Integrated Analyses of Canada’s Water Resources: A System Dynamics Approach

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Abstract: An integrated water resources management model for Canada, CanadaWater, has been developed using the system dynamics simulation approach. The CanadaWater model takes into consideration dynamic interactions between quantitative characteristics of the available water resources and water use that are determined by the socio-economic development level, population and physiographic features of Canada’s territory. It is a unique tool that integrates the water quantity and quality sectors with seven sectors that drive economic development: population; agricultural development; food production; capital investment; energy generation; use of non-renewable resources; and persistent pollution. The CanadaWater model is a system dynamics simulation model that provides for investigation of different scenarios. Model simulations are performed for 12 scenarios designed to investigate policy options in the area of fresh water availability, wastewater treatment, economic growth, population growth, energy generation and food production. The conclusions point to a very strong dependence of Canada’s future development and well being on maintaining acceptable quality of the water resources and controlling the level of water use in different sectors.

Résumé : Un modèle de gestion intégrée des ressources en eau pour le Canada, CanadaWater, a été conçu à l’aide de l’approche par simulation de la dynamique du système. Le modèle CanadaWater prend en considération les interactions dynamiques entre les caractéristiques quantitatives des ressources en eau disponibles et entre l’utilisation de l’eau, lesquelles sont déterminées par le degré de développement socio-économique, la population et les caractéristiques physiographiques du territoire canadien. Il s’agit d’un outil unique qui intègre les secteurs de la quantité et de la qualité de l’eau à sept secteurs qui stimulent le développement économique : population; développement agricole; production alimentaire; investissement de capitaux; production d’énergie; utilisation de ressources non renouvelables et pollution continue. Le modèle CanadaWater consiste en un modèle de simulation dynamique du système qui permet d’effectuer des recherches quant à différents scénarios. Les simulations de modèle sont exécutées pour 12 scénarios conçus dans le but d’étudier des options stratégiques ou des propositions de politique dans les domaines de la disponibilité de l’eau douce, du traitement des eaux usées, de la croissance économique, de la croissance de la population, de la production d’énergie et de la production alimentaire. Les conclusions semblent indiquer que le bien-être et le développement futurs du Canada seront...
fortement tributaires de la préservation d’une qualité acceptable des ressources en eau ainsi que du contrôle du degré d’utilisation de l’eau dans différents secteurs.

**Introduction**

Canada is a country with an abundant supply of fresh water (Environment Canada, 2003). While Canada’s population represents just 0.5% of the global population, it has access to nearly 20% of the world’s stock of fresh water and 7% of the total renewable water resources. Canadians are also among the highest consumers in terms of per capita water use (1,471 m$^3$ per capita per year). The supply of fresh water is not limitless and is shared among many users. Canada is presently facing a number of water issues including water availability, distribution, water use, quality of water and water management. There is currently no methodology available to address water-related issues in Canada in an integrated manner.

This paper introduces a system dynamics simulation approach for integrated analyses of Canada’s water resources through the development of the CanadaWater model. The CanadaWater model takes into consideration dynamic interactions between quantitative characteristics of the available water resources and water use that are determined by the socio-economic development level, population and physiographic features of Canada’s territory. It is a unique tool that integrates the water quantity and quality sectors with seven sectors that drive economic development: population; agricultural development; food production; capital investment; energy generation; use of non-renewable resources; and persistent pollution.

The development of the CanadaWater model (Simonovic, 2003; Simonovic and Rajasekaram, 2003) took into consideration the following specific characteristics of the region: (a) a large territory; (b) concentration of the population within a narrow belt along the United States border; (c) concentration of the population in a small number of large urban centres; (d) spatial distribution of the available water resources; (e) sharing of the Great Lakes and many other river basins with the United States; (f) a great increase in water demand in the United States; (g) change in land use; (h) spatial and temporal distribution of water-caused natural disasters (floods and droughts); and (i) large decrease in fresh water quality due to pollution.

The following section provides a brief review of the pertinent literature. The system dynamics modelling approach is presented along with a review of global models developed using this approach. A description of the CanadaWater model follows with the main emphasis on the fresh water and the water quality sectors. Details of the system structure representation, choice of state variables and mathematical equations are also presented. Finally, the applicability of the model is discussed and the simulation scenarios and the simulation results are presented. The paper ends with a set of conclusions.

**Literature Review**

**Global Water Resources Assessment Models**

Due to the complex process of global change caused by various development activities around the world, water related issues, such as fresh water availability, and water quality have drawn the attention of many researchers. Water is central to the complex cycle of global change and future development. The call is out for all water professionals, policymakers, scientists and academics to enhance their collaboration and, together with the general public, take an active role in addressing the current and worsening fresh water crisis (UNESCO, 2003). One of the first steps in addressing the crisis is an accurate assessment of water resources and their use that forms the basis for future predictions. Leading research work on global water resources assessment includes L’vovich (1979), Baumgartner and Reichel (1975), Shiklomanov (1997), Gleick (1993, 1998, 2000), Maidment et al. (1998), Oki et al. (2001), Simonovic (2002a) and Alcamo et al. (2003 a, b). Methodologically, all of these assessments estimate quantitative characteristics of renewable water resources using observed river runoff data. Relationships between the important factors are not explicitly addressed and their important temporal and spatial dynamics are lost in integration. Therefore, the prediction of future water use and balance is very difficult and subject to a wide margin of error. The work presented in this paper is based on the use of the system dynamics approach for innovative assessment of water resources.

System Dynamics Simulation Approach to Modelling Water Resources

The scope of the assessment models discussed in the previous section is limited in terms of their ability to capture the dynamic behaviour of the complex systems they are modelling. There are dynamic feedback relationships among water availability and use and other important sectors such as: (1) population growth; (2) development of economy, industry and agriculture; (3) resource exploration and utilization; (4) pollution; and (5) water resources management. The global development model World3 (Forrester, 1973; Meadows et al., 1974) is the first global model to include the dynamic relationships among various development-related sectors. However, the main shortcoming of the World3 model is that neither fresh water quantity nor quality were part of this modelling effort.

System dynamics is a rigorous method of system description that facilitates feedback analysis usually via a simulation model of the effects of alternative system structures and control policies on system behaviour (Forrester, 1961; Sterman, 2000). It relies on understanding complex inter-relationships between different elements of a system. This understanding is achieved by developing a model that can simulate and quantify the behaviour of the system. The major steps that are carried out in the development of a system dynamics model are understanding the system and its boundaries, identifying the key variables, representation of the physical processes or variables through mathematical relationships, mapping the structure of the model and simulating the model for understanding its behaviour.

The principles of system dynamics are well suited for modelling and application to water resources problems (Wurbs, 1993; Keyes and Palmer, 1993; Matthias and Frederick, 1994; Simonovic et al., 1997; Fletcher, 1998; Simonovic and Fahmy, 1999; Ahmad and Simonovic, 2000; 2001; 2002; Simonovic, 2002a, b; Li and Simonovic, 2002; and Simonovic and Li, 2003).

A system dynamics model is less useful in predicting exact future system states than in specifying how alternative choices would alter the tendency to move towards each of those conditions (Simonovic, 2002a). There are only two global dynamic models that take water into consideration: TARGETS (Rotmans and deVries, 1997) and WorldWater (Simonovic, 2002a) and two dynamic watershed scale models: ErhaiSD (Guo et al., 2001) and WRSD (Xu et al., 2002).

TARGETS is constructed as a set of metamodels that have been linked and integrated. It consists of five submodels: population and health, energy, land and food, water and the cycles submodel describing the biogeochemical element fluxes. These submodels are interlinked and related to the economic scenario generator. The conceptual principle of pressure-state-impact-response is the main driving mechanism of the TARGETS model. The water submodel AQUA takes into account the functions of the water system that are considered most relevant in the context of global change. Human related functions considered include the supply of water for the domestic, agricultural and industrial sectors, hydroelectric power generation and coastal defense. Ecological functions taken into account are natural water supply to terrestrial ecosystems and the quality of aquatic ecosystems. A pressure module describes both socio-economic and environmental pressures on the water system. Total water demand is calculated as a function of population size, economic activity levels, demand for irrigated cropland and water supply efficiencies. The model includes the option of treatment of wastewater before discharge. The state module simulates hydrological fluxes and changes in fresh water quality. The hydrologic cycle is modelled by distinguishing ten water reservoirs and simulates
the flow between these reservoirs. An impact module describes the impacts of water system changes on the environment and human society. The main limitation of the TARGETS modelling tool is its emphasis on assessing global change. Its structure and functionality are heavily dependent on the needs for evaluating future directions as a consequence of global climatic change and determining whether the chosen future directions are sustainable.

World3 model is used as the basis for the development of WorldWater model (Simonovic, 2002a). Two new sectors are introduced (water quantity and quality) together with multiple feedback links between the new sectors and the rest of the model. The total water stock in the model includes the precipitation, ocean resources and non-renewable groundwater resources. The model also takes into account water recycling as a portion of water use. The water use side is modelled in a traditional way to include municipal water use for the needs of the population, industrial and agricultural water needs. However, the most important difference between WorldWater and other global water models is the ability to address the needs of fresh water resources for transport and dilution of polluted water. Numerous simulations with WorldWater, documented in Simonovic (2002a), generated two very important conclusions: (i) Water is one of the limiting factors that needs to be considered in global modelling of future world development; and (ii) Pollution of water is the most important future issue on a global scale. In addition to warnings of many water experts, results of WorldWater simulations are explicitly, and for the first time, bringing water pollution to the forefront as the most alarming issue that needs attention of world population, water experts, and policymakers. The main limitations of the WorldWater model are in the assumptions used in its development: (a) water is a partially renewable resource; (b) water is limiting the growth of population, food production and industry; (c) water can be polluted; (d) water is a finite resource; (e) oceans are an important source of fresh water through desalination; and (f) pollution consequences of desalination are not incorporated in the model.

ErhaiSD (Guo et al., 2001) is an environmental management model for the Lake Erhai Basin in China. It has been developed for an in-depth study of water quality deterioration associated with rapid socio-economic development. The model incorporates the effects of various non-point pollution sources on the basin’s eutrophication, industrial activities and wastewater treatment processes. It takes into consideration the main development issues such as the growth of population, economy and agriculture.

WRSD (Xu et al., 2002) is a water resources system dynamics model for the Yellow River Basin in China. It has been developed to analyze sustainable water resources management in the basin. The existing and potential water supply is estimated from surface water, groundwater aquifers and treated wastewater. Potential water supply is compared to the estimated water demand for agriculture, domestic and industrial sectors. Through the analyses of various water supply and demand scenarios, the sustainability indices of the water supply system for different regions within the basin are estimated.

CanadaWater Model

Modelling Issues

CanadaWater allows for the investigation of the interrelationships between different sectors that drive development and the water cycle. Model simulations are performed for 12 scenarios for investigating policy options in the area of fresh water availability, wastewater treatment, economic growth, population growth, energy generation and food production.

The CanadaWater model facilitates water resources decision-making through a hierarchical modelling of water availability. Growing water demand in different sectors is first provided from renewable surface water resources. When the water demand exceeds the available renewable surface water resources an additional amount can be taken from the groundwater resources. After the demand exceeds the available surface and groundwater resources, water reuse is considered. The model also provides for the consideration of other water consumption-related policy issues such as net-migration of population; foreign trade of goods, services and energy; agricultural land development; and maintenance of water quality standards. As a policy-based modelling tool, the CanadaWater model offers facilities for development and simulation of different future scenarios and compilation of results to address the critical issues for immediate consideration.
Spatial Discretization of the Model

The CanadaWater model includes the entire territory of Canada plus the United States' portion of the Great Lakes Basin (Figure 1). The study area is discretized into a series of water units — in some cases a water unit is a watershed and in some cases a number of watersheds are lumped together. Precipitation in a water unit is confined for use within the drainage boundary of the unit. However, large water transfers between different units (for example, water export to the United States) are taken into consideration. Water consumption for different sectors, such as agriculture, industry and thermal power, is provided from the water unit in which they are located. In the case of water shortage, the water demand will need to be reduced. In the case of water surplus, the excess water drains to the sea at no benefit to any other water unit. Most of the activities dependent on water, such as agricultural production and the accumulation and discharge of pollution load, take place within the water unit.

Activities that are not specific to a particular water unit are considered at the national level. Economic activities, for example, are modelled for the whole country and are available only in an aggregated form. Energy production and use, food production and use, and exploration and use of non-renewable resources all fall into this category. Agricultural production is considered at the water unit level, as it requires water and contributes to the pollution. However, the agricultural products from one water unit can be exported and consumed in other units, or traded with other countries.

Figure 1. Major water units.
Figure 1 shows the water units used in the CanadaWater model. Sections of the Yukon River and the Columbia River that fall within Canada are denoted by YK and CO, respectively. FR and MK denote areas covering the drainage basins of the Fraser and the Mackenzie Rivers, respectively. The NL water unit includes the Nelson River Basin, the North and the South Saskatchewan Rivers and the watershed of the Churchill River. The Great Lakes watershed area and the drainage area of the St. Lawrence River have been integrated together and divided into two water units, one within Canada (SLCA) and the other one within the United States (SLUS). The Pacific seaboard water unit covers the western coastal river basins as well as Vancouver Island and is denoted by PSB. The Maritime Provinces and the eastern coastal river basins are contained in the Atlantic seaboard water unit, and denoted by ATSB. Those river basins that drain into Hudson Bay, excluding the Nelson and Churchill River Basins are combined and named as the Hudson seaboard water unit, and denoted by HSB. Those river basins that drain into the Arctic Ocean, excluding the Mackenzie River Basin, are combined and named as the Arctic seaboard water unit, as indicated by ASB. For detailed modelling of some important water related issues, the Mackenzie River and the Nelson River Basins are further divided into sub-basins. Therefore, the total number of water units included in the CanadaWater model is 30.

Modelling Principles

Water is a basic necessity of life. It has a strong influence on the development of Canada as a country and it is an important part of our national natural wealth. Socio-economic development activities use water in one form or another. Water is essential for the survival of humans, animals and plants. It is also one of the key ingredients for agricultural development. Industrial activities, power generation and mining activities require water. Large amounts of clean water are mobilized for the treatment of waste and pollution that result from other development activities. Thus, with the continuous development of Canada’s economy, the demand for water increases. Canada has one of the largest supplies of fresh water in the world. However, this supply is not limitless and is shared among many users. The three leading water users in Canada, according to Statistics Canada (2003), are electric power generation, the agriculture industry and personal and government use (various organizations and service providers such as hospitals, recreation centres, educational institutions, government services and households).

The CanadaWater model contains nine sectors, shown in Table 1 with a detailed list of key modelling issues. Figure 2 presents the causal links among different sectors and the key variables used in the model.

The growth of population and economy (both directly linked to GDP) are the key determinants of

<table>
<thead>
<tr>
<th>Model Sector</th>
<th>Key Modelling Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population (PO)</td>
<td>Growth of population; fertility; mortality; net migration</td>
</tr>
<tr>
<td>Capital (CP)</td>
<td>Growth of GDP; capital stock; capital investment; capital depreciation; goods and services requirement; export and import of goods and services; goods and services shortage</td>
</tr>
<tr>
<td>Agriculture (AG)</td>
<td>Land development; agricultural production; land fertility</td>
</tr>
<tr>
<td>Food (FD)</td>
<td>Food production; food consumption; food export and import; food shortage</td>
</tr>
<tr>
<td>Fresh water (FW)</td>
<td>Surface water resources; groundwater resources; sectoral water demand; dilution water requirement; water export; conservation/waste of water</td>
</tr>
<tr>
<td>Water quality (WQ)</td>
<td>Water quality index; water quality standard threshold; water quality treatment level</td>
</tr>
<tr>
<td>Energy (EN)</td>
<td>Energy production; energy consumption; energy export and import; energy generation capacity expansion; energy resources depletion; energy shortage</td>
</tr>
<tr>
<td>Persistent pollution (PP)</td>
<td>Persistent pollution development; persistent pollution index; pollution assimilation</td>
</tr>
<tr>
<td>Non-renewable resources (NR)</td>
<td>Resources exploration; wood regeneration; resources stock index; use of non-renewable resources; resources shortage</td>
</tr>
</tbody>
</table>
Figure 2. The causal diagram of CanadaWater model.
development within the model. Population growth is governed by basic factors such as fertility, mortality and net migration. An increase in population results in: (a) an increase in demand for food, water, energy and resources; and (b) an increase in air, water and soil pollution. Economic development depends on increased industrial activities, which require consumption of resources and energy. Increased industrial activities contribute further to the increase in pollution of the environment. Economic growth and related policy decisions result in stronger agricultural development that provides more food for consumption and trade. However, increases in agricultural development require larger amounts of water for irrigation and generate increases in water and soil pollution. The byproduct of development activities is greater air, water and soil pollution. Persistent pollution and deteriorating water quality conditions require additional amounts of clean water for treatment and dilution. Water re-use in the form of return flows is taken into consideration in the model.

High persistent pollution, low water quality conditions, and shortages of resources and supplies have a severe negative impact on the overall development process. Persistent pollution and low water quality affect human fertility and increase human mortality, generating a negative feedback on population growth. Pollution and water quality conditions also affect the land fertility, reducing agricultural yield. This is another negative feedback that affects the food production cycle. Different development activities rely on intensive use of non-renewable resources, especially energy resources such as natural gas, coal, oil and uranium.

As the non-renewable resources play an important role in industrial production, energy production, and agricultural production, their shortage at some stage may pose a severe impact on the overall development. Thus, shortages of non-renewable resources, energy, food and consumable capital (in the form of goods and services) are incorporated in the model together with their effects on other processes.

Precipitation (rain and snow) are the principal sources of fresh water, of which a usable portion provides the different water demands and dilution requirements. Water to be used can either be used instream (for example, hydroelectric power generation or navigation) or withdrawn from its source. Water demand includes municipal, agricultural and industrial water requirements. Agricultural demand is met from the available soil moisture and irrigation. A portion of the water that is withdrawn eventually returns to the original source, often within a short timeframe. Polluted water bodies require additional clean water for dilution in order to provide for maintenance of acceptable water quality standards. The CanadaWater model uses a water unit-based index of water quality, which is an integrated measure of the concentration of different water quality parameters. The model effectively compares the water quality index with the acceptable water quality standards and on the basis of the difference determines the dilution water requirements to keep the water media at a safe level. Water treatment level is a policy variable in the model.

### Model Development

System dynamics simulation models can be effectively developed using available object-oriented computer development tools that can easily capture a system structure using objects such as stocks, flows, converters and connectors. The dynamic behaviour of a system is represented using feedback and delay mechanisms appropriately (Sterman, 2000). A stock object represents a system variable that changes its value over time, associated with flow objects that represent inflow/outflow rates determined by external conditions. The CanadaWater model is comprised of a number of stock variables, including population, capital, arable land, food, non-renewable resources and persistent pollution. Examples of the flow type variables include immigration/emigration rates, birth/death rates, capital investment/depreciation rate, land development/erosion rates, persistent pollution development/decay rates and non-renewable resources exploration/exploitation rates. Converter objects represent any other variables, mathematical transformations, unit conversions, or similar. Connector objects are used to describe the flow of information through the system structure.

The elements of a system are connected in a system dynamics model in such a way to depict the flow of data in reality. The first step in mapping the system structure and links between the elements of system structure is to develop a causal diagram, which illustrates the cause-and-effect relationship between the connected system elements. The CanadaWater
model development process involved a number of causal diagrams. For the purpose of illustration, the fresh water sector causal diagram is shown in Figure 3 and the water quality sector causal diagram is shown in Figure 4.

The links in a causal diagram carry a positive or negative sign, which indicates the nature of the relationship between two connected variables. For example, in the case of the fresh water sector diagram, the amount of fresh water is linked to rainfall. The positive sign associated with this link indicates that an increase in rainfall increases the amount of fresh water. Groundwater supply has a similar effect. However, increase in evaporation/losses and water use reduces the amount of fresh water as indicated by the negative sign in the diagram. The amount of consumed fresh water decreases with water conservation activities and increases with waste of water. Since the return flow is proportional to the water withdrawal, it increases with an increase in fresh water use. An increase in return flow, in turn, increases the outflow. An increase in the amount of available fresh water also increases the outflow. The dilution requirement (to meet the water quality standards) increases with the extent of water pollution. This reduces the amount of available fresh water.

The causal relationships among various variables in the water quality sector are presented in Figure 4. An increase in population, the industrial component of GDP or the amount of agricultural land increases the concentration of water quality parameters. An increase in water quality treatment level decreases the concentration of water quality parameters. When the dilution ratio increases the dilution water requirement also increases. An increase in the water quality concentration decreases the water quality index of the basin, indicating adverse water quality conditions.

Figure 3. Causal diagram of the fresh water sector.

Figure 4. Causal diagram of the water quality sector.
Model Setup and Mathematical Relationships

The CanadaWater model is developed using a structured computer programming approach, where the sectoral models are developed independently and then linked using common variables. The model consists of nine sectors, over 200 variables and over 3,000 equations. This paper presents the basic stock-and-flow equations for different sectors and provides details of the setup of the fresh water and the water quality sectors. Parameters of the equations are obtained from the available data through a calibration process, as presented later in the paper.

The state of the system, at any point in time during a simulation, is expressed in terms of a set of state variables. Development-related variables, such as the growth of population and GDP, are used as the primary system state variables. Food and energy production, linked to population and GDP, provide vital system performance information, and are thus included in the set of system state variables. A portion of GDP available to Canada's population is in the form of available goods and services. An index that measures the shortage of goods and services (GSSI) is introduced in the model. Food (FSI) and energy (ESI) shortage indices are used to measure the sufficiency of food and energy for consumption by the population. The availability of non-renewable resources is represented as the non-renewable resources stock index (NRRI). The status of water quality is expressed with the water quality index (WQI) and the status of accumulated persistent pollution with the persistent pollution index (PPI). All shortage indices together with WQI and PPI are considered as system state variables in the model.

Population Sector

The basic system state differential equation of the population sector is provided in equation (1), in the simplest form. However, in the CanadaWater model, variables in equation (1) are 2-dimensional arrays representing watersheds and age groups.

\[
\frac{d}{dt} (PO_{\text{pop}}) = PO_{\text{mat} \_ \text{rate}} - PO_{\text{death} \_ \text{rate}} + PO_{\text{mig} \_ \text{rate}} - PO_{\text{emig} \_ \text{rate}}
\]

where \(PO_{\text{pop}}\) is the population (Million persons); \(PO_{\text{mat} \_ \text{rate}}\) is the maturity rate from one age-group to the other (Million persons/year); \(PO_{\text{death} \_ \text{rate}}\) is the death rate (Million persons/year); \(PO_{\text{mig} \_ \text{rate}}\) is the migration rate (Million persons/year); and \(PO_{\text{emig} \_ \text{rate}}\) is the emigration rate (Million persons/year).

Total emigration and immigration are related to the GDP on the basis of available historical data as

\[
PO_{\text{total} \_ \text{emig}} = 0.0487 \times \exp(-1.292E-06 \times CP_{\text{gdp} \_ \text{CA}})
\]

(2)

where \(PO_{\text{total} \_ \text{emig}}\) is the total emigration (Million persons); and \(CP_{\text{gdp} \_ \text{CA}}\) is the total GDP (Million $, 1997 const.).

\[
PO_{\text{total} \_ \text{mig}} = 3.006E-07 \times CP_{\text{gdp} \_ \text{CA}}
\]

(3)

where \(PO_{\text{total} \_ \text{mig}}\) is the total migration (Million persons).

Capital Sector

The system state equation of the capital sector (which constitutes an array representing different types of capital pertaining to industry, agriculture and services) is written as

\[
\frac{d}{dt} (CP_{\text{cap} \_ \text{stock}}) = CP_{\text{inflow} \_ \text{rate}} - CP_{\text{depr} \_ \text{rate}}
\]

(4)

where \(CP_{\text{cap} \_ \text{stock}}\) is the capital stock (Million $, 1997 const.); \(CP_{\text{inflow} \_ \text{rate}}\) is the capital inflow (domestic and foreign) rate (Million $, 1997 const./year); and \(CP_{\text{depr} \_ \text{rate}}\) is the capital depreciation rate (Million $, 1997 const./year).

The GDP is directly linked to the capital stock and population. Using historical data and a Cobb-Douglas production function format, the following relationship is developed among the variables

\[
CP_{\text{gdp} \_ \text{CA}} = [44.435 \times \ln(year - 1975) + 714.67] \times (CP_{\text{cap} \_ \text{stock}}^{0.3}) \times (PO_{\text{pop} \_ \text{CA}}^{0.7})
\]

(5)
where PO_pop_CA is Canada’s population (Million persons).

The shortage index of goods and services is expressed as

\[
GSSI = \frac{GDP \text{ for Consumption}}{Goods \& Services \text{ Requirement}}
\]

where GDP for Consumption is the portion of GDP allocated for consumption in various forms of goods and services and the Goods & Services requirement is a function of population.

**Agriculture and Food Sectors**

The arable land state equation (which constitutes an array of arable land corresponding to each water unit) is written as

\[
\frac{d}{dt}(AG_{\text{ar}_\text{land}}) = \text{AG}_{\text{ar}_\text{dev}_\text{rate}} - \text{AG}_{\text{ar}_\text{ero}_\text{rate}}
\]

where AG_ar_land is the arable land (Million Ha); AG_ar_dev_rate is the land development rate (Million Ha/year); and AG_ar_ero_rate is the land erosion rate (Million Ha/year).

In the CanadaWater model, food is measured in terms of equivalent kilograms of vegetable (EKGV). The EKGV conversion factor is developed based on the food consumption of an average Canadian and the caloric value for different types of food in their consumable form. Accordingly, any type of food can be converted into its EKGV using the following relationship

\[
\text{EKGV Conversion Factor} = \frac{\text{Calories per kg. of the given food}}{\text{Calories per kg. of vegetables consumed by an average Canadian}}
\]

The basic system state equation for the food sector, including various sources of food and their utilization, is written as

\[
\frac{d}{dt}(FD_{\text{food_stock}}) = \text{FD}_{\text{agri_food_prod_rate}} + \text{FD}_{\text{pou_lvstk_prod_rate}} + \text{FD}_{\text{fish_prod_rate}} + \text{FD}_{\text{import_rate}} - \text{FD}_{\text{cons_rate}} - \text{FD}_{\text{export_rate}}
\]

where FD_food_stock is the food stock (EKGV); FD_agri_food_prod_rate is the agricultural food production rate (EKGV/year); FD_pou_lvstk_prod_rate is the total poultry and livestock food production rate (EKGV/year); FD_fish_prod_rate is the fish food production rate (EKGV/year); FD_food_import_rate is the food import rate (EKGV/year); FD_food_cons_rate is the food consumption rate (EKGV/year); and FD_food_export_rate is the food export rate (EKGV/year).

The food shortage index is derived as

\[
FSI = \frac{\text{Food Supply}}{\text{Food Requirement}}
\]

where Food Supply refers to the available food for consumption; and Food Requirement links the Canadian population and the GDP using the following empirical relationship

\[
FD_{\text{food_req}} = 1.037E+09 \times \text{PO}_{\text{pop_CA}} + 140531 \times \text{CP}_{\text{gdp_CA}}
\]

**Non-Renewable Resources Sector**

The state equation for the non-renewable resources sector is written as

\[
\frac{d}{dt}(NR_{\text{stock}}) = \text{NR}_{\text{expl_rate}} + \text{NR}_{\text{regen_rate}} - \text{NR}_{\text{depl_rate}}
\]

where NR_stock is the stock of non-renewable resource (resource unit); NR_expl_rate is the resource exploration rate (resource unit/year); NR_regen_rate is the resource re-generation rate (resource unit/year); and NR_depl_rate is the resource depletion rate (resource unit/year).

The non-renewable resources stock index is defined as the summation of individual stock ratios with respect to their corresponding stock values in the year 2000

\[
NRRI = \sum_{i=1}^{NRR} \left[ \frac{\text{NRR Stock (i)}}{\text{NRR Stock (i) 2000}} \right]
\]
The non-renewable resources include wood, energy resources and metal/mineral resources. In order to simplify the model, wood as a renewable resource is included in this sector since wood regeneration and consumption are identical to the exploration and depletion of the non-renewable resources. The variables in the non-renewable resources sector are dimensioned using an array (wood, iron, copper, nickel, lead, zinc, gold, silver, molybdenum, potash, sulphur, uranium, coal, gas, oil).

**Persistent Pollution Sector**

The development of persistent pollution due to various activities is accounted for by computing the persistent pollution stock, which is an assumed function of the persistent pollution development factor (PPOLL Dev Factor) defined by equation (14). The PPOLL Dev Factor is the summation of the ratios of development variables, such as arable land (AR Land), industrial component of the GDP (IND GDP) and the population (POP), with respect to their values in 2000.

\[
PPOLL \text{ Dev Fac} = \omega_{AR} \frac{AR \text{ Land}}{AR \text{ Land}_{2000}} + \omega_{IND} \frac{IND \text{ GDP}}{IND \text{ GDP}_{2000}} + \omega_{POP} \frac{POP}{POP_{2000}}
\]  

(14)

The coefficients \(\omega_{AR}\), \(\omega_{IND}\), and \(\omega_{POP}\) represent the weighting factors associated with the respective development ratios. The system state equation for the accumulated persistent pollution is written as

\[
\frac{d}{dt}(PP_{\text{stock}}) = PP_{\text{appr \ rate}} - PP_{\text{assml \ rate}}
\]  

(15)

where \(PP_{\text{stock}}\) is the persistent pollution stock; \(PP_{\text{appr \ rate}}\) is the persistent pollution appearance rate (per year); and \(PP_{\text{assml \ rate}}\) is the persistent pollution assimilation rate (per year).

\(PP_{\text{stock}}\) is used to represent the persistent pollution index.

**Energy Sector**

The total energy demand is related to the population and the GDP in the following form

\[
EN_{\text{dem}} = 182430 \times PO_{\text{pop \ CA}} + 2.215 \times CP_{\text{gdp \ CA}}
\]  

(16)

where \(EN_{\text{dem}}\) is the total energy demand (PJ).

Energy production in Canada is comprised of different forms of energy such as hydropower, nuclear and thermal (which includes production from coal, oil, gas and steam sources). Energy shortage for consumption is computed as

\[
ESI = \frac{\text{Energy for Consumption}}{\text{Energy Demand}}
\]  

(17)

**Fresh Water Sector**

The model setup (stock and flow diagram) of the fresh water sector is shown in Figure 5. The equations that give rise to the dynamic behaviour of the fresh water sector are described as follows.

The total amount of water in a water unit (indexed i) is expressed as

\[
FW_{\text{basin \ total \ water}[i]} = FW_{\text{runoff coeff}[i]} \times FW_{\text{net \ precip}[i]} \times FW_{\text{dr \ area}[i]} / 1000
\]  

(18)

where \(FW_{\text{basin \ total \ water}}\) is the total water inflow for the water unit (million cubic metres, MCM); \(FW_{\text{runoff coeff}}\) is the runoff coefficient; \(FW_{\text{net \ precip}}\) is the net precipitation (mm); and \(FW_{\text{dr \ area}}\) is the drainage area of the water unit (km\(^2\)).

The runoff coefficients are estimated for different basins on the basis of available data through the calibration process. Since the simulation time step is one year, seasonal runoff variation was not considered in the model.

The amount of water discharge (the complement of the amount of usable water) is expressed as

\[
FW_{\text{basin \ usable \ water}[i]} = FW_{\text{usable \ water \ frc}[i]} \times FW_{\text{basin \ total \ water}[i]} + FW_{\text{ground \ water}[i]}
\]  

(19)
where FW\_basin\_usable\_water is the usable water within the water unit (MCM); FW\_usable\_water\_frc is the fraction of usable water; and FW\_ground\_water is the usable ground water (MCM).

The sectoral unit water demand with the conservation factor applied is calculated as

\begin{equation}
FW\text{\_sec\_dem\_consvd}[i, j] = FW\text{\_sec\_unit\_demand}[j] \times FW\text{\_sec\_consv\_fac}[i, j]
\end{equation}

where FW\_sec\_unit\_demand is the water demand for water use sectors (MCM); FW\_sec\_consv\_fac is the sectoral demand conservation factor; FW\_sec\_dem\_consvd is the conserved sectoral demand (MCM); and \( j \) represents the water sector.

The sectoral demand conservation factor, for different water-use sectors, varies around one. A value of less than one indicates conservation in the sector while a value greater than one indicates waste of water.

Under normal operating conditions, these factors are equal to 1.0 for all sectors. Suppose a particular sector ‘a’ in water unit ‘x’ conserves water by a fraction of \( \delta \), then the conservation factor is calculated as

\begin{equation}
FW\text{\_sec\_consv\_fac}[x, a] = 1 - \delta
\end{equation}

On the other hand, if sector ‘b’ in water unit ‘y’ wastes water by a fraction of \( \gamma \) the conservation factor is given by

\begin{equation}
FW\text{\_sec\_consv\_fac}[y, b] = 1 + \gamma
\end{equation}

The water demand for different water use sectors is defined as

\begin{equation}
FW\text{\_sec\_dem}[i, \text{Agri}] = FW\text{\_sec\_dem\_consvd}[i, \text{Agri}] \times FW\text{\_ar\_land}[i]
\end{equation}
where \( FW_{sec\_dem} \) is the sectoral water demand (MCM); \( FW_{ar\_land} \) is the arable land (M Ha); \( FW_{pop} \) is the population (Million persons); \( FW_{gdp\_min\_manu} \) is the GDP component of mining and manufacturing (M $); and \( FW_{th\_power} \) is the thermal power (PJ).

The dilution water requirement is calculated using the critical dilution ratio, denoted by the variable \( XX_{crit\_dil\_ratio} \). The critical dilution ratio is the amount of fresh water that is required to bring the concentration of critical water quality parameters to acceptable levels.

\[
FW_{dil\_water\_req}[i] = FW_{dil\_rflow\_fac}[i] \times FW_{return\_flow}[i] \times (XX_{crit\_dil\_ratio}[i]-1)
\]

The water balance computation (illustrated in Figure 6) in different water units \( i \) is performed according to

\[
FW_{sec\_dem}[i, Domestic] = FW_{sec\_dem\_consvd}[i, Domestic] \times FW_{pop}[i]
FW_{sec\_dem}[i, Ind] = FW_{sec\_dem\_consvd}[i, Ind] \times FW_{gdp\_min\_manu}[i]
FW_{sec\_dem}[i, ThPower] = FW_{sec\_dem\_consvd}[i, ThPower] \times FW_{th\_power}[i]
FW_{basin\_water\_bal}[i] = FW_{basin\_usable\_water}[i] - FW_{dil\_water\_req}[i] - FW_{water\_export}[i] + FW_{return\_flow}[i] - \sum_{j = Sector} FW_{sec\_dem}[i, j]
\]
**Water Quality Sector**

The model setup of the water quality sector is shown in Figure 7. The CanadaWater model uses 26 water quality parameters associated with different development activities, where \( i \) refers to the water unit and \( k \) refers to the water quality parameter.

\[
WQ_\text{devconc}(i, k) = \sum \left( WQ_\text{crop}_\text{land}(i) \times WQ_\text{para}_\text{ar}(i, k) + XX_\text{gdp}_\text{ind}(i) \times WQ_\text{para}_\text{ind}(i, k) + XX_\text{pop}(i) \times WQ_\text{para}_\text{pop}(i, k) + WQ_\text{para}_\text{corr}(i, k) \right)
\]

where \( WQ_\text{devconc} \) is the water quality concentration (\( \mu g / litre \)); \( XX_\text{gdp}_\text{ind} \) is the industrial component of the GDP (Million $, 1997 const); \( XX_\text{pop} \) is the population (Million persons); \( WQ_\text{crop}_\text{land} \) is the arable land (M Ha); and \( WQ_\text{para}_\text{ar}, WQ_\text{para}_\text{ind}, WQ_\text{para}_\text{pop} \) and \( WQ_\text{para}_\text{corr} \) are correlation coefficients.

Water quality parameters used in the model include \{dsO; HCO3; dsCa; dsCl; totSolids; totCaCO3; dsMg; dsK; dsSiO2; dsNa; dsSO4; dsF; totN; totP; totC; totAl; totAs; totBa; totBe; totB; totCd; totCr; totCo; totCu; totFe; totPb; totLi; totMn; totHg; totMo; totNi; totSe; totAg; totSr; totVa; totZn\} where the prefix ds stands for ‘dissolved’ and tot stands for ‘total’.

The concentration of each water quality parameter being considered within the water unit for the particular level of wastewater treatment is computed according to the schematic shown in Figure 8. With a water quality treatment level of \( x \), the treated concentration of a parameter is computed as

\[
WQ_\text{treatedconc} = WQ_\text{devconc} - x \times \left( WQ_\text{devconc} - WQ_\text{threshold} \right)
\]

where \( WQ_\text{treatedconc} \) is the concentration after treatment (\( \mu g / litre \)); and \( WQ_\text{threshold} \) is the threshold value (\( \mu g / litre \)).
The water quality dilution ratio is calculated using the concentration of a water quality parameter in a water unit according to

\[
WQ_{\text{dilution\_ratio}}[i, k] = \frac{WQ_{\text{treated\_conc}}[i, k]}{WQ_{\text{threshold}}[k]}
\]  

(28)

where \(WQ_{\text{dilution\_ratio}}\) is the dilution ratio; and \(WQ_{\text{threshold}}\) is the water quality parameter threshold value (µg/litre).

When the dilution ratio derived from equation (28) is smaller than one, it is normalized to one. This adjustment is required to derive the water quality index for the water unit. The critical dilution ratio, \(WQ_{\text{crit\_dil\_ratio}}\), for the water unit under consideration is found as the maximum of the normalized dilution ratio values for different water quality parameters

\[
WQ_{\text{crit\_dil\_ratio}}[i] = \max_{k = WQ_{\text{Para}}} \left\{ \frac{WQ_{\text{norm\_dil\_ratio}}[i, k]}{WQ_{\text{threshold}}[k]} \right\}
\]  

(29)

The water quality index for the water unit \(i\) (\(WQ_{\text{index}}\)) is then computed as

\[
WQ_{\text{index}}[i] = \prod_{k = WQ_{\text{Para}}} \left\{ \frac{1}{WQ_{\text{norm\_dil\_ratio}}[i, k]} \right\}
\]  

(30)

**System Delays**

The integrated system development activities in the model are impacted by the combination of different indices pertaining to shortages, persistent pollution, and water quality conditions. Capital development is based on capital assets, as is shown by equation (4) in the capital sector. However, the amount of NRR, goods and services, and energy are the basic ingredients for production. Therefore, shortages in these inputs will delay production activities. Land fertility depends mainly on persistent pollution and water quality. Thus, high persistent pollution and low water quality delay land re-generation. Human fertility and life expectancy depend largely on goods and services, energy, food, persistent pollution and water quality. The combination of these factors will reduce human fertility and life expectancy. Therefore, system delays are introduced in the model to establish realistic relationships between different variables. In most cases, historic data are used to select the delay value. Where data were insufficient, extensive sensitivity analysis was performed to evaluate the impact that delays have on model simulation results.

**Model Input Data, Calibration and Verification**

The CanadaWater model is data intensive. Historical data from many different sources are used. Miscellaneous data for the United States’ portion of the Great Lakes Basin are obtained from the U.S. Geological Survey. The demographic data for Canada, such as population, birth and death rates, migration and emigration, fertility and mortality rates, and the life expectancy tables are obtained from Statistics Canada (CANSIM II Tables 510001, 510002 and 510013; and Catalogue 11-516-XIE). The data on capital assets, GDP, capital depreciation, and capital investment pertaining to different production sectors, as well as the trade and consumption of goods and services are obtained from Statistics Canada (CANSIM II Table 310002, 310002 and 3800030, 3800027). Food production-related data, such as food consumption and caloric values of different types of food are obtained from the statistical database of the Food and Agriculture Organization (FAOSTAT), while the agriculture related information is obtained from the Census of Agriculture, 1991, 1996 and 2001, and the Canada Year Books 1950-2000.

The CanadaWater simulation model uses a yearly time step and 100 years time horizon (2001-2100). The main input for determining the available future water quantity is the net precipitation (precipitation-evaporation), which is taken from the Canadian Global Circulation Model – CGCM1 developed by the Canadian Centre for Climate Modelling and Analysis.
CGCM1 is a spectral model with a surface grid resolution of approximately 3.7° × 3.7° (http://www.cccma.bc.ec.gc.ca/models/cgcm1.shtml - accessed March 23, 2004). The Canadian land area under study falls within the geo-coordinates of (142.5W, 79.78N) and (56.25W, 42.68N), allowing the use of data for 24 × 11 grid points of CGCM1.

Water requirements are obtained from different model sectors (population, agriculture, industry, energy). The major uses of water are taken from the past record of water use in 1981, 1986, 1991 and 1996 (Table 2.1, page 12 - Statistics Canada, 2003). Activities of each sector are the consequence of the state of the system (for example amount of available energy generation capacity or land area used for agricultural production), future needs of people and the environment and numerous sectoral policy decisions.

Data on surface water are obtained from the Environment Canada HYDAT database. Daily climate data and water quality data are also obtained from Environment Canada (direct communication). The water quality threshold values are obtained from the Environmental Quality Guidelines (Canadian Council of Ministers of the Environment – http://www.ccme.ca/publications/can_guidelines.html - accessed March 23, 2004).

Data on energy production and energy trade are obtained from Statistics Canada (CANSIM II Table 1280002). The power production plant capacities pertaining to different types of production are obtained from Statistics Canada (Catalogue 57-206-XIV). Data on recovery, depletion and addition of fuel resources are taken from Natural Resources Canada.

Data for all model sectors are collected from 1976 to 2000 for model calibration and verification. The calibration of the model parameters and relations has been carried out using the data from 1976 to 1985. The data from 1985 to 2000 were used to verify the model performance. Selected verification results are provided for illustration purposes. Total observed and model computed population over the verification period are shown in Figure 9, historical and modelled GDP are shown in Figure 10 and observed and model calculated runoff of the St. Lawrence Basin are shown in Figure 11.

**Use of CanadaWater Model**

CanadaWater simulates the water balance over 100 years (2001-2100). Each simulation run is performed for a particular scenario, which is defined as a combination of policy variables from different model sectors that are developed to address an issue.

An effective user interface (Figure 12a) provides access to model parameters for each sector, policy variables for setting a simulation scenario and results for each sector. In addition, the main interface provides access to integrated results that show the state of the system as a combined presentation of selected outputs from different sectors. An example of the main input device (model parameters window) is shown for the fresh water sector in Figure 12b. The policy variables interface, which allows for the development of simulation scenarios, is shown in Figure 12c. Simulation of CanadaWater provides results for each of the model sectors and in aggregated form. Analyses of simulation results show the insight into the relationships between Canada's water quantity and quality and the main set of socio-economic indicators of development. For example, results shown in Figure 12d are aggregated indicators of the state of Canada under the 'status quo' scenario. Very detailed output data can be obtained for the scenario under analysis from different sectors. For example, Figure 12e shows the detailed water quality results.

**Analyses of Canada’s Water Resources**

The CanadaWater model structure allows for comprehensive simulation of the dynamic interactions between the available and required water quantity and quality. The main input for determining the available future water quantity is the net precipitation (precipitation-evaporation).

Water requirements are obtained from different model sectors (population, agriculture, industry, energy, etc.). The activities of each sector are the consequence of the state of the system (for example, the amount of available energy generation capacity or land area used for agricultural production), future needs of people and the environment, and numerous sectoral policy decisions.
Figure 9. Model calibration – Population of Canada (line 1 – calculated; line 2 – observed).

Figure 10. Model calibration – GDP (line 1 – calculated; line 2 – historical).

Figure 11. Model calibration – St. Lawrence River Basin runoff (line 1 – calculated; line 2 – observed).
Figure 12. The CanadaWater model interface.
Model simulations are performed for 12 scenarios selected to investigate different policy options related to: (a) population growth; (b) economic growth; (c) water conservation; (d) fresh water export; (e) wastewater treatment; and (f) energy production and trade. A scenario is defined as a combination of policy variables from different model sectors that is developed to address an issue.

**Basic Scenario**

Prior to considering any future policy options, model simulation is performed by extending current trends over the simulation period. The migration and emigration of population is driven by gross domestic product (GDP) defined as the total value of all goods and services produced in Canada during a given year.

The main variables in the capital sector are used to distribute the capital investment between agriculture, industries and services. The current trend indicates that the fraction of investment in the agriculture sector decreases exponentially over time. An extension of this trend over the time horizon could have a severe impact on agricultural production. Investment in the industrial sector is constant while the investment in the services sector is derived as a fraction of the investment in the other two sectors.

Energy sector variables for the basic scenario are an extension of the present trends. Energy production from the hydropower sector is limited by the undeveloped power potential of Canada's rivers. Energy production from the non-hydropower production sectors is limited by the availability of energy resources such as uranium, coal, natural gas and oil. Gas-fired plants in Canada represent about 44.4% of the total non-hydropower production in the year 2000, while oil, coal and nuclear production are at 37%, 13.3% and 5.3%, respectively. This distribution is assumed to continue over the simulation period.

The main variable in the agricultural sector is the annual maximum land area that can be developed for agricultural production in each water unit. This value is limited by the amount of investment in the agricultural sector.

The fresh water sector of the model receives the demand for water in different water-use sectors including domestic water needs, water demand for agriculture, industrial water needs and water requirements for thermal power production.

The main variables in the water quality sector of the model are threshold values for various water quality parameters as well as the wastewater treatment levels. Setting the water quality parameter threshold at low values increases the critical dilution ratio and requires more water for dilution in the basins. Both environmental and health concerns are considered in setting the threshold values. The level of treatment determines how close the concentrations of water quality parameters are to the threshold values in the effluents from water-use facilities. It is assumed that facilities allow an average treatment level of 75%.

**Population Growth Scenarios**

Canada's population growth is determined by two factors: (a) natural population growth; and (b) net migration. Natural growth refers to the difference between births and deaths; net migration refers to the difference between immigration and emigration. Immigration and emigration depend on policy decisions. However, in this study those factors are analyzed in relationship to the GDP. Two artificial scenarios of immigration and emigration are simulated in order to investigate model performance under population growth that can be a product of a policy decision. The first scenario considers an increase in immigration rate of 50% and the second one an increase in emigration rate of 50%.

**Economic Growth Scenarios**

Economic growth scenarios are generated in the CanadaWater model by modifying a share of goods and services among capital elements such as investment, export and import. In the base scenario, these relationships are represented in analytical form as functions of GDP. It has been noted that these functions are vulnerable to negative development in the case of low values of GDP. Alternatively, in this group of scenarios, these elements are interpreted as fractions of GDP using year 2000 as the base year. Accordingly, investment is $0.177 \times GDP$, export is $0.607 \times GDP$ and import is $0.550 \times GDP$. A range of values is considered for each fraction as follows:
investment 0.15–0.25; export 0.50–0.70; and import 0.45–0.65.

**Water Conservation Scenarios**

Water conservation is considered only in relationship to agricultural production in the Prairies. The Nelson River Basin is divided into 15 water units for better spatial resolution and detailed analysis of water use. Agricultural water demand is reduced in the range 1.00–0.70 (simulation is performed with four values within this range).

**Water Export Scenario**

To test the CanadaWater model’s ability to consider export of water to the United States, one scenario has been developed for transfer of water from the St. Lawrence Basin through the Chicago diversion in the maximum amount of 2,870 MCM/year.

**Wastewater Treatment Scenarios**

In the basic scenario, the treatment level variable is taken as 0.75, assuming that the treatment facilities treat the effluent to this level before discharging it to the watercourse. However, the effluent will typically need to be further diluted to meet the environmental water quality standards. Such dilution is achieved through computation of the critical dilution ratio for each water unit. Two additional scenarios are developed using a treatment level of 0.99 (level that ensures relatively clean effluent with no harmful effect on humans and agriculture) and a relatively low level of treatment of 0.50.

The need for clean water for dilution can be affected through the introduction of different threshold values for water quality parameters. In this group of scenarios a typical threshold value of hardness in the form of total CaCO$_3$ (180,000 micrograms/litre) has been increased and decreased by 50,000 micrograms/litre.

**Energy Production Scenarios**

The Canadian economy is energy dependent. The amount of available energy may have a severe impact on the growth of population and GDP. Measures to avoid energy shortages in Canada may include an increase in energy import, a decrease in energy export, an increase in production from those resources that are available in sufficient quantities and reduction in production from resources that are available in limited quantities.

By extrapolating the past record, the import in 2100 reaches 2.678 times (3,231,670 PJ) the import in 2000. A set of scenarios is developed with an increase in the energy import factor to values of 5, 7.5 and 10 in 2100. Similarly, the extrapolation of the amount of energy exported results in energy export in 2100 of 4.705 times (9,001,437 PJ) the export in 2000. A set of scenarios with the export factor of 4.0, 2.0, and 0.5 is developed in order to reduce future export.

Using the assumption of the distribution of energy production (between natural gas, oil, coal and nuclear) in the same ratio as in the year 2000 (basic scenario) it was observed that the natural gas reserves were fully exhausted by 2050. Oil resources were close to depletion towards the end of the simulation in most scenarios. One energy scenario considers increase in production from nuclear and coal resources to a maximum of 10 times the production in year 2000, oil production to a maximum of five times the production in year 2000, and reduction in natural gas production to 0.5 times the production in year 2000. Another scenario focuses on the adjustment of energy production ratio between natural gas, oil, coal and nuclear energy to 20%, 20%, 50% and 10%, respectively.

**Simulation Results**

The twelve scenarios investigated provide plenty of information in all sectors of the model. This presentation will be limited to integrated results focusing on water quantity and quality.

Figure 13 shows the variation of the main system state variables ($PO_{pop_CA}$ total population; $CP_{gdp_CA}$ GDP value; $EN_{prod_total}$ total energy production; $FD_{prod_total}$ total food production and $NR_{stock_index}$ total stock of non-renewable resources) over the simulation period of 2000 through 2100 for the basic scenario. The pertinent production indicators,
population and GDP, show a steady increase over the first half of the simulation period. The population reaches a peak value of 42.3 million in 2045 and drops to 18.6 million at the end of simulation period. The GDP reaches its maximum of 1,227,416 million dollars (1997 const) in 2050, gradually dropping during the second half of the simulation period to 665,473 million dollars (1997 const) in 2100. Food production decreases steadily from $2.285 \times 10^{11}$ to $1.981 \times 10^{11}$ equivalent kg of vegetables. Energy production starts dropping around 2042, after reaching a maximum of $26.4 \times 10^6$ PJ. This drop is attributed to the depletion of natural gas reserves. One of the most significant results of the CanadaWater model simulation is that the maintenance of the same rate of natural gas use for energy generation and other purposes as in year 2000 is not possible for future development conditions. Due to this shortage, both population and GDP start to decrease.

The second most significant finding is related to the general decline in water quality over the simulation period. Figure 14 shows, for example, the critical dilution ratio for Canadian and the United States portions of the St. Lawrence River unit (SLCA, SLUS), the Atlantic Seaboard (ATSB) and the Nelson River unit (NL). The dilution ratio is defined as the ratio between the concentration of a particular pollutant (microgram/litre) and its threshold value (microgram/litre) and is calculated for every water unit and for every relevant water quality parameter. The critical dilution ratio is the maximum dilution ratio for a particular water unit. A considerable amount of clean water is required for dilution if the treatment remains at the same level. The ATSB experiences high concentration of water pollution and its dilution ratio reaches 1.14 in 2048. Thus, it requires 14% more clean water than available to bring the effluent from different sources to acceptable environmental standards. SLCA dilution ratio reaches 1.13, while SLUS and NL ratios reach maximum of 1.1 and 1.00, respectively.

Different population growth scenarios resulted in different values for total population and GDP at the end of the simulation period. The system dynamics did not change considerably in comparison with the basic scenario. In these simulations, increased population imposes a high requirement for food production resulting in food shortages towards the end of the simulation period.

Simulations of different economic growth scenarios show strong population growth but weaker...
GDP growth (Figure 15). The maximum population is 43.6 million in 2044, declining to 18.5 million in 2100. GDP reaches its maximum of 1,183,960 million dollars (1997 const) in 2045, through steady growth during the first half of the simulation period. However, during the second half, there are frequent disturbances ending with 635,699 million dollars (1997 const) in 2100. The decrease in overall GDP growth has a severe impact on non-renewable resources (NRR) exploration. The NRR stock index reaches its maximum of 10.0 in 2100. As exploration of energy resources is directly linked to GDP, there appears to be a shortage of energy resources leading to unsteady energy production during the second half of the simulation period. In 2040, gas resources have been fully exploited, while in 2059 the amount of oil resources explored is no longer sufficient to meet the energy demand. Figure 16 indicates the total dilution requirement and the total water consumption pertaining to all water units. The dilution water requirement peaks at 12,041 MCM in 2041, while the total water consumption has a maximum of 19,468 MCM around the same time. Both the dilution requirement and the total consumption show irregularities during the second half of the simulation period, corresponding to changes in GDP during that time.

Water conservation simulations are focused on the Canadian Prairies and the impact of reduced agricultural water use. The total impact of conservation is insignificant due to the difference between the available water and the agricultural water demand. Total outflow from the Nelson water unit (NL) varies between 100,631 MCM (in 2008) and 82,920 MCM (in 2067), while in 2048 the total consumption (municipal, agriculture, industry and energy) reaches 5,855 MCM and dilution requirement only 2,330 MCM.

The water export scenario simulated includes transfer of water from the St. Lawrence water unit through the Chicago diversion. The current maximum capacity of 91 m$^3$/sec (2,870 MCM/year) has been increased up to 20,000 MCM/year to evaluate the sensitivity of the water unit balance to the water export. Water export leads to a reduced outflow from the St. Lawrence water unit. However, water export does not significantly affect the water requirements and total consumption in the water unit. The total outflow from the St. Lawrence water unit varies between 299,800 MCM (in 2006) and 228,100 MCM (in 2062). However, the maximum dilution requirement is 7,491 MCM and the maximum consumption is 9,123 MCM in 2041.
Wastewater treatment scenarios confirmed the importance of water quality as shown in the basic scenario. Demand for clean water for dilution increases with a decrease in the treatment level. This impact propagates through other model sectors. Figure 17 shows the comparison of population growth under different wastewater treatment levels. There is a considerable difference between the conditions of 0.99 and 0.75 treatment levels. The peak population differs by about four million. Under the treatment level of 0.5, the maximum population drops to 40 million in 2032. Population growth differs dramatically during the first half of the simulation period, whereas during the second half the declining trend levels off.

Simulation results in Figure 18 show steady population growth to a maximum of 45.8 million people in 2100. Steady growth of GDP reaches a maximum of 1.41×10^6 million dollars (1997 const) in 2100. The total energy production has a peak value of 11.92×10^6 PJ in 2034. The NRR index shows an increasing trend, with a maximum of 31.5 in 2100. This is an indication that this scenario conserves NRR much better than the other scenarios.

Conclusions

Aggregated conclusions are presented for twelve scenarios developed using the CanadaWater model. The scenarios are clustered into four groups: population, water, economy and energy.

Population Scenarios

With an increase in immigration, the total population and GDP exhibited a strong growth. These trends resulted in an increase in water consumption, dilution water requirement, energy production and food production. The peak value of total water consumption rose by 3.4% compared to 44% and 20% demonstrating similar dynamics for the main system state variables.

Energy production scenarios were developed based on new options regarding the import and export of energy and redistribution of energy production from different sources. As a general guide for reducing energy shortages, import is doubled and export is quartered in all scenarios. As the general modelling principle is to promote energy production from resources that are available in sufficient quantity, coal energy production is increased. For the scenario simulation in Figure 18, energy production fractions are set at 10% for nuclear, 50% for coal, 20% for gas and 20% oil. Another scenario has been tested with the energy production fraction for coal between 26% and 50% and natural gas fraction between 36% and 44% and 20% demonstrating similar dynamics for the main system state variables.
the basic scenario, while the peak value of dilution water requirement rose by 22.5%.

The increase in GDP leads to the exploration of additional NRR. The NRR stock index peaks at value of 11.8 which is 11.2% higher than the value for the basic scenario. While there were no noticeable differences in the energy shortage index and the persistent pollution index, the goods and services shortage index extended over 50 years.

Conclusion 1: Immigration strengthens both the population growth and the growth of GDP, with a slight increase in water consumption and dilution water requirement and slight changes in the shortage and persistent pollution indices.

Water Scenarios

Agricultural water conservation results in a reduction of total water consumption but it does not impact the growth indicators such as the total population and GDP. However, water conservation in one sector may compensate for deficiencies in other sectors, if there are any. No such deficiencies are identified within the set of scenarios considered in this study.

Conclusion 2: Water conservation in agricultural water use brings about significant changes in agricultural production. In cases with shortages in other water use sectors, which have a direct impact on total population and GDP, meeting those shortages with conservation is recommended.

Increase in wastewater treatment level to 99%, from its default of 75%, generates an increase in peak population of 8.9% compared to 42.3 million persons in the basic scenario. The GDP peak increases by 7.7% from its peak value of 1.2×10^6 Million $ (1997 const) in the basic scenario. Improvement of water quality affects the growth of population and GDP, which in return increases the total water consumption by 1.4% from its value of 19.61 MCM in the basic scenario. However, the peak value of dilution water requirement drops by 99.7% from its value of 23,010 MCM in the basic scenario. As the GDP increases, more NRR is developed and the NRR stock index grows to 11.3 in 2100 in comparison to 10.4 in the basic scenario.

Shortage indices and the persistent pollution index did not show much deviation from the basic scenario.

Conclusion 3: An increase in the wastewater treatment level results in a steadier growth of population and GDP. Water quality improvement increases the total water consumption slightly, but reduces the dilution water requirement significantly.

Water export reduced the water available for consumption. However, there is no significant scarcity of water in the St. Lawrence water unit resulting from water export. No conclusion on water export is derived based on the scenarios analyzed.

Economic Scenarios

The economic scenarios came out of the various divisions of GDP among capital investment, export and import of goods and services. All the simulations show an increase in population growth and increase in GDP growth. The scenario with an increase in capital investment reveals a greater consumption of water and requires additional water for dilution. The NRR stock index shows a maximum of 11.5 in the case of increased capital investment, compared to its corresponding value of 10.4 in the basic scenario. Other scenarios ended up with the NRR stock indices of 9.5, indicating less NRR exploration due to the limited growth of GDP.

Conclusion 4: Increase in the GDP fraction for investment results in strong capital growth. Increase in the GDP fraction for export and/or decrease in the fraction for import together decrease the amount of goods and services available for consumption, with significant impact on population growth.

Energy Scenarios

The energy scenarios are developed to reduce energy shortages and strengthen the growth of population and GDP. Since the natural gas energy resources appear to be fully exploited by the middle of the 21st century, at the current rate of consumption, new energy scenarios are developed by reducing the use of natural gas resources, and increasing the energy
production from oil resources as well as increasing the energy import. Hydropower energy production is assumed to continue growing at the current rate. The modified energy scenarios yield very promising results in terms of population and GDP growth. Peak energy production varies from scenario to scenario. The total water consumption and the dilution water requirement dynamics closely follow the variation in energy production.

Conclusion 5: All policy options aimed at the reduction of energy shortages have a positive impact on the growth of population and GDP. These options may include reduction of energy export; increase in energy import; slower utilization of natural gas; and/or increase in oil production. A combination of these options, along with a plan for the re-distribution of the energy requirement from different resources, yields the best results. This conclusion is based on the assumption that hydropower energy production continues growing at the present rate.

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References


