

Assessment of Water Resources Through System Dynamics Simulation: From Global Issues to Regional Solutions

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Abstract

The growing scarcity of fresh and clean water is among the most important issues facing civilization in the 21st century. Despite the growing attention to a chronic, pernicious crisis in world's water resources our ability to correctly assess and predict global water availability, use and balance is still quite limited. WorldWater model is developed and used to assess global world water resources using system dynamics approach. It has shown that: (a) there is a strong relationship between the world water resources and future industrial growth of the world, and (b) the water pollution is the most important future water issue on the global level. Solutions for water problems are at the regional level and the work presented in this paper includes initial results of the transformation of WorldWater into CanadaWater regional model. Regional characteristics of Canadian water resources demand considerable increase in the complexity of the model. First results indicate that CanadaWater model has a potential to identify water-related issues of national priority and assist policy makers in evaluating various sustainable solutions for Canadian 'troubled' waters.

1. Introduction

Water is in the middle of the complex cycle of global change and future development. The call is out for all water professionals, policy makers, scientists and academics to enhance their collaboration and, together with general public, take an active role in addressing the current and worsening fresh water crisis. 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. The milestone work in this area includes L'vovich (1974), Gleick (1993), and Shiklomanov (2000) among others. Methodologically, all the above studies are estimating 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.

A limited effort has been devoted to global modeling of water resources that is taking into consideration dynamic interactions between quantitative characteristics of available water resources and water use. However, the following models should be mentioned for possible expansion and use in the future: the Policy Dialogue Model PODIUM developed by the International Water Management Institute (www.cgiar.org/iwmi/software/podium.htm); the International Model for Policy Analysis of Agricultural Commodities and Trade IMPACT developed by the International Food Policy Research Institute (www.ifpri.cgiar.org/themes/impact.htm); the POLESTAR developed by the Stockholm Environment Institute (www.seib.org/polestar/psbro.html); Water Evaluation and Planning System WEAP developed by the Stockholm Environment Institute – Boston Tellus Institute (www.seib.org/weap/weapbro.html); and www.tellus.org); Water – Global Assessment and Prognosis WATERGAP developed by the University of Kassel (www.usf.uni-kassel.de); Tool to Assess Regional and Global Environmental and health Targets for Sustainability TARGETS developed by the Netherlands National Institute of Public Health and the Environment (RIVM) (www.baltzer.nl); and *WorldWater* developed by Simonovic (2001; 2002)

All the above-mentioned models except TARGETS and *WorldWater* are not dynamic in nature. Different models treat a water sector with the different level of detail. Dynamic feedback relationships between physical characteristics of water balance and population growth; development of agriculture and industry;

technological development; and use of other resources; are not captured explicitly.

Global dynamic modeling has, however, received attention of many researchers culminating with the World3 model developed by Jay W. Forrester and his collaborators at the Sloan School of Management, MIT supported by the “Club of Rome”, a group of high-level European and American statesman and industrialists. Two books *World Dynamics*, (Forrester, 1971) and *Limits to Growth*, (Meadows et al, 1972) drew much attention to the global system dynamics modeling of the planet. However, global world modeling devoted very little attention to water resources. The main argument is that the water is a regional, not a global, resource. This statement is in contrast to main findings of the water community that realizes the importance of regional differences in solving water-related problems, but clearly indicates the existence of the global water crisis (Cosgrove and Rijbersman, 2000).

Two efforts (the TARGETS and the *WorldWater*) in the field of global world modeling deserve special attention. The TARGETS model is constructed as a set of metamodels which have been linked and integrated. It consists of five submodels: the population and health, the energy submodel, the land and food, the water submodel and the submodel describing the biogeochemical element fluxes (‘cycles’) (Rotmans and deVries, 1997). 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. The main limitation of the TARGETS modeling 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 or unsustainable.

The *WorldWater* model is discussed in more details in the following section of the paper. In this paper an attempt is made to present first steps in the development of a regional model, *CanadaWater*, for assessing the Canadian water resources. The regional integrated assessment model builds on the global model. Both of them integrate the water sector with the five sectors that drive industrial growth, population, agriculture, economy, nonrenewable resources, and persistent pollution. The main objectives of the presented research are: (i) to promote the system dynamics approach for modeling complex water resources systems; (ii) to use

the *WorldWater* modeling framework and develop a regional model, focusing on Canada; and (iii) to incorporate adaptation capabilities of water resources systems into the regional water assessment model. This will allow for investigations of the interrelationships between the five sectors that drive the economic development and the water cycle.

Canada as many other countries around the world is caught between growing demand for fresh and clean water on one side and limited and increasingly polluted water supplies on the other side. Choices are difficult. Geographic position of the country, large territory, uneven population density, climate change and close relationship with a much larger neighbour make management of Canadian water resources a very complex task.

The availability of the *CanadaWater* regional model allows for an intensive study of different feedbacks between human activities, environmental change, ecosystem integrity, and social and economic factors. Long-term benefits from the proposed research include the use of the model in Canada and abroad to predict, manage and mitigate the potential adverse impacts of changes associated with population growth, economic development, climate variability and change and limits to existing water resources. *CanadaWater* is being developed to address a set of regional water issues including: (a) climate variability and change (floods and droughts); (b) bulk water export; (c) water pollution; (d) urban water management; (e) institutional arrangements; and (f) aging infrastructure for water supply and drainage.

The following section of the paper presents the global water modeling approach and the *WorldWater* model. Then, the results of the model simulations are discussed in detail. The follow up section of the paper presents the *CanadaWater* model structure and discusses the issues of regional importance. I close with a set of conclusions and recommendations for the future work.

2. Global water assessment

Social systems, technology and the natural environment interact in different ways to produce growth, change and stress. In the past, the main forces of change were dealt with through migration, expansion, economic growth and technology. However, more recently we have become aware of some forces that cannot be resolved through historical solutions.

2.1. WorldWater model

Model structure of the *WorldWater* contains seven sectors: population, agriculture (food production, land fertility, and land development and loss), nonrenewable

Assumptions used in the development of *WorldWater* model are: (a) water is 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 freshwater through desalination; and (f) pollution consequences of desalination are not incorporated in the model.

One of the most important conceptual assumptions in the *WorldWater* is hierarchical modeling of water availability. Growing demand in different sectors is being provided for, first from the renewable surface water resources. When the water demand exceeds the available renewable surface water resources an additional amount can be taken from non-renewable groundwater resources. After the demand exceeds the available surface and groundwater resources, water reuse is considered. If the demand is still higher than the available supply, desalination of seawater is considered. The general agreement is that desalination is not the solution for the global world water crisis (Gleick, 1993). This process is technologically mature, but energy intensive and expensive.

A number of relationships is used to fully integrate water quantity and quality with the indicators of global development:

- *Domestic water use* is expressed as a function of **population**.
- *Population without sanitation and water supply* is expressed as a function of **population**.
- **Population** is expressed as a function of *domestic water supply*.
- **Life expectancy** is expressed as a function of *total water quantity*.
- **Life expectancy** is expressed as a function of *water quality*.
- *Irrigated land* is expressed as a function of **arable land**.
- **Land yield** is expressed as a function of *irrigation water supply*.
- *Industrial water use* is expressed as a function of **industrial capital**.
- **Industrial output** is expressed as a function of *water capital needs*.
- *Urban population* is expressed as a function of **industrial output**.
- *Amount of wastewater* is expressed as a function of **pollution index**.

2.2. Simulation Results

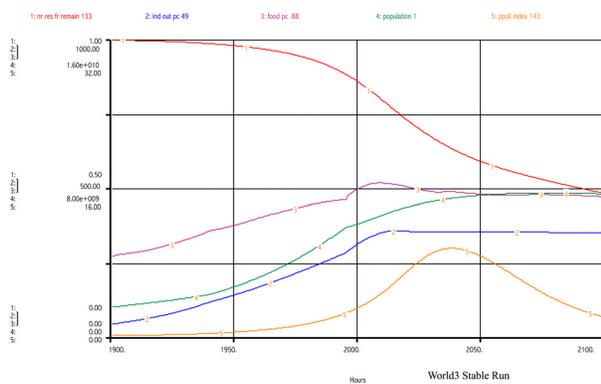
In the simulated environment of *WorldWater* model, the inherent assumption is one of continuous economic growth. Population in the model will stop growing only when it is rich enough or supporting resources are depleted. The world's resource base is limited and erodable. The feedback loops that connect and inform decisions (Figure 1) in *WorldWater* contain many delays, and the physical processes have considerable momentum. The most common mode of behavior is overshoot and collapse. In *Beyond the Limits*, Meadows et al (1992) investigated a broad range of twelve scenarios using World3 model that does not take water into consideration. Simonovic (2002) used for the demonstrations of *WorldWater* model three of the twelve scenarios: (a) standard run; (b) double run; and (c) stable run.

WorldWater simulations are clearly demonstrating the strong feedback relations between water availability and different aspects of world development. Results of numerous simulations are contradictory to the assumption made by the most of global modellers that water is not an issue on the global scale. It is quite clear that water is an important resource on the global scale and its limits do affect food production, total population growth and industrial development (Figure 2). Graphs in the Figure 2a describe the state of the world according to the World3 model and one development scenario. Graphs in Figure 2b show the same state of the world for the same scenario generated with the *WorldWater* model. Obvious difference between these two pictures of the world is demonstrating that water is an issue on the global scale.

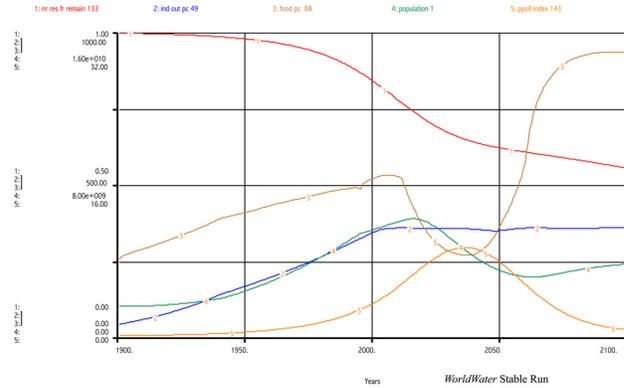
WorldWater provides detailed insight into the dynamics of water use over the simulation horizon. Figure 3 shows predicted water use patterns for the set of data from the standard scenario run. Two major observations can be made from this simulation. First, the use of clean water for dilution and transport of wastewater, if not dealt in other ways, imposes a major stress on the global world water balance. Using conservative data on wastewater disposal and rate of dilution from Shiklomanov (2000) and IHP (2000) it is shown that this use exceeds the total water use by six times. Therefore the main conclusion of the global water assessment modeling is that the water pollution is the most important future water issue on the global scale. Second, water use by different sectors is demonstrating quite different dynamics then predicted by classical forecasting tools and other water-models. Inherent linkages between water quantity and quality sectors with food, industry, persistent pollution, technology, and nonrenewable resources sectors of the model create an overshoot and collapse behavior in water use dynamics.

For the standard run simulation, water use is increasing in all sectors by the year 2015. Use of water for agriculture stops growing after 2015 but afterwards remains at the approximately same level since the food production is starting to suffer from the impact of pollution (line 1 in Figure 3). Water use for municipal supply follows the total population and grows until 2015 and then collapses with the decrease in the total population. After 2060, when the water dilution and transport demand is brought under control, municipal

water use begins to rise again (line 3 in Figure 3). Industrial water use shows the very same behavior (line 2 in Figure 3). Reservoir losses rise with the moderate pace following the expected development of water storage around the world (line 4 in Figure 3). Use of water for dilution and transport of wastewater follows the dynamics of persistent pollution. It peaks around 2040 and then after reduction in the growth of food production and the population, starts to decrease.



(a)



(b)

Figure 2. State of the World - 'Stable run' results of World3 (a) and WorldWater (b) models (after Simonovic, 2002)

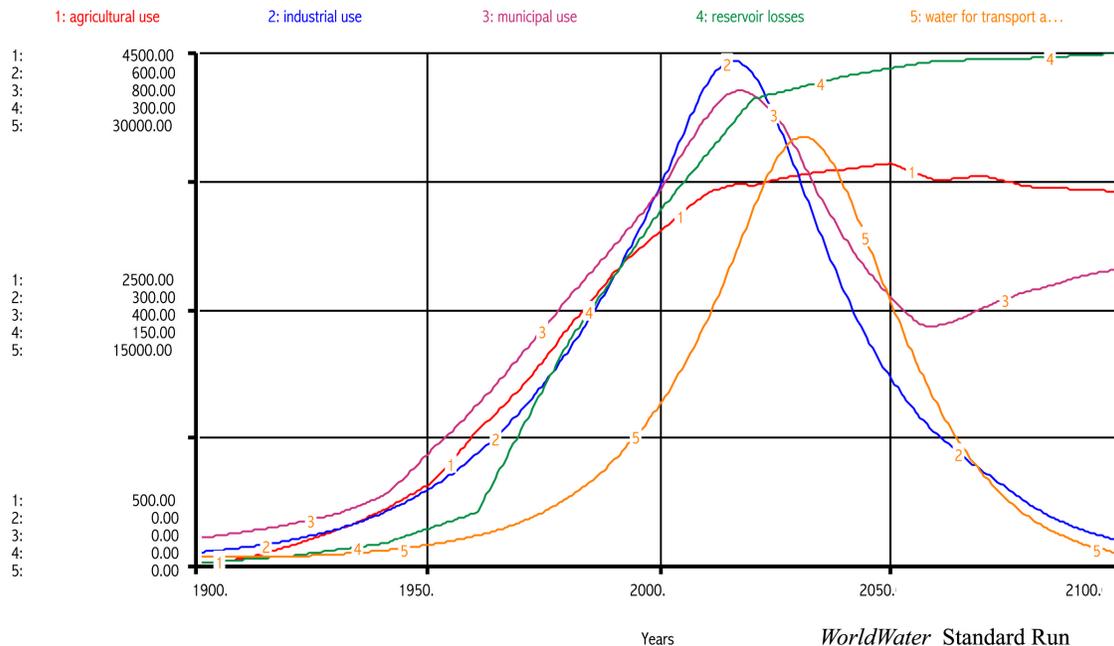


Figure 3. Use of water - 'Standard run' results of WorldWater (after Simonovic, 2002)

3. Regional water assessment

WorldWater is a powerful tool. However, its use is limited to identification and understanding of the main water issues at the global scale. Simonovic (2002) states: “The most important direction for the continuation of this research will be the transformation of *WorldWater* into numerous ‘*RegionalWater*’ models”. Solutions to water problems are at the regional level and power of dynamic regional models developed using the principles of *WorldWater* can increase our understanding of water problems and our ability to reach sustainable solutions for them.

3.1. Regional water issues

Canada is at a crossroads. With little effort, we could simply allow Canadian freshwater to become another commodity governed by the marketplace, trade agreements and large corporations. Or, we can take a different path: one that embraces conservation as a national policy and allows us to assist countries in truly desperate need. Canadian Federal Government issued a ban on the bulk export of Great Lakes water in March of 2000 and supported provinces in their attempt to regulate bulk water sale.

What are the long-term consequences of these decisions? How is the further population growth and economic development of Canada and United States going to be impacted by water? What is the role of NAFTA and World Trade Organization rules in management of our water resources?

Bulk water sale is only one of the important issues that requires an answer. Tragedy of the citizens of small town of Walkerton caused by the pollution of drinking water supply is another example. List can be expanded easily: aging water supply and drainage infrastructure; water institutional arrangements; climate variability and change (floods and droughts); water management in large urban areas; etc. These questions motivated the development of *CanadaWater* system dynamics model.

3.2. CanadaWater model structure

Global modeling experience and *WorldWater* modeling framework, principles and assumptions are used in the development of *CanadaWater* model. However, the transition process from global to regional model was characterized by the increase in model size and complexity due to the specific characteristics of the region. Some of the driving forces are: (a) large territory; (b) concentration of the population within the narrow belt along the US border; (c) concentration of the population in a small number of very large urban centres;

(d) spatial distribution of the available water resources; (e) sharing of the Great Lakes and many other river basins with the USA; (f) great increase in water demand in the USA; (g) change in land use; (h) spatial and temporal distribution of water-caused natural disasters (floods and droughts); and (i) large decrease in the fresh water quality due to the pollution.

CanadaWater model is being developed in ten sectors. Populations sector, shown in Figure 4, divides the population into four stocks according to the age group. Mortality, fertility and life expectancy are the main factors that determine the value of each stock variable. Introduction of migration and emigration was required to account for the specific character of population change in Canada.

Agriculture sector, shown in Figure 5, is build around amount of arable land, its capacity to produce food and erosion or loss of land for production. Three main specific requirements for this regional model include: (a) division of arable land between prairies (80%) and nonprairies (20%); (b) introduction of food export which represents one of the main elements of Canadian economy; and (c) consideration of government food production subsidies.

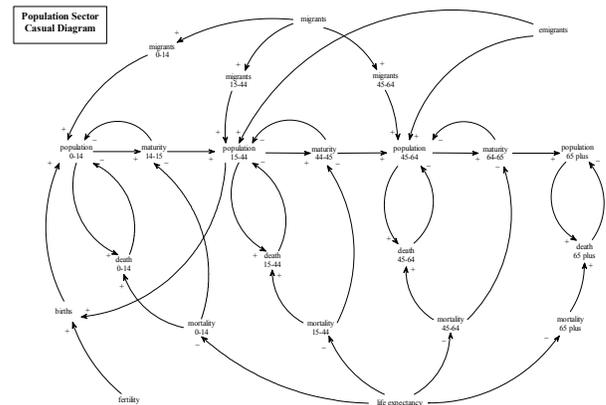


Figure 4. *CanadaWater* population sector causal diagram

Industry sector captures the flow of capital for the industrial development of the country, Figure 6. Model includes the free flow of capital in and out of the country. The main role of the energy generation and the use of nonrenewable resources in the industrial development is captured within the model.

Service sector of the regional model is shown in Figure 7. The main elements of the service sector include: (a) transport; (b) health; (c) education; and (d) social services. These four services provided by the different levels of government are determining the flow of service capital.

Agriculture Sector Causal Diagram

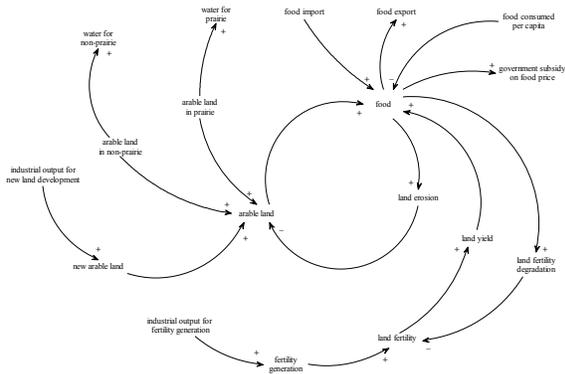


Figure 5. *CanadaWater* agriculture sector causal diagram

Industrial Capital Sector Causal Diagram

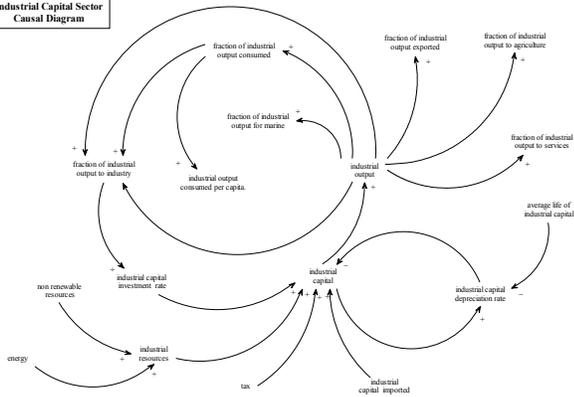


Figure 6. *CanadaWater* industry sector causal diagram

Service Capital Sector Causal Diagram

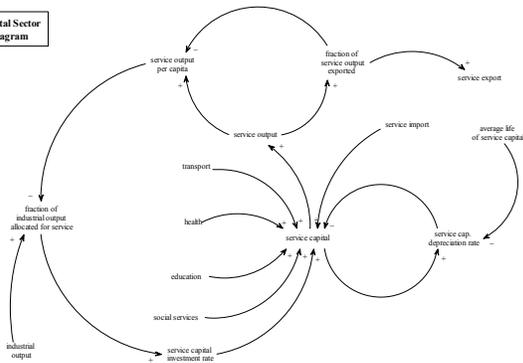


Figure 7. *CanadaWater* service sector causal diagram

Nonrenewable resources are historically playing very important role in Canada. Nonrenewable resources sector of the model is shown in Figure 8. Some specific issues addressed in the model development include consideration of wood and mineral within this sector. Wood is not a nonrenewable resource and correct

treatment of the forest renewal rates is provided within the model. Import of nonrenewable resources from other regions is also given proper consideration.

Non-renewable Resources Sector Causal Diagram

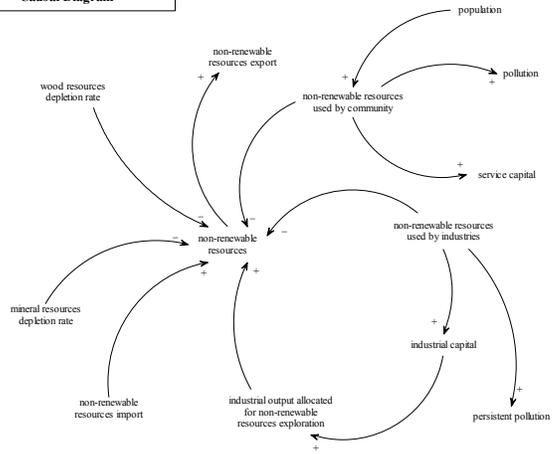


Figure 8. *CanadaWater* nonrenewable resources sector causal diagram

Energy generation for domestic use within the region and for exchange (export and import) between Canada and US is captured in the energy sector shown in Figure 9. Model considers hydro, thermal (coal, oil and gas) and nuclear power generation and takes into account export and import of energy. Important links are made between this sector and pollution sector. Water used for cooling thermal power plants for example, if returned back into the environment with higher temperature is considered as polluted.

Energy Sector Causal Diagram

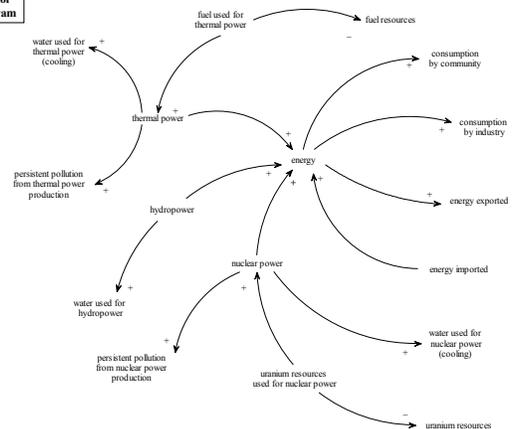


Figure 9. *CanadaWater* energy sector causal diagram

Persistent pollution sector, shown in Figure 10, has a very specific structure due to the characteristics of the region. Beside the classical sources of pollution coming from people, industry and agriculture, model takes into

account specific issues related to the pollution of the north, pollution of the Great Lakes (shared with the USA) and air pollution being transferred across the regional borders and deposited on the ground by the rain (acid rain).

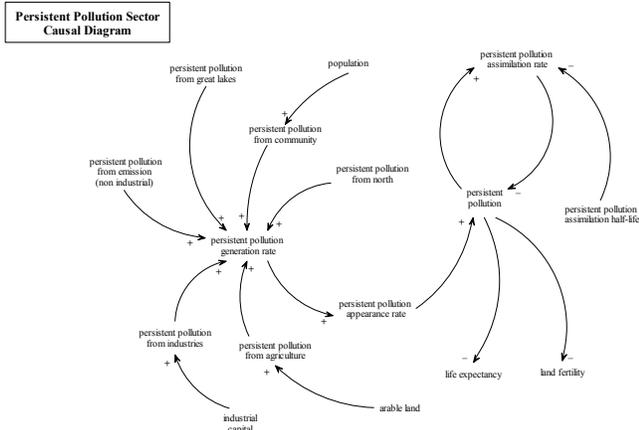


Figure 10. *CanadaWater* persistent pollution causal diagram

Marine sector of the model, shown in Figure 11, captures the importance of oceans surrounding the region from three sides. Importance of oceans and shores as population centres, food source, transportation and tourism development are all captured within this sector of the model together with the real threat of coastal pollution.

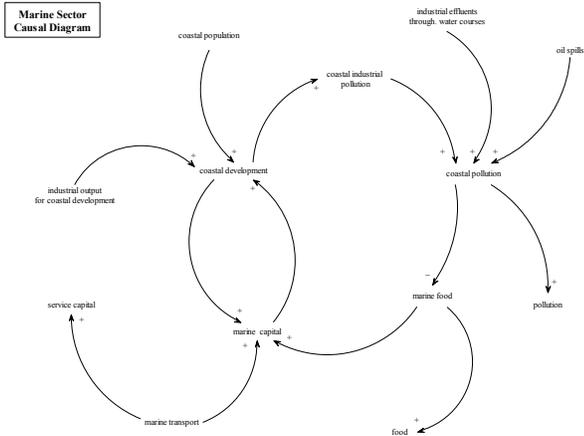


Figure 11. *CanadaWater* marine sector causal diagram

Two sectors of the model are dealing with the fresh water quantity and quality. Fresh water sector, shown in Figure 12, captures the main water balance including multiple sources of fresh water (rivers, lakes and aquifers) and multiple water demand for municipal,

agricultural and industrial water supply. Both, water quantity and quality are modeled within this sector.

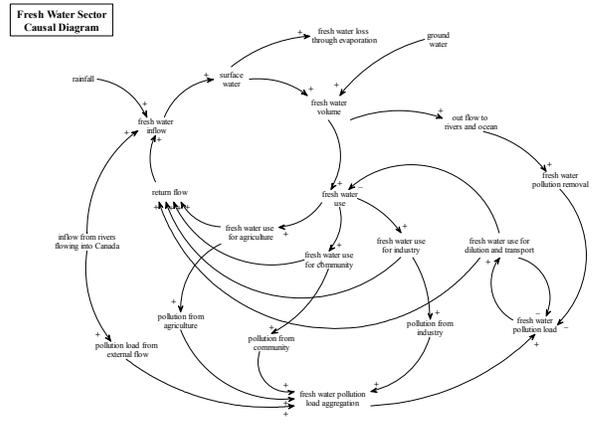


Figure 12. *CanadaWater* fresh water sector causal diagram

Great Lakes represent a very large body of water shared between Canada and the USA. Their role in the regional economy requires a special treatment in the *CanadaWater* model. Special sector of the model, as shown in Figure 13, captures the Great Lakes water quantity and quality balance. In this sector a complete balance between the water flowing in and out of the Great Lakes is modeled taking into consideration municipal, industrial and agricultural water needs in the region from both sides of the boarder. Only the

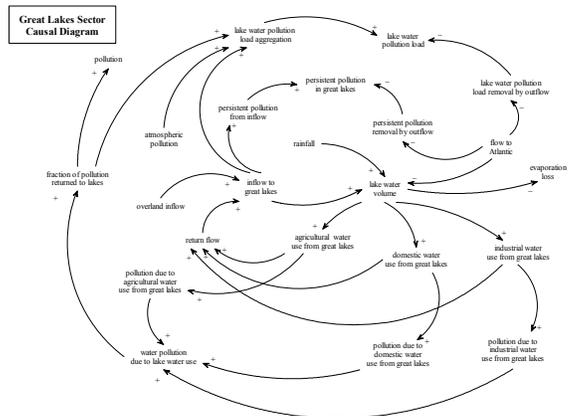


Figure 13. *CanadaWater* Great Lakes sector causal diagram

Canadian portion of the water quantity and quality balance is linked to the other sectors of the model. Considering the complexity of the Great Lake region and its international character it is prudent to plan and further

develop a regional model for the Great Lakes region only. One of the future activities in modeling water assessment using system dynamics will be devoted to the Great Lakes region.

3.3. Future work

When completed, *CanadaWater* model will need to be validated and used for simulation of various policy scenarios. This work will be completed in close collaboration with the potential users of the model. Validation of model results is planned to be done against expected behaviour for different scenarios. The starting point is going to be current policy and then various options will be developed in collaboration with model users. Future schedule of follow up activities is developed for periodic evaluation of model performance against indicators captured within the model structure.

4. Conclusions

CanadaWater model is being developed as a unique tool to assist in sustainable management of Canadian water resources. It is based on the system dynamics and draws from the experience gained in modeling global water assessment using *WorldWater* model.

In this review, the complete model structure has been presented that is accommodating specific needs of the region. When completed, this model will be used to address many important policy issues including: bulk water export from Canada, aging water supply and drainage infrastructure, institutional arrangements necessary for improved management of Canadian water resources, impact of climate variability and change on Canadian water resources (floods and droughts) and water pollution.

System dynamics simulation allows evaluation of regional solutions and will provide answers to above raised questions. It is expected that *CanadaWater* will play the major role in the development of new policy options, structural and non-structural water solutions (from planning new systems to operating existing ones) and contribute to the sustainable water resources management in general.

5. Acknowledgments

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6. References

- [1] Cosgrove, W.J., and F.R., Rijbersman, *World Water Vision*, Earthscan Publications Ltd, London, 2000.
- [2] Forrester, J.W., *World Dynamics*, Wright-Allen Press, Cambridge, Massachusetts, 1971.
- [3] Gleick, P.H. (editor), *Water in Crisis*, Oxford University Press, New York, New York, 1993.
- [4] International Hydrologic Programme (IHP), *World Freshwater Resources*, CD-ROM prepared by I.A.
- [5] Shiklomanov, International Hydrologic Programme, UNESCO, 2000.
- [6] L'vovich, M., *World Water Resources and their Future*, English translation by R.L. Nace, AGU, Chelsea, Michigan, 1979.
- [7] Meadows, D.H., D.L. Meadows, J. Randers, and W.W. Behrens III, *Limits to Growth*, Universe Books Publishers, 1972.
- [8] Meadows, D.H., D.L. Meadows, J. Randers, *Beyond the Limits*, McClelland&Stewart Inc., Toronto, Ontario, 1992.
- [9] Shiklomanov, I.A., 'Appraisal and Assessment of World Water Resources', *Water International*, **25**(1), 11-32, 2000.
- [10] Simonovic, S.P. 'WorldWater: A Tool for Global Modeling of Water Resources', *Canadian Civil Engineer*, **18**(3), 6-12, 2001.
- [11] Simonovic, S.P. 'World Water Dynamics: Global Modeling of Water Resources', *Journal of Environmental Management*, in print, 2002.
- [12] Rotmans, I., and B. deVries, *Perspectives on Global Change*, Cambridge University Press, Cambridge, UK, 1997.