation equation. This model can be used in integrated management, particular in agricultural areas where erosion is problematic.
HSPF. In the mid-1970s, the USEPA began to develop tools and procedures to quantify non-point source pollution (Donigian et al., 1995). Field-based investigations were carried out to test known mathematical models with data collection programs, in order to estimate non-point source pollution loads and evaluate alternative management options. The conclusion of these tests was that the known models were unable to estimate these values in large watersheds. Thus the USEPA
began an extensive program to develop more global models that integrated the effects of scale in hydraulics and water quality. Then to conduct simulations in watersheds with multiple land uses, numerous lakes and resources, complex networks, etc. The HSPF model was officially published in 1980 (Johanson et al., 1980). This model is made up of three models: ARM (Donigian and Davis, 1978), NPS (Donigian and Crawford, 1979) and HSP (Hydrocom, 1977). It simulates hydrological processes and water quality in both natural and/or developed areas. This analytical tool can be used to plan and evaluate projects and to operate water resources systems (Donigian et al., 1995). The model can predict flow, sediment loads and nutrient and pesticide concentrations. This model is widely used, particularly in North America. Since 1980, it has been further developed and improved continually.

**QUAL2E**

The first version of this model (QUAL-I) was developed by the Texas Water Development Board (1970). Following usage difficulties, improvements were made and a new version, QUAL2E, was established. Additional improvements have been made since that time.

The model can simulate up to 15 water quality variables (dissolved oxygen, BOD, organic nitrogen, fecal coliforms, temperature, ammonia, organic phosphorus, dissolved phosphorus, nitrate, nitrite, chlorophyll a, and three conservative constituents)(LePage, 2005).

The model assumes that the river water is well-mixed vertically and laterally. The transport, advection and diffusion mechanisms only occur on the principal current axis, that is the longitudinal axis of the canal. The model is limited to simulation periods where stream flow in river basins and waste load...
inputs are constant.

Figure 17 illustrates the various interaction possibilities between the major constituents or water quality variables (except temperature, fecal coliform, the conservative constituents and non conservation constituents) of the QUAL2E model.

QUAL2E treats each river as a group of reaches, each having uniform hydraulic characteristics. Each reach is divided into a series of computational elements or sub-reaches of equal length (Figure 18).

A mass balance is conducted for each sub-reach to follow the evolution of the constituents/variables in a permanent or quasi permanent river flow regime. This model has been widely used. One must have a good understanding of the model to use it correctly and to draw accurate conclusions.

This model lends itself to the study of effects of pollutant loading in a river (amplitude, quality and location) and the evolution of water quality in its tributaries. This possibility and its ease-of-use, despite some calibration difficulties, make this a good tool for integrated management.
MIKE 11 (Havno et al., 1995)

This one-dimensional model simulates flow, sediment transport and water quality in estuaries, irrigation systems and reservoirs. The first version became available in 1987. The model’s modular structure contains units to simulate hydrological and hydrodynamic processes, water quality and sediment transport. The hydrological model is a conceptual global rain-flow model that requires little data. The hydrodynamic model is based on the one-dimensional Saint-Venant equations (Figure 19). A module to evaluate flood zones is also available. The sediment transport module uses two models, that of Engelund and Hansen (1967) and of Ackers and White (1973). The water quality parameters modelled are as follows: BOD/dissolved oxygen, bacteria, phosphorus, heavy metals and eutrophication.

For the hydrological simulation, the discretization is done by dividing the surface area into sub-basins and calculating the hydrological budget for each. The outflows of each sub-basin are integrated as lateral inflows to the river hydrodynamic model. This water quality simulation model is another tool that can be used for integrated management.

SWAT

SWAT (Soil and Water Assessment Tool) is a model that simulates hydrology and water quality at a watershed scale (Neitsch et al., 2005). It was created in the early 1990s and has undergone numerous improvements since then. It is a deterministic model that can determine the impact of various changes (management practices, climate, vegetation, etc.) in a watershed. It is particularly well adapted to integrated watershed management studies.

![Figure 19 Grid for the hydrodynamic calculations in the MIKE 11 model (Taken from Havno et al., 1995).]

The model was not developed to analyse a specific rain event, but rather for continuous simulation and long-term impact studies. The conceptual representation in SWAT follow directly from the SWRRB model (Williams et al., 1985; Arnold et al., 1990), that was modified and adapted to conduct simulations on basins divided into hundreds of sub-basins (or hydrological response units, HRU). Each HRU is characterized by one land use, one soil type and one management type only. The algorithms of numerous other models were integrated into SWAT, such as CREAMS (Knisel,
1908) principally for nutrient transport, GLEAMS (Leonard et al., 1987) for pesticide tracing and EPIC (Williams et al., 1984a,b), for simulating crop growth. The EPIC model determines the impact of development in one land parcel on agricultural production, on soil and on water resources. The model can be applied to small basins (approx. 100 ha). Notably, it simulates the fate of pesticides, nitrification and erosion. The most recent EPIC model developments have facilitated research on the impact of climate change on plant growth (effects of modifying atmospheric CO₂ concentrations and climate change effects on water usage).

Overall, SWAT can model on a daily time step, a variety of hydrological processes (forest cover interception, infiltration, percolation, evapotranspiration, groundwater flow, surface flow, accumulation and melt of the snow cover, lake and reservoir budgets, canal flow and base flow), in addition to plant growth, erosion and also transport of sediments, the production and transport of nutrients and pesticides. The model is able to integrate various agricultural management practices (fertilization, irrigation, pasturing, manure spreading, tilling, agricultural drainage, etc.). The plant growth module of SWAT is particularly detailed and can integrate, for example, CO₂ variations in the air (for climate change studies), variations of dormancy periods relative to climate or differences based on if biomass was removed or left in place at the end of the growing season. SWAT includes various options that distinguish it from other water models, such as the simulation of accumulation and transport of pollutants on urban surfaces (SWMM algorithms) and modelling of wetlands and paddy fields. This model has been validated several times, most recently by Cao et al. (2006), who reproduced the hydrology in a highly heterogeneous mountainous region.

INTEGRATED MANAGEMENT

Water that makes the long trip through a watershed is the perfect indicator of the environmental health of that basin. In effect, water is a vector that accumulates and transports the negative impacts and positive improvements that it undergoes during its long journey towards the outflow of the basin. It qualitative and quantitative state at one point in a watercourse is the result of surrounding water uses and land uses.

Management of usage and land use at a watershed scale is the only approach that will guarantee the protection of water resources and ensure its future sustainability. At the same time, it promotes wise usage of land that best protects the environment.

Integrated management is not a new concept, but its application on a watershed-scale was practically impossible until recently. Due to their complexity, it wasn’t until recently that the relationships between: land use; hydrological, biological, chemical and physical processes; and the characteristics of the watershed could be modelled. Also, modelling is now conducted at a small enough scale that the impact of a development or land use change on the water resource can now be evaluated. Since the early 1990s, increasingly elaborate and precise computational tools that are also oriented towards integrated management, have been developed. Several examples are presented below.

Watershed integrated management is a philosophy, a way to evaluate, choose and decide how water and land will be used within a watershed. It aims to establish development, management and operational rules to ensure the wise use of the resource, favouring positive economic outcomes; all while reducing the negative impacts on the resource and on the environment.

Environmental and resource protection has become a social issue that, in many countries, is no longer negotiable. This is exemplified by the Loi sur la qualité de l’environnement in Quebec (Government of Québec, 1984), the Clean Water Act in the United States (United States Congress,
Integrated management has thus become a necessary part of good watershed management. To undertake integrated management, there are five principal steps that should be followed to ensure operational success:

(a) A social consensus in regards to the development options.

(b) Development scenarios.

(c) Knowledge of the area:
   (i) an inventory of the usage level and lands uses of the area;
   (ii) a sufficient knowledge of the physical and hydrological characteristics of the basin; and,
   (iii) a database containing information on the quality and quantity of water resources.

(d) Modelling tools:
   (i) computational tools to model the processes of concern; and
   (ii) human resources with a sufficient understanding to put in place and use the modelling tools intelligently.

(e) Political will to follow the resulting recommendations and apply the scenario retained during the integrated management process.

In order to undertake this approach, various stakeholders must be engaged. The first group is the watershed users, often represented by a watershed group or committee. Their role is to find and build social consensus with respect to resource and land use. Following that, they can help to elaborate various development scenarios.

The second group is often made up of governmental agencies, where one role is data acquisition (usage, land use, water resources, resource quality, basin characteristics, etc.).

The third group is made up of scientific and technical analysts. These individuals have a comprehensive understanding of the computational tools that will be used and of the models that will represent each process. They are tasked with simulating and evaluating the impacts of the scenarios proposed and to identify which scenarios should be retained. Hubert (1986) underlines that a decision-maker can longer simply weigh the pros and cons of a decision but rather it requires an analyst (working for the public authority) “to arbitrate a competition between different stakeholders.” The best solution must be found within the technological, institutional and regulatory frameworks in play.

The fourth group is the decision-makers, that is, those that will apply the selected scenario and who will also determine how it will be financed. They will also have the often difficult task of prioritizing each action within the plan.

An integrated management approach is now used in several countries (e.g., Brazil: Johnsson, 2004; United Kingdom: Quinn et al., 2004) and has been subject of numerous publications around the
world. After briefly describing a couple of models dedicated to integrated management, several examples using a model developed in Quebec (GIBSI) will be presented.

TOOLS FOR INTEGRATED MANAGEMENT

A. MIKE SHE

MIKE SHE is a modelling system that simulates flows, water quality and sediment transport at the watershed scale (Refsgaard and Storm, 1995). MIKE SHE developments are based the modelling concepts of SHE (presented above). This modelling system includes a series of pre- and post-processors that include, among others, the digitization, editing and graphic representations of the results. MIKE SHE is module-based, the principal module being MIKE SHE WM (representing Water Movement). The MIKE WM module is made up of sub-modules that each reproduce one hydrological process: precipitation (rain or snow), interception/evapotranspiration, surface runoff, channel flow, unsaturated and saturated zone flow, snowmelt and surface water/groundwater interactions. The user can create their own configuration by choosing the sub-modules based on the hydrological conditions of the modelled watershed and the study objectives. To study water quality, soil erosion or irrigation, the modules that can be added to MIKE SHE WM include: (1) advection and dispersion of solutes (AD); (2) geochemical processes (GC); (3) crop growth and nitrogen processes in the root zone (CN); (4) soil erosion (SE); (5) dual porosity (DP); and (6) irrigation (IR).

MIKE SHE can be used for various spatial scales, varying from simple soil profiles (for infiltration studies) to basin-scale regional analyses. MIKE SHE can be directly related to the MIKE 11 model (see preceding section) for river modelling (Li et al., 2007).

B. BASINS

The BASINS system (Better Assessment Science Integrating Point and Nonpoint Sources), developed by the USEPA, includes environmental databases, simulation models, evaluation tools and pre- and post-treatment tools, in addition to report generating capabilities (see Figure 20). The objective of the system was to integrate the components necessary to perform a watershed scale water quality and quantity analyses into a single software (Donigian and Imhoff, 2002). In BASINS, the physiographic data, the field data and all of the tools are integrated into a GIS platform.
Figure 20 Diagram of the interactions between the different cells of the BASINS system.

To begin, the HSPF model was the core simulation model in BASINS. More recent versions have allowed the user to select between several different models as follows: HSPF or SWAT for hydrological and water quality simulations at the basin-scale; QUAL2E, for water quality simulations in watercourses/rivers; or PLOAD, to estimate pollutant loading from non-point sources. The choice of model depends on the particular characteristics of the basin, and more importantly, to best meet the modelling objective.

PLOAD, a simplified model based on GIS, estimates pollutant loads from non-point sources on an annual basis, by using annual precipitation, land use and management practice data. Given its annual time scale, PLOAD should only be used during preliminary or exploratory studies.

For a watercourse where the primary water quality problems are linked to dissolved oxygen and where the principal sources of pollution are known (point-source), the QUAL2E model is the most appropriate with the condition that the model’s assumption of constant flow can be justified.

For basins in which non-point sources of pollution are significant or for a detailed hydrological model of a basin, the SWAT and HSPF models are most appropriate. The developers of BASINS recommend HSPF when hourly meteorological data is available and SWAT when only daily meteorological data is available or when flow measurements do not exist for the basin or another proximate basin (EPA, 2001). SWAT is particularly well adapted to long-term simulations and to predict the impacts of land use management changes (e.g., climate and vegetation changes, agricultural practices, reservoir management, groundwater extraction, water transfers) on the flows and sediment loads or chemical concentrations in the watercourses. With both SWAT and HSPF, the simulations can be conducted in one watershed or multiple watersheds or sub-basins, delimited by the user. BASINS has been used in numerous watershed-scale studies, notably Cruise et al.
(1999) to estimate the climate change impacts on water quality in the south-east United States.

C. GIBSI

The development of GIBSI (fr. Gestion Intégrée par Bassin versant à l’aide d’un Système Informatisé) began in 1995 and the first operational version was produced in 1998. The objective that guided the developers was a focus on allowing watershed users to evaluate \textit{a priori} the impacts on water resources from various land uses and usage levels. The ultimate goal is to provide objective information to decision-makers for the wise use and protection of water resources. The benefit of this approach is the protection and conservation of the environment.

The approach used to develop this tool consisted of grouping the simulation models available at INRS (Université de Québec, Canada) with models available in the public domain for the missing modules. An exhaustive study of the models available lead to the selection of the following: RUSLE for erosional processes (Renard, 1997); SWAT/EPIC for aspects of chemical transport (Arnold \textit{et al.}, 1995); QUAL2E for water quality in river (Brown et Barnwell, 1987); and HYDROTEL for the hydrological modelling (Fortin \textit{et al.}, 1995).

![GIBSI Model Operating Structure](image)

**Figure 21** GIBSI Model Operating Structure.

To make the link and integrate these different models, a graphic interface was developed and GRASSLAND GIS was used (L.A.S., 1996). The GIBSI operating structure is illustrated in Figure 21. A complete description of GIBSI can be found in Villeneuve \textit{et al.} (1998, 2003). Numerous improvements have been made and continue to be made to this model (Quilbé and Rousseau, 2007).

**APPLICATION OF GIBSI TO THE CHAUDIÈRE RIVER WATERSHED (QUÉBEC)**
Since the developmental beginnings of GIBSI, the Chaudière River watershed has been used as the test basin. The Chaudière River is a tributary of the Saint-Lawrence river and is situated south of Quebec city (Figure 22). The watershed area is 6 680 km². The area is primarily forested (64%) and also used for agriculture (33%).

To illustrate the utility of integrated management tools, we have presented four examples where GIBSI was applied, below.

**Verifying the impact of a government policy (Mailhot et al., 2002)**

In 1978, the Government of Quebec developed and enacted a broad-based program to treat point-sources of wastewater in order to restore surface water quality throughout the province. The
program led to the placement of 38 wastewater treatment plants in the Chaudière river. By 1994, all of the plants were operational. The authors wanted to verify the effect of this policy on the water quality of the Chaudière river using GIBSI.

To do so, GIBSI was calibrated using the 1997 existing conditions (quantity and quality) (Turcotte et al., 1999). The calibrated model thus became the reference state simulating the behaviour of the basin after the placement of the treatment plants. Two scenarios were tested. The first consisted of simulating flows and water quality in 1987 with all of the treatment plants in place, excluding non-point agricultural inputs. A second scenario consisted of simulating the situation if the treatment plants were not installed and all other watershed characteristics remained the same. The year 1987 was selected for these simulations because it represented mean hydrological conditions. Figures 23 and 24 illustrate the positive impact of the treatment plant installation policy. Indeed, in terms of coliforms, we observe (Figure 23) that on June 25, 1987, the guideline of 100 MPN per 100 ml would have been exceeded most of the time along the entire watercourse if the treatment plants had not been installed. Also, in Figure 24, one observes that at the outlet of the Chaudière river between March 15th and July 15th, 1987, that the total phosphorus concentration decreases by half due to the installation of the treatment plants. This example illustrates well how we can evaluate a priori the impact of an environmental policy within an area. This type of approach also allows treatment choices and plant placement within the watershed to be evaluated based on meeting quality guidelines.

Figure 23 Changes in coliform concentrations along the Chaudière river, before and after the application of Quebec’s water treatment program, PAEQ, for the hydrological conditions present on June 25, 1987. (Taken from Mailhot et al., 2007).
Verifying the potential impact of forest harvesting on flow (Rousseau et al., 2000)

An intensive forest harvesting scenario was evaluated in the Famine river watershed (Figure 22). A sub-basin of the Chaudière River watershed, the Famine sub-basin, covers an area of 667 km$^2$, 10% of the Chaudière River watershed. The ‘cut scenario’ used is that 180 km$^2$ of forest would be cut within this sub-basin, totalling 27% of its surface area. The scenario was applied by changing the land use characteristics of the watershed. The forest sections that were cut were treated as bare soil. The simulation was run with these new characteristics and compared to the simulation without any forest harvesting. Figure 25 illustrates the impact of the ‘cut scenario’ on flow at the outlet of the Famine river basin, from March 15 to June 15, 1987.

We can observe that the floods are greater and that they arrive earlier following a cut. Because
there is a flooding problem on the Chaudière River, we can expect that forest harvesting would worsen the problem. These results alert decision-makers a priori about the consequences of harvesting before they make decisions concerning forest harvesting in the sub-basin. The analysis also raises questions about the management strategies or planning that should be undertaken to minimize the negative impacts if forest harvesting is permitted.

Cost-benefit analysis of various manure management strategies (Salvano et al., 2004, 2006)

This study evaluated the cost-benefit relationship when using various agricultural manure management strategies. First, the potential benefits generated by improving water quality needed to be evaluated. Secondly, these benefits were compared to the relative costs of manure management. The benefits considered related to recreational activities (swimming, canoeing, kayak, and hiking) that could be undertaken when the phosphorus concentration in the watercourse was below 0.02 mg/L. The monetary value of these benefits was established based on participation data and willingness-to-pay data estimated from an Environment Canada survey (Environment Canada, 2001).

For a case study in the Beaurivage river watershed (a tributary of the Chaudière river), two management scenarios were developed: (a) the base scenario assumed the application of as much manure as possible; and (b) a farm-scale management scenario based on satisfying the phosphorus requirements of crops by using manure and then treating the remaining manure. For the second scenario, two separate management areas were considered: (i) a group of three contiguous municipalities (communities); and (ii) two sub-basins associated with reaches of the river where recreational activities may be practiced. The costs of implementing these management strategies were calculated based on the costs and revenues associated with animal production, manure storage and treatment costs, and fertilization costs.

Because the summer is the primary period during which these activities are practiced, the simulations were undertaken, separately, with summer meteorological data from 1977 to 1986. The simulations first showed that the management scenarios increased the number of days during which recreational activities could take place in two reaches of river and in the three contiguous communities. The results of the cost-benefit analysis are provided in Table 1. These results show that for each the management scenarios considered, the cost-benefit relationship is less that 1. Meanwhile, a sensitivity analysis shows that this relationship could surpass 1 if manure treatment costs were reduced, a technically feasible possibility.

Table 1 Results of the Cost-benefit Analysis

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Management Unit</th>
<th>Total Benefits (Can$)</th>
<th>Net Benefits (Can$)</th>
<th>Net Costs (Can$)</th>
<th>Cost/Benefit Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>Basin</td>
<td>34 932 318</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Manure Management</td>
<td>Municipalities</td>
<td>39 879 554</td>
<td>4 947 236</td>
<td>13 358 754</td>
<td>0,37</td>
</tr>
<tr>
<td></td>
<td>Sub-basin 1</td>
<td>39 343 865</td>
<td>4 411 547</td>
<td>6 017 262</td>
<td>0,73</td>
</tr>
<tr>
<td></td>
<td>Sub-basin 2</td>
<td>40 168 706</td>
<td>5 236 388</td>
<td>9 282 867</td>
<td>0,56</td>
</tr>
</tbody>
</table>

1 The benefits are for recreational activities associated to water use in both reaches of the river.
2 It is the difference between the benefits of the management scenarios versus the reference scenario.
3 The costs were calculated for a management period of one year.

Climate Change Effects on the Hydrological Regimen (Rousseau et al., 2007; Quilbé et al., 2008)

To evaluate the impact of climate change, we used temperature and precipitation scenarios for
Jean-Pierre Villeneuve et al.

2025 originating from six general circulation models (GCM). These increases were applied to a series of observed temperature and precipitation data from 1970 to 1990. With this data, flows at the outlet of the Chaudière watershed from 2010 to 2039 were modelled. On the basis of these six scenarios, six series of simulated flows were obtained. From these simulated flows, we calculated the mean monthly and yearly outflows. Figure 26 illustrates the cumulative frequency curve of the mean monthly level and annual outflows for each of the six future climate scenarios as well as the reference scenarios that used historical data. First, one observes the large monthly variability between the results from each GCM. The interest of these curves lies primarily in the evaluation of which probabilities should be used when designing infrastructure that can adapt to climate change. Currently, there has not been an assessment of the effects of climate change on water quality using GIBSI. This will be subject to a future study.

![Cumulative frequency curves of annual outflows for different climate change scenarios as well as for historical reference conditions.](image)

**Figure 26** Cumulative frequency curves of annual outflows for different climate change scenarios as well as for historical reference conditions.

### Conclusion

These GIBSI examples evidence the capacity and potential of integrated management tools. Nevertheless, it is often observed that there is not enough data to calibrate the simulation models and thus to apply them. This problem is not pertinent to integrated management because, in this case, the scenarios are being compared to a base scenario. One can calibrate the models with available information and simulate a scenario that will act as the base scenario for the comparison and analysis. It is understood however, that for the most part these models are physically-based and that a good understanding of the processes being modelled will allow the informed modeller to adjust the model parameters intelligently to closely reflect the reality in the field. In terms of field data, we can now access satellite observations and soil maps, some of them digitized. There are no longer any excuses for not applying the integrated management tools we have at our disposition.

### FINAL CONCLUSION

The evolution of hydrology from a “descriptive science” to a “base science” (i.e., quantitative
hydrological models) that integrates hydrological process, then to integrated watershed management occurred in four steps. The first step took place up to the 18th century. Until then, there was descriptive hydrology only. The second step occurred during the 18th and 19th century with the increase in resource use linked to industrial development. At this time, hydrological science became more quantitative. The third step, around 1930 and shortly thereafter, is when modern hydrological concepts were formed; that is the quantitative description of those processes that form the water cycle. The fourth step occurred in the early 1960’s. There were no new scientific concepts or laws that were added to hydrological science during this step. Rather, it is the technological advances that increased the societal impact of the science. The arrival of computers allowed the modelling of hydrological concepts and laws and the application of these to more complex hydrological problems. Since 1990, it is the ease of use and the availability of computer-based tools that have driven model improvements to a level detailed enough to determine the impact of various land uses. Georeferenced databases and teledetection have become indispensable for distributed models. By joining these models to water quality models, we now have all of the necessary tools to conduct integrated watershed management. The distribution and applicability of these models should lead to better land use and heightened environmental protection especially for water resources.

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