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World water dynamics: global modeling of water resources

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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. An attempt is documented here in modeling global world water resources using system dynamics approach. Water resources sector (quantity and quality) is integrated with five sectors that drive industrial growth: population; agriculture; economy; nonrenewable resources; and persistent pollution. WorldWater *model is developed on the basis of the last version of World3 model. Simulations of world water dynamics with* WorldWater *indicate that there is a strong relationship between the world water resources and future industrial growth of the world. It is also shown that the water pollution is the most important future water issue on the global level.*

Keywords: water resources, global modeling, system dynamics, water balance.

Introduction

Many countries around the world are caught between growing demand for fresh and clean water on one side and limited and increasingly polluted water supplies on the other side. Many countries face difficult choices. Populations continue to grow rapidly. Yet there is no more water on earth now than there was a few thousand years ago, when the population was less than 3% of its current size. Today, some 1·1 billion people in developing countries lack access to safe drinking water. In addition, 2·4 billion lack adequate sanitation (WHO, 2000). Four million children die each year from water-related diseases (e.g. Falkenmark, 1989; Hinrichsen *et al.*, 1997; Vakkilainen and Varis, 1999; Al-Rashed and Sherif, 2000; Cosgrove and Rijsberman, 2000). At the occasion of World Day for Water 2000, Professor Obasi, Secretary-General of the World Meteorological Organization points that 'Water for the Twenty-first Century': will be scarce; will be under increasing threat from pollution; there will be increasingly severe periods of flood and drought; and should be the concern and responsibility of all.

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), Baumgartner and Reichel (1975), Shiklomanov (1997), Gleick (1993, 1998, 2000) and Maidment *et al.* (1998), among others. Methodologically, all the above studies are estimating quantitative characteristics of renewable water resources using observed river runoff data. The mean value of renewable global water resources is estimated at 42 750 km^3 per year with considerable spatial and temporal variation (Shiklomanov, 2000). Quantitative characteristics

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of water use on the global scale are determined using several basic factors such as: the socio-economic development level, population, and physiographic (including climatic) features. Combinations of these factors determines the volume and character of water use, its dynamics and future tendencies (Table 1). 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 takes into consideration dynamic interactions between quantitative characteristics of available water resources and water use. However, the following models should be reviewed 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 model developed by the Stockholm Environment Institute (www.seib.org/polestar/psbro.html); Water Evaluation and Planning System WEAP developed by the Stockholm Environment Institute and Boston Tellus Institute (www.seib.org/weap/weapbro.html and www.tellus.org); Watery—Global Assessment and Prognosis WATERGAP developed by the University of Kassel (www.usf.unikassel.de); and 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).

The PODIUM model was developed as the analytical framework to structure discussions about future water and food demand issues. It can be used to generate water/food scenarios by country or on the global level. There are two versions of PODIUM, a country scale model and a global scale model. Using the country scale model, planners can analyze water availability and food production scenarios based on the data they enter. The global model presents a spreadsheet that organizes countries into groups, providing a global or regional picture of water scarcity. An appropriate use of PODIUM would be to test different diet scenarios and the required agricultural output, by entering data from international databases (such as FAOstat, World Resources Institute (WRI), IRRI/Huke and United States Department of Agriculture, USDA). PODIUM scenarios can capture the technical, social and economic interactions of a country's water and food security situation. PODIUM can determine the national grain requirements based on assumptions about population, daily calorie intake, composition of diets and import-export volumes. Estimates of requirements include both food and feed grains. Model estimates projected future cereal production (for year 2025) based on the expected yields and cultivated areas, with and without irrigation. Predicted grain production is then converted into irrigation water demand and compared with actual withdrawals in 1995 and the available renewable water resources. Adverse impacts of increased water withdrawals on the groundwater balance are assessed against projected domestic and industrial water demands.

The IMPACT model provides a consistent framework to test the effect of different food policies, different rates of investment in agricultural research in crop productivity growth, and income and population growth on long-term food balances and food security. It is specified as a set of country-level supply and demand equations. Each country scale model is linked to the rest of the world through trade. In order to explore food security effects, the number of malnourished pre-school children in developing countries is projected as a function of per capita calorie availability, social expenditures, female education, and access to clean water. It is currently being extended to include the effects of water availability on food supply and demand. The primary objectives of this effort are (i) to develop an understanding on a global basis of the relationship between water scarcity, food production, and food security; (ii) to develop projections of water supply and demand, including water demand for the household and industrial sectors, and the implications of intersectoral competition for water on the availability of water for food; (iii) to analyze alternative futures for food production and demand and food security taking into account water availability for crops and livestock production; and (iv) based on this analysis, to assess the impact of alternative scenarios for water availability on food supply, demand and trade and food security and water demand, taking into account policy reforms and investments in water and irrigation management and development.

The POLESTAR model is a comprehensive and flexible software tool for sustainability studies. The software is both a scenario-building tool and, through its global scenarios dataset provides, a comprehensive database of current global indicators covering social, economic and environmental issues.

The POLESTAR model is applicable at national, regional and global scales. The user can customize data structures, time horizons, and spatial boundaries, all of which can be expanded or altered easily in the course of an analysis. The system accepts information generated from formal models, from existing studies, or other sources. An application begins with the 'Current Accounts', a snapshot of the current state of affairs. Scenarios are then developed to explore alternative futures. A scenario is a set of future economic, resource and environmental accounts, based on assumptions and models developed by the user. Finally, environmental and resource pressures are computed and evaluated in comparison to user-defined sustainability criteria.

Current Accounts and scenarios are developed through a series of modules. The three modules (Pop, GDP and Income) contain the major economic, demographic and social variables that, in part, drive the scenario. More detailed data and scenario assumptions are introduced in the other modules describing Society (Households, Transport, Services, Industry, Agriculture and Energy Conversion). Environmental Pressures are accounted for in the Resource modules (Energy Resources, Minerals, Land and Water Resources) and in the Pollution modules (Air, Water, Toxics and Solid Waste). The data in modules may be disaggregated by region, by subsector (e.g. household type, industrial category, transportation mode, crop) and further by process (e.g. household end-use devices, manufacturing process, vehicle type, farming practice). The number and types of regions, subsectors and processes are set by the user in order to match the aims of the analysis and data availability.

WEAP is a PC-based water planning tool that provides a comprehensive, flexible and user-friendly framework for water resource assessment. WEAP is distinguished by its integrated approach to simulating water systems and by its policy orientation. WEAP treats the demand side of the equation: water use patterns, equipment efficiencies, re-use, prices and allocation equally as the supply side: streamflow, groundwater, reservoirs and water transfers. As a database, WEAP provides a system for maintaining water demand and supply information. As a forecasting tool, WEAP simulates water demand, supply, flow, storage, and pollution generation, treatment and discharge. As a policy analysis tool, WEAP evaluates a full range of water development and management options.

Operating on the basic principle of water balance accounting, WEAP is applicable to municipal and agricultural systems, single subbasins or complex river systems. Moreover, WEAP can address an immense range of issues, e.g. sectoral demand analyses, water conservation, water rights and allocation priorities, streamflow simulations, reservoir operations, hydropower generation, pollution loading and project cost-benefit analyses.

WEAP applications generally include several steps. The study definition sets up the time frame, spatial boundary, system components and configuration of the problem. The current accounts provide a snapshot of actual water demand, pollution loads, resources and supplies for the system. Alternative sets of future assumptions are based on policies, costs and factors that affect demand, pollution, supply and hydrology. The base case projection serves as a reference. Scenarios are constructed consisting of alternative sets of assumptions or policies. Finally, the scenarios are evaluated with regard to water sufficiency, costs and benefits, compatibility with environmental targets, and sensitivity to uncertainty in key variables.

The WATERGAP model was developed to provide a scientific-based overview of global water resources from a long-term perspective. It belongs to a class of integrated models. It consists of two main components: a water use model; and a water availability (or hydrology) model. Water use and water availability are computed for 4000 river basins covering most of the world.

The water availability model calculates the detailed daily soil water balance taking into account physical characteristics of watersheds (such as soil, vegetation, slope and aquifer type). It is divided into three sectors: agriculture; domestic; and industrial. Two main integrative concepts are used for simplifying modeling of water use: structural change and technological change. Structural change concepts assumes that the per unit water use changes with the development of economies and lifestyles. Meaning, per unit water use is related to family income (GDP/cap). Technological change is used to introduce the improvements in the efficiency of water use.

Not one of the above-mentioned models is 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. Therefore, the utility of these models for understanding the impact of water on world development at the global scale is quite limited.

Global modeling has, however, received attention of many researchers (Meadows *et al.*, 1982) culminating with the work of 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 (Elichirigoity, 1999). Two books, *World Dynamics* (Forrester, 1971, 1973) and *Limits to Growth* (Meadows *et al*., 1972) drew much attention to the global system dynamics modeling of the planet. They reported the results of a study of the future under the present growth conditions. Simulations of the future were performed using the system dynamics model named World3. The response to this seminal work was bipolar. Support came from environmentalists, engineers, scientists and senior executives. The strongest criticism came from economists (LaRouche, Jr, 1983). Although there is a basis for criticisms, the central issue raised by these works was not dismissed. The main conclusion reached was that if the present growth trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within next one hundred years. In a follow up study Meadows *et al*. (1992) the authors showed that the world development has already surpassed some of its limits. The World3, system dynamics model is unique tool that can be used to see far into the 21st century. By varying the basic global policy assumptions a range of outcomes is possible, from collapse to sustainability.

Global world modeling devoted very little attention to water resources. The main argument is that the water is a regional, not a global, resource (Meadows *et al*., 1992). 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). In the simple accounting of most global modelers (Meadows *et al*., 1992, pp. 54–57), the renewable flow from which all freshwater inputs to the human economy are taken is estimated to be 40 000 km^3/year. When the amount of water flowing to the sea is deducted (28 000 km^3/year) and seasonal characteristics of the runoff taken into consideration (5000 km^3/year) human population is left with approximately 7000 km^3/year of accessible stable runoff. This figure is compared with the approximate total water use of 3500 km^3/year leading to the conclusion that we do not have a problem on the global scale. As it will be shown later in this paper this accounting is subject to some major flaws. Also, global world modelers assume that there are ways to increase the water limit by using technical measures (storage facilities and desalination) as well as some non-technical solutions like bringing people closer to the water or water closer to the people. Many of these concepts are infeasible today. Dams are receiving a serious opposition (Takeuchi *et al*., 1998); desalination is still very costly and unaffordable for the most of the world (Gleick, 2000); and the other two options for relocating population or providing long distance transfer (export) of water are rich with social problems (de Villiers, 1999).

One effort in the field of global world modeling deserves special attention. The TARGETS model is the only global modeling tool that takes water into consideration. It is constructed as a set of metamodels which 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 (Rotmans and deVries, 1997). 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 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 modeled 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 actual water supplies are calculated as is the impact of sea-level rise on the world's coast lines. A response module enables the user to model human response to negative impacts in the form of water policy measures comprising financial, legislative and managerial measures.

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 not. More detailed discussion of shortcomings of the TARGETS model related to the simplification of economic system is provided in Rotmans and de Vries (1997).

In this paper an attempt was made to model future world development taking into consideration water resources limitations. A system dynamics approach is used in this work. The two main objectives of this research are: (a) to demonstrate the importance of strong feedback links between water availability and the future development of human economy; and (b) to identify the most important water issues on the global scale.

The following section of the paper presents the *WorldWater* model. Then, the results of the model simulations are discussed in detail. I close with a set of conclusions and recommendations for future research.

New approach to world water balance modeling

The traditional approach to modeling water balance during the latter part of the 20th century used projections of population growth, unit water demand, agricultural production, industry growth, amongst others (Gleick, 2000). These projections are then used to estimate future water demand and water balance. Gleick demonstrates that future water projections are variants of current trends and as such are subject to considerable uncertainty (Figure 1). The use of different periods for making predictions results in a high variability in the value of predicted variable. The dynamic character of main variables and how they affect water use in the future is not captured through the traditional approach. Although not a novel approach, system dynamics offers a new way of modeling the future dynamics of complex systems. This approach is used in modeling world development (Forrester, 1971, 1973; Meadows *et al.*, 1974) but was never tested in addressing the global issues of future water availability, use and balance. Although some work has been conducted on the regional level (Simonovic *et al.*, 1997; Simonovic and Fahmy, 1999).

System dynamics modeling approach

System dynamics is a theory of system structure and a set of tools for representing complex systems and analyzing their dynamic behavior (Forrester, 1961). Perhaps the most important feature of system dynamics is to elucidate the endogenous structure of the system under study, to see how the different elements of the system actually relate to one another, and to experiment with changing relations within the system when different decisions are included. In system dynamics, the relation between structure and behavior is based on the concept of information feedback and control. According to this theory time delays, amplifications and structural relationships between a system's elements could be more important in determining aggregate system behavior than the individual components themselves. A system dynamics study is less useful in predicting exact future system states than in indicating how alternative choices would alter the tendency to move toward each of those conditions.

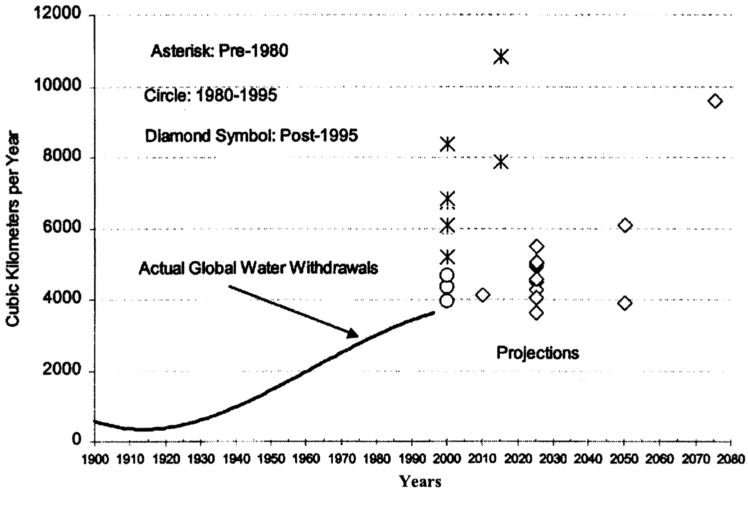


Figure 1. Water scenarios: projected and actual global water withdrawals, from (Gleick, 2000).

This issue will be addressed in more detail later. System dynamics has been applied to issues ranging from corporate strategy to the dynamics of diabetes, from the cold war arms race to the interaction between HIV and the human immune system. System dynamics can be applied to any dynamic system, at any temporal and spatial scale (Sterman, 2000).

In any modeling effort, it is a good idea to remind ourselves that we are not dealing with the 'real world' but a representation of the world that is realistic in some respects and unrealistic in others. There is a common tendency by the users of models like one discussed in this paper to consider them as a 'truth machines' (Rotmans and deVries, 1997) rather than as tools for raising and understanding important issues. This easily leads to vigorous but rather pointless debates (Meadows *et al.*, 1992).

Meanings of exact numbers of model predictions are quite different in the context of global modeling. Every prediction needs to be evaluated with care taking into consideration all model assumptions and specific characteristics of the scenario under consideration. According to the 'father of system dynamics', J. W. Forrester, understanding patterns of behavior is much more important than obtaining exact prediction of a variable value in one point of time.

World3 model

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. World3 is a system dynamics model of world scope (Forrester, 1971, 1973; Meadows *et al.*, 1974, 1992). It comprises of five main sectors: population, agriculture (food production, land fertility, and land development and loss); non renewable resources; economy (industrial output, services output, and jobs); and persistent pollution. The original World3 model was created in the DYNAMO simulation language (Pugh II, 1976) and later converted into STELLA (High Performance Systems, 1994). It is developed for research purposes and lacks friendly user interface. Sufficient documentation of the data and their sources are incorporated in the model.

The time horizon of the World3 model is 200 years starting from 1900. The period from 1900 to 2000 is used for calibration of model relationships and verification of model performance. The authors of the model indicated that many other sectors (like fresh water, forest, fish etc.) could be added to make the model more complete. However, they are omitted from the World3, since their dynamic similarity to food indicates that their inclusion would not produce any behavior modes not already contained within the agricultural sector (Meadows *et al.*, 1974, p. 10).

World3 is a model that attempts to represent the continuous dynamic interaction between the human population and the global resource base. The model contains numerous feedback relations representing demographic and techno-economic means of achieving a balance between the population size and the supply of resources. Two basic characteristics of human populations that are captured by the model are a tendency toward exponential growth, and a long delay in the population's adaptive response to changing external conditions. The major factors affecting population growth that are included in the model are: births, deaths, fertility, life expectancy, industrial output, pollution, food, health, service output and crowding among others.

The main assumption of the agricultural sector of World3 is that the total amount of food that can be produced on earth each year has some limit. Physical resources that can be allocated to food production are limited. In World3 the available agricultural land is limited, the amount of fertilizer is limited by the total industrial production capacity, and the land fertility is limited by pollution absorption mechanisms. The major factors incorporated in this sector include: arable land, land yield, land erosion, land fertility, food per capita, agricultural investment and land development among others.

In World3 nonrenewable resources are assumed to be finite and defined as mineral or fossil fuel commodities that are essential to industrial production and are regenerated on a time scale longer than the 200-year time horizon of the model. Unknown resources and proven reserves are aggregated into one level that decreases over time as resources are utilized by the industrial sector. Pollution generation is modeled as a function of resource use. The main factors in this sector of the model are: nonrenewable resources, their usage rate, per capita resource usage and fraction of capital allocated to obtaining resources among others.

The main objective of the capital sector of the model is to relate the basic components that would demonstrate long-term patterns in the population's access to material goods, services and food. This sector is based on the gross national product (GNP) as a measure of historical global productivity. However, industrial output is used in the model instead of GNP. Three categories of capital (service, agricultural, industrial) and four categories of output (service output, agricultural output, production of nonrenewable resources and industrial output) are included in World3. Two uses of the model output are defined, consumption and investment. The main factors in this sector of the model are: three named categories of capital, investment rates, four named outputs, fractions allocated to consumption and fractions allocated to investment among others.

Among a broad spectrum of 23 environmental problems associated with demographic and material growth, World3 models a group of material pollutants of potential importance to the world system over the next 100 years. Persistent pollutants in World3 are materials that cause damage to some form of life, are released through many different forms of industrial and agricultural activity, and are sufficiently long lived that they may be transported through the global environment. These persistent material pollutants include industrial and agricultural chemicals, radioactive isotopes, and heavy metals. These are generated at increasing rates, accumulate in the global environment, and there is a delay between their release and the time their full effects on the ecosystem finally appear. The main factors in this sector of the model are: pollution generation, appearance and assimilation rates, fraction of resources that are persistent materials, industrial and agricultural materials toxicity index among others.

In the last version of World3, referred to as World3/91, a concept of adaptive technology is implemented. In the adaptive approach there is a system goal and when the actual system state deviates from the goal in negative direction, capital is allocated to new technologies (Meadows *et al*., 1992).

WorldWater *model*

World3 model is used as the basis for the development of *WorldWater* model. 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 graphical presentation of causal relationships between the water and other model sectors is shown in Figure 2. The total water stock in the model includes the precipitation, ocean resources and nonrenewable groundwater resources. The model is also taking into account water recycling as a portion of water use (not visible directly in the Figure 2). The water use side is modeled in a traditional way to include: municipal water use for the needs of population, industrial, and agricultural water needs. However, the most important difference between the *WorldWater* and other global water models is in its ability to address the needs of freshwater resources for transport and dilution of polluted water.

Most of the future water balance assessments based on the other models are optimistic due to the fact that they were obtained with no account of qualitative depletion of water resources consisting in ever increasing pollution of natural water. This problem is very acute in industrially developed and densely populated regions of the Earth where no efficient wastewater purification takes place (Lundquist, 1998). For example in the IHP (2000) following estimates are provided: '... By assessments made, in 1995 waste water volume was 326 km^3/year in Europe, 431 km^3/year in North America, 590 km^3/year in Asia, and 55 km^3/year in Africa. Many countries practice discharging a greater part of wastewater containing harmful substances directly into the hydrographic network. No preliminary purification is carried out. Thus water resources are polluted and their subsequent use becomes unsuitable, especially for water supply to the population. It is estimated that every cubic meter of contaminated wastewater discharged into water bodies and streams make unsuitable 8–10 cubic meters of pure water (IHP, 2000). This means that the most regions and countries of the world already at present are facing the threat of catastrophic qualitative depletion of water resources ... '

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. The total stock of renewable water resources of the world is estimated at 42 650 km^3/year (Gleick, 1993; Shiklomanov, 1997, 2000) and then reduced by 67% to account for variability of surface runoff. When the water demand exceeds the available renewable surface

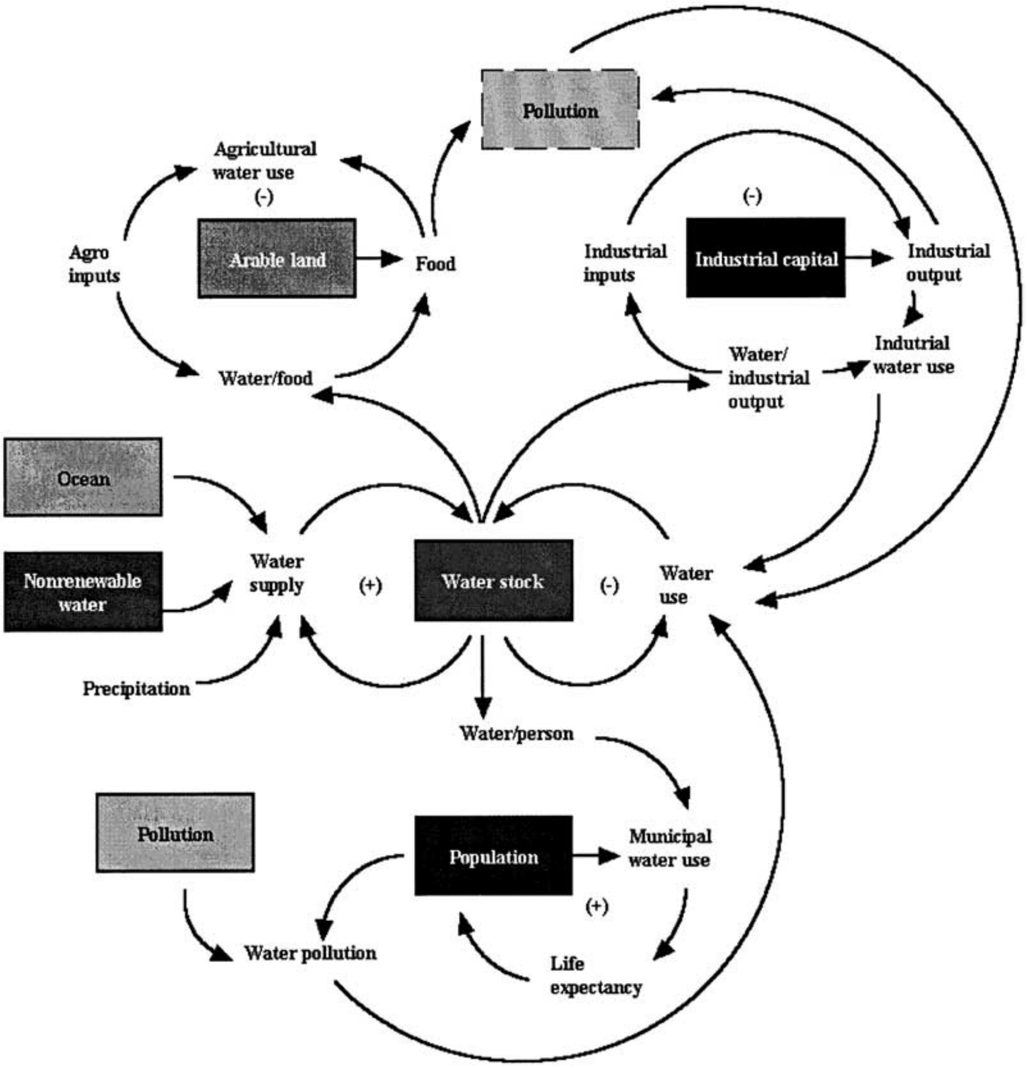


Figure 2. *WorldWater* model causal diagram.

water resources an additional 8·4 km^3/year can be taken from non-renewable groundwater resources. After the demand exceeds the available surface and groundwater resources, water reuse is considered. From all the water used, 55% is being returned into the environment and available for reuse after treatment. A conservative estimate of 20% reuse is used in the model. It is important to note that some countries of the world, such as Israel, are already at the level of 65–80% reuse. 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, 2000). This process is technologically mature, but energy intensive and expensive. Total global desalinating capacity of the world is currently 4·82 km^3/year. More than 60% of all capacity is in the oil-rich Middle Eastern countries. The economic attractiveness of desalination is directly tied to the cost of energy. Production of one liter of desalinated water requires 2·8 kJ of energy. Despite the high current cost ($1 to $8 per m^3) some estimates are available that indicate the cost could be reduced to $0·55 per m^3 without the consideration of serious pollution being caused by desalination processes. In the *WorldWater* testing, initial runs are made using existing desalination capacity and then this limit is removed assuming that unlimited seawater will be available for desalination. Therefore, the water quantity limits are replaced with their economic surrogate—capital needs for water production.

Full integration of water quantity and quality sectors with World3 is established through the development of following set of relationships (italics—variable in *WorldWater*; bold—variable in World3):

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

Historical data (food production, health sector, industrial production and manufacturing, demographic, etc.) and numerous runs of World3 were used in the development of these relationships. It is important to note that most of the relationships should be strengthened through the enhancement of newly available databases.

Data

WorldWater model is data intensive. Most of the data effort was focused on the water quantity and quality sectors and the relationships used to link these two sectors with the rest of the World3 model. The data required for the five sectors of original World3 were used as provided from the authors of the model for 12 different scenarios described in Meadows *et al.* (1992). Historical data on water availability and use are taken from Shiklomanov (1997, 2000), Gleick (1998, 2000) and IHP (2000). A summary of the basic data is given in Table 1. In addition, the model is provided with the estimates described in the previous section.

Using the input from population sector the model performs a calculation of domestic water needs. Quantification of water use in *WorldWater* is based on water demand for public and domestic needs, industrial production, and agriculture (irrigation). Water losses from large reservoirs were also taken into account. All the future projections have been made ignoring potential anthropogenic global climate change, i.e. they are for a stationary climatic situation. In the future model revisions issues related to climate change will be addressed. The volume of public water use depends on the size of urban population and the services and utilities provided, as well as climate conditions. In many large cities, present water withdrawal amounts to 300–600 l/day per person. By the end of this year, the specific per capita urban withdrawal is expected to increase to 500–1000 l/day per person (Cosgrove and Rijbersman, 2000). On the other hand, in developing, more agricultural countries public water withdrawal is a mere 50–100 l/day. In certain individual regions with insufficient water resources, it is no more that 10–40 l/day of water per person. *WorldWater* is using three municipal water demand scenarios: (a) optimistic—assuming growth, between now and the year 2100, in

Table 1. Assessment of water use in the world by sector of economic activity (km^3/year), (IHP, 2000)

Sector	Assessment year							
	1900	1940	1950	1960	1970	I980	1990	1995
Population (million)			2542	3029	3603	4410	5285	5735
Irrigated land area (million ha)	47·3	75·9	101	142	169	198	243	253
Agricultural use	513	895	1080	1481	1743	2112	2425	2504
	321	586	722	1005	1186	1445	1691	1753
Industrial use	21·5	58·9	86·7	118	160	219	305	344
	4·61	12·5	16·7	20·6	28·5	38·3	45·0	49·8
Municipal use	43·7	127	204	339	547	713	735	752
	4·81	11·9	19·1	30·6	51·0	70·9	78·8	82·6
Reservoirs	0·30	7·00	11·1	30·2	76·1	131	167	188
Total (rounded)	579	1088	1382	1968	2526	3175	3633	3788
	331	617	768	1086	1341	1686	1982	2074

Remarks: First line—water withdrawal, second—water consumption.

municipal water withdrawal up to the level of today's maximum water supply in developing world of 2000 l/day; (b) status quo—maintaining the level of today's water supply in developing world of 1000 l/day until the end of simulation period (year 2100); and (c) realistic—making redistribution of municipal water withdrawal between the developed and the developing world that will end with overall municipal water withdrawal of 700 l/day in the year 2100. Nonlinear relationships over time are developed using the available data between 1900 and today.

Relationship between life expectancy and domestic water supply is modeled using, so called, life expectance multiplier. It is represented as an exponential function indicating that life expectancy is equal to zero if there is no water available and reaching maximum of one for maximum supply. Since the qualitative data to support this relationship is not available, extensive sensitivity of model results is performed to evaluate the impacts of changing the shape of this relationship.

Distribution of population, between urban and rural, is taken from the United Nations Population Fund (UNFPA) (1997). This data is then correlated with the industrial output (generated by the industrial sector of the model), which is taken as a measure of life standard. *WorldWater* model simulations are based on the use of this dynamic relation.

The population sector of the model is linked to water quality sector through the set of relationships ending in the life expectancy—water quality function. Historic data on the rural and urban populations not served with water supply and sanitation services are used to develop this relationship. Available data on the mortality due to the water-related diseases were not used. At the current level of model detail it was impossible to extract more general relationships from the available mortality data.

Water in industry is used for cooling, transportation and washing, as a solvent, and also sometimes entering the composition of the finished product. Thermal and nuclear power generation lead the list of major users. Analysis of the available data on the industrial water use demonstrated a very strong correlation with the industrial output and industrial capital. Therefore in the *WorldWater* model, industrial water use has been expressed as the function of industrial capital.

Development of surface water infrastructure (diversion projects, storage projects), groundwater development and recharge, recycling and desalination require major capital investment. The cost of water supply is taken from Gleick (1993) and expressed in 1980 dollars. Valid cost estimations and comparisons among different types of technologies are extremely difficult to make, given the differences in capital costs, repayment periods, operation and maintenance requirements, and non-economic externalities. The data used in the model are average values for typical facilities built today. Two costs are available within a very wide range: desalination cost \$0·55 to \$8 per m^3; and recycling \$0·07 to \$1·8 per m^3. A sensitivity analysis of model output was performed to evaluate the impact of different costs.

Land irrigation has been practiced for millennia in order to maximize food production for humanity. At present, about 15% of all cultivated lands are being irrigated. Food production from irrigated areas amounts to almost half the total crop production in terms of value. Agriculture accounts for more than 70% of the total water consumption in Europe and in North America. In Asia, Africa, and South America agriculture, irrigation in particular, is the major component of water withdrawal (65–82% of the total water withdrawal in 1990). The specific water use for irrigation varies considerably around the world: 7000–11 000 m^3/ha in the eastern Europe; 8000–10 000 m^3/ha in the USA; 20 000–25 000 m^3/ha in Africa; and 5000–17 000 m^3/ha in Asia, South and Central America. In the future these values will change considerably depending on advancements in irrigation systems, and improvements in watering requirements, regimes, and techniques. The total irrigation water use data from 1900 to 1995 used in the *WorldWater* model are from Postel (1999), Gleick (1993) and Shiklomanov (1997, 2000). Two, different irrigation scenarios are considered for the future: (a) continuation of current trend—slow reduction in irrigation water demand to reach an average 9000/m^3/ha by the year 2100; and (b) major irrigation efficiency scenario—which will dramatically reduce irrigation water demand to 650 m^3/ha by the year 2100. These nonlinear relationships are combined with the increase in irrigated land, which is estimated by Postel (1999) to be considerably below the level of increase we have witnessed in the past (3% per year between 1970 and 1982; 1·3% between 1982 and 1994). Using the data from FAO summarized by Postel (1999) the increase in agricultural land has been estimated to be 0·6% per year for the period 2000–2025; 0·4% for 2025–2050; and 0·3% for 2050–2100. These data are used to define the relationship between available arable and irrigated land. Data from 1900 to 1995 are used for relationship calibration, from 1995 to 2000 for relationship verification and three future scenarios are included in the model: (a) no change (ending with 15% of arable land being irrigated in the year 2100); (b) optimistic (ending with 20% of arable land being irrigated in the year 2100); and (c) pessimistic (ending with 13·8% of arable land being irrigated in the year 2100).

The *WorldWater* model contains an additional relationship to capture the feedback effect of water availability for agriculture on the land yield. This relationship is represented as an exponential function that starts with zero land yield (for no water supply) and ends with the maximum value of one (for maximum water supply). The qualitative data is not available to describe this relationship. Extensive sensitivity analyses of model output were conducted to evaluate the impacts of different shape of this relationship.

The development of large surface reservoirs leads to major transformation in the temporal and spatial distribution of river runoff and an increase in water resources during low flow limiting periods and dry years. At the present time, the total volume of the world's reservoirs is about 6000 km^3 and their total surface area is up to 500 000 km^2. Evaporation losses from existing reservoirs are considerable for the global world water balance. Data from Shiklomanov (1997, 2000) are used in the *WorldWater* model. Future reservoir development is thought to be limited as most of the best sites are already used, and considerable opposition to future development of reservoirs is being expressed in the developed countries (Takeuchi *et al*., 1998). Extension of the data for the next 100 years is performed according to the classical s-shaped growth curve ending at reservoir losses of just above 300 km^3/year in the year 2100.

WorldWater differs from most of the available models in the consideration of water pollution. IHP (2000) estimates for 1995 are used to calibrate the relationship between clean water needs to dilute the wastewater being discharged directly into the hydrographic network. A conservative estimate totaling 700 km^3/year of wastewater discharge in 1995 (representing only 50% of the total 1995 estimate in IHP (2000)) is used in the *WorldWater*. This value is then related to the pollution index from the persistent pollution sector to help us develop a predictive relationship between pollution index and amount of generated wastewater. Fixed need of clean water for dilution of waste, in the ratio of 9 : 1, is then applied in the simulations.

Calibration and verification of the *WorldWater* model with data available for the period between 1900 and now provides confidence in the results of the model and the data being used. Calibration is performed using the period between 1900 and 1995. Data for standard run of World3 is used for calibration. The standard run of World3 is based on the 'limits to growth' and assumes that the world society proceeds along its historical path as long as possible without major policy change. Since only the period between 1900 and 1995 was of our interest the standard run assumptions were judged acceptable. Period between 1995 and 2000 is used for the verification of the model and its main relationships. Data for calibration and verification required by water sectors of *WorldWater* are used from IHP (2000), Cosgrove and Rijbersman (2000) and UNFPA (1997). Simulations of future states of the world, for the period from 2000 to 2100, are performed according to different scenarios that are described in the following section.

World water dynamics

In the simulated environment of World3 and *WorldWater* models, the inherent assumption is one of continuous economic growth. Population in both models 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 2) in *WorldWater* contain many delays, and the physical processes have considerable momentum. The most common mode of behavior, as pointed out by Meadows *et al.* (1992) is overshoot and collapse. In *Beyond the Limits*, Meadows *et al.* (1992) investigated a broad range of twelve scenarios. By varying the basic global policy assumptions they show a range of outcomes, from collapse to sustainability. They are used with *WorldWater* too. However, the presentation of results in this article will be limited to three of the twelve scenarios: (a) standard run; (b) double run; and (c) stable run.

Importance of water for the future of the world

(a) The standard run is taken from *Limits to Growth* (Meadows *et al*., 1972) and assumes that the world society proceeds along its historical path as long as possible without major policy change. Population and industry output grow until a combination of environmental and natural resource constraints eliminate the capacity of the capital sector to sustain investment. As it falls, food and health services

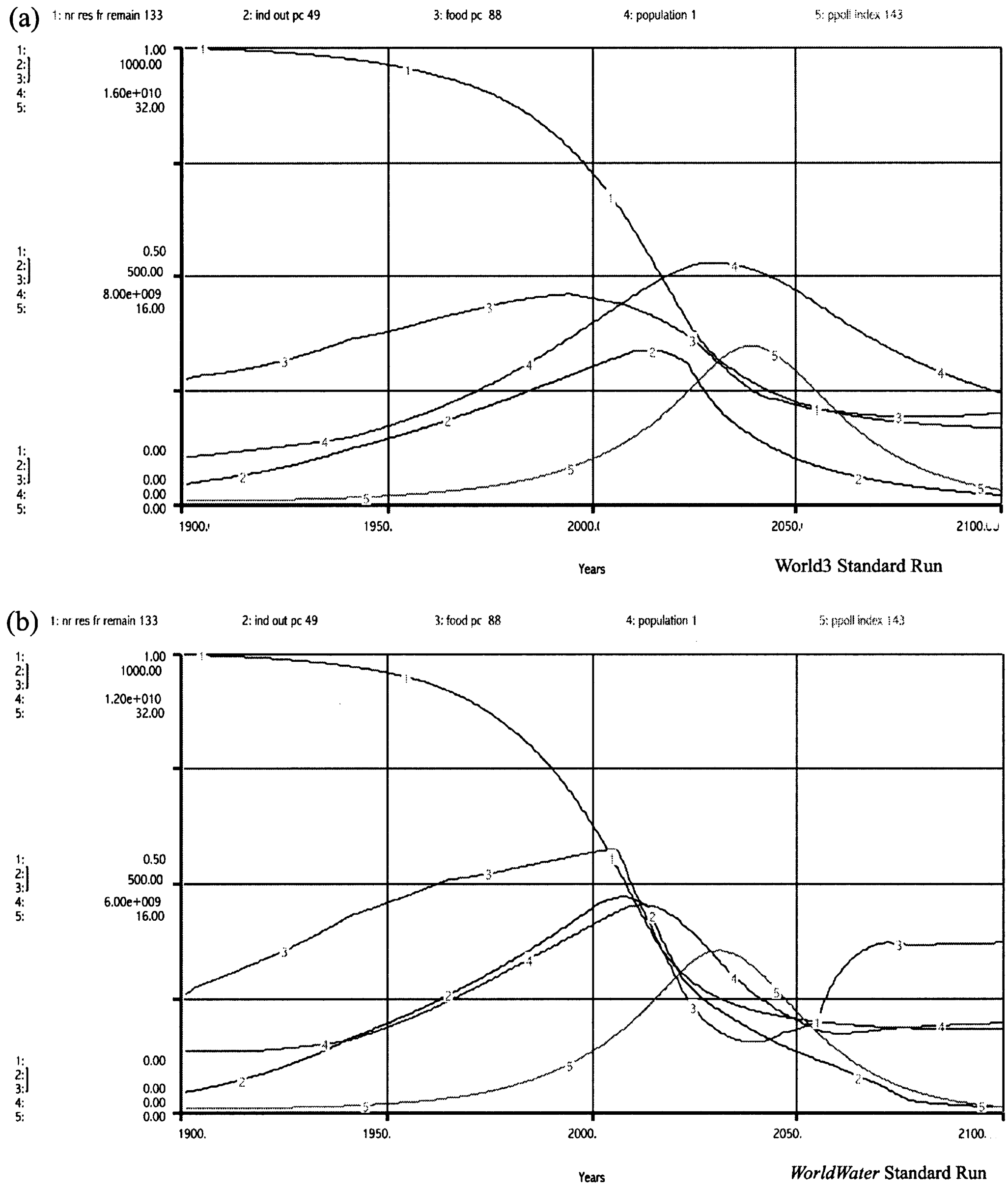


Figure 3. State of the world—'Standard run' results of World3 (a) and *WorldWater* (b) models.

also fall, decreasing life expectancy and raising the death rate.

The global population in this simulation (line 4 in Figure 3a) rises from 1·6 billion in the simulated year 1900 to over 6 billion in the year 2000. Total industrial output expands by factor 20 between 1900 and 2000 (line 2 in Figure 3a). Between 1900 and 2000 only 27% of the earth's stock of nonrenewable resources is used (line 1 in Figure 3a). Pollution in the year 2000 is starting to show significant rise (line 5 in Figure 3a). Food production is increasing and major changes are starting to show in the late 1990s (line 3 in Figure 3a). In this scenario the growth of the economy stops and reverses due to a combination of limits. As we can see after the year 2000 pollution rises rapidly and begins to seriously affect the fertility of the land. Total food production continues to decline after 2000. This causes the economy to shift more investment into the agriculture sector to maintain the output. During the first simulated 20 years of the 21st century, increasing population and industrial output use much more nonrenewable resources than in the past. Therefore a shift in capital investment is required to support this development. As both, food and nonrenewable resources become harder to obtain in this simulated world, capital is diverted to producing more of them.

WorldWater simulation of this scenario (Figure 3b) shows quite a different picture. Water is demonstrated to be the main limitation to future growth. With the rise in pollution and demand for clean water after 2010 shortages are starting to occur in the food production (line 3 in Figure 3b). Capital resources are being drained and industry is starting to collapse (line 2 in Figure 3b). Total population is also affected by water and food shortages, decreasing at a faster rate then in the simulated scenario in Figure 3a.

(b) The double run is a scenario in which the simulated world is developing powerful technologies for pollution abatement, land yield enhancement, land protection, and conservation of nonrenewable resources. All these technologies are assumed to require capital investment and to take 20 years to be fully implemented. Figure 4a shows that their implementation allows growth to continue longer into the future.

Population is on the rise (line 4 in Figure 4a) reaching about 11 billion by 2100. Food production remains adequate but not abundant after 2040 (line 3 in Figure 4a). Pollution remains quite low (line 4 in Figure 4a). Nonrenewable resources do not become scarce despite their constant decrease (line 1 in Figure 4a). Industry stagnates

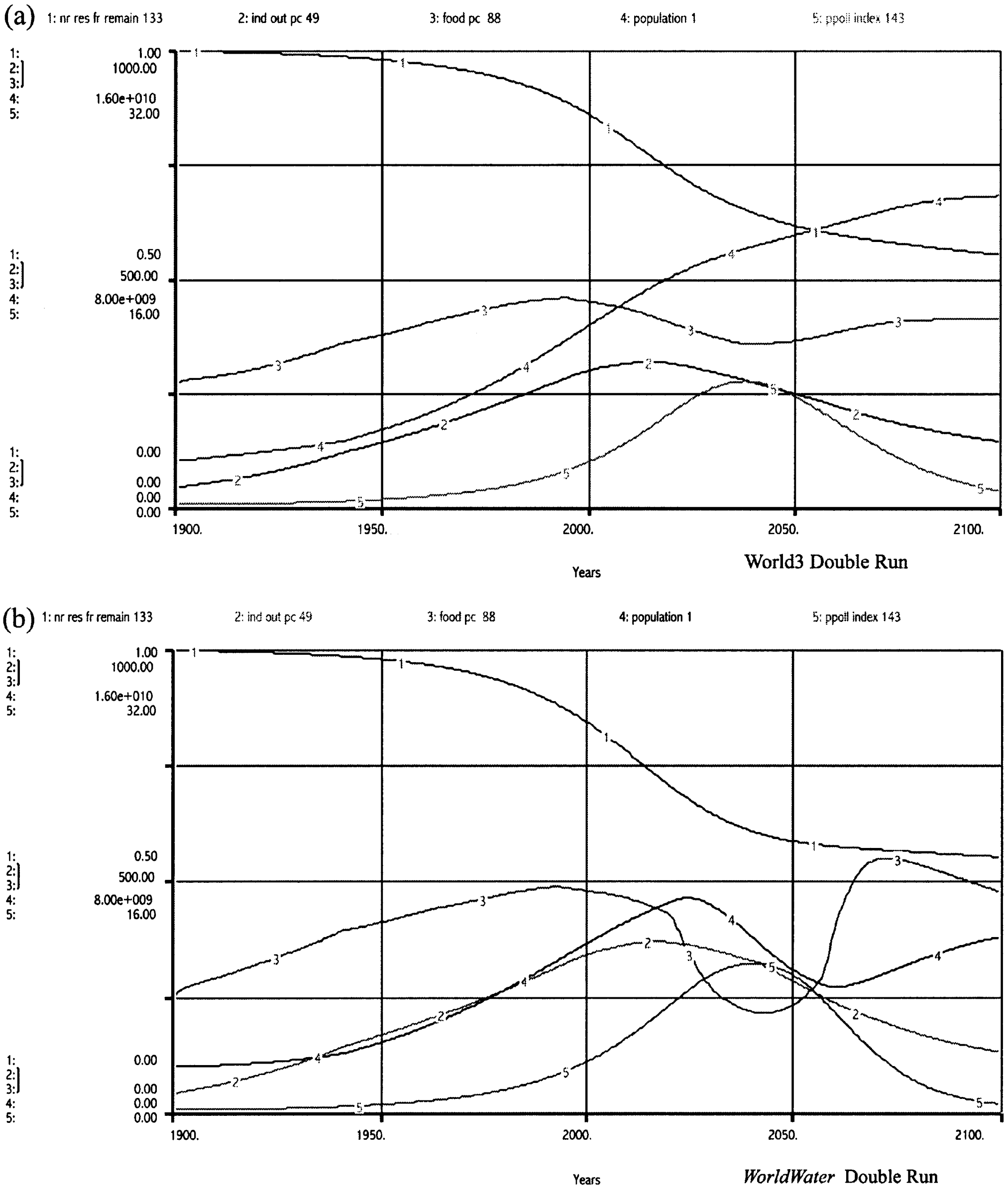
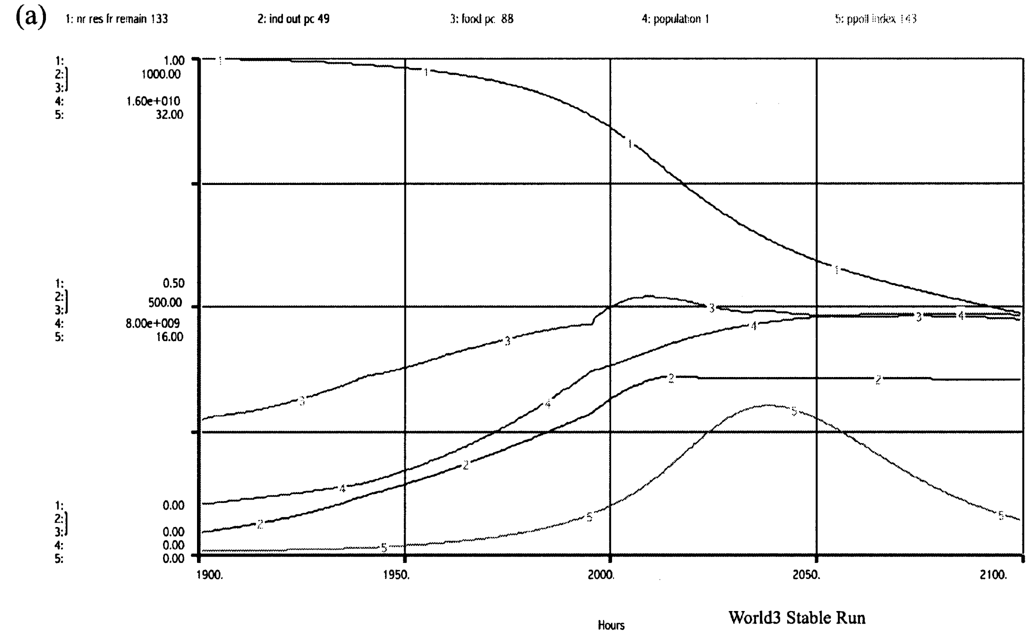


Figure 4. State of the world—'Double run' results of World3 (a) and *WorldWater* (b) models.

and starts to decline after 2020 (line 2 in Figure 4a).

WorldWater simulation shows a different future. Due to the major impact of the increasing demand for water and heavy pollution load, food production is experiencing a major collapse in 2040 (line 3 in Figure 4b) causing the total population decline that starts in 2025 and culminates in 2060. With the water demand and pollution decline, more water becomes available for food production and recovery of the population growth with total population reaching 7 billion by 2100 (line 4 in Figure 4b). However, capital resources are taken from industry and its decline continues at the slower rate (line 2 in Figure 4b).

(c) The stable run is taken from *Beyond the Limits* (Meadows *et al.*, 1992) as an illustration of possible path towards a sustainable world. In this scenario population and industrial growth are moderated and technologies are developed to conserve resources,



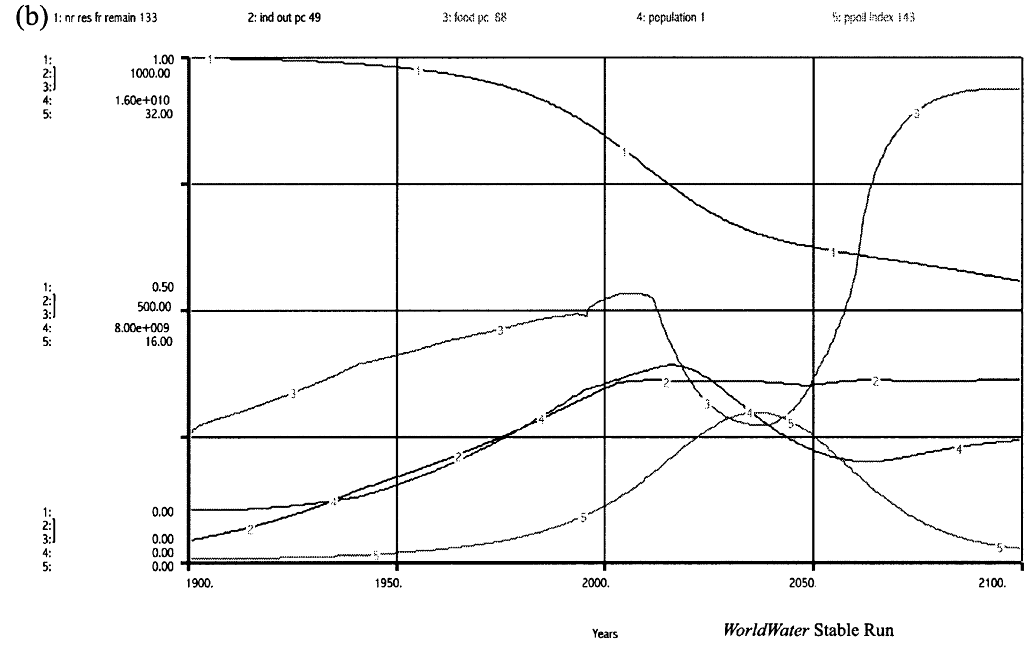


Figure 5. State of the world—'Stable run' results of World3 (a) and *WorldWater* (b) models.

protect agricultural land, increase land yield, and reduce pollution.

In this scenario population levels off at just under 8 billion by 2060 and lives at desired standard of living for the rest of the time (line 4 in Figure 5a). Pollution peaks and falls before it causes irreversible damage (line 5 in Figure 5a). Nonrenewable resources depletion rate is very slow and about 50% of original resources are still available in the simulated year 2100. The world avoids an uncontrollable collapse, maintains its standard of living, and holds itself nearly in equilibrium.

WorldWater again reveals a different picture (Figure 5b). The link between persistent pollution and wastewater production creates a tremendous demand for clean water around 2040. This is reflected in the major decline in food production (line 3 in Figure 5b) and impact on population growth (line 4 in Figure 5b), which begins to decline in 2020. However, as in the case of the double run this collapse is reversible. With better control of persistent pollution, water pollution is reduced and the demand for clean water for dilution and transport of wastewater declines allowing more water for food production and use by the population. In this scenario equilibrium is not reached within the simulation period.

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 developers of World3 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 (Figures 3b, 4b and 5b).

Water issues on the global scale

WorldWater provides detailed insight into the dynamics of water use over the simulation horizon. Figure 6 shows predicted water use patterns for the set of data from the standard run of World3. Two major observations can be made from this simulation. First, the use of clean water for dilution and transport of wastewater, if not modified, 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 this research 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 resource

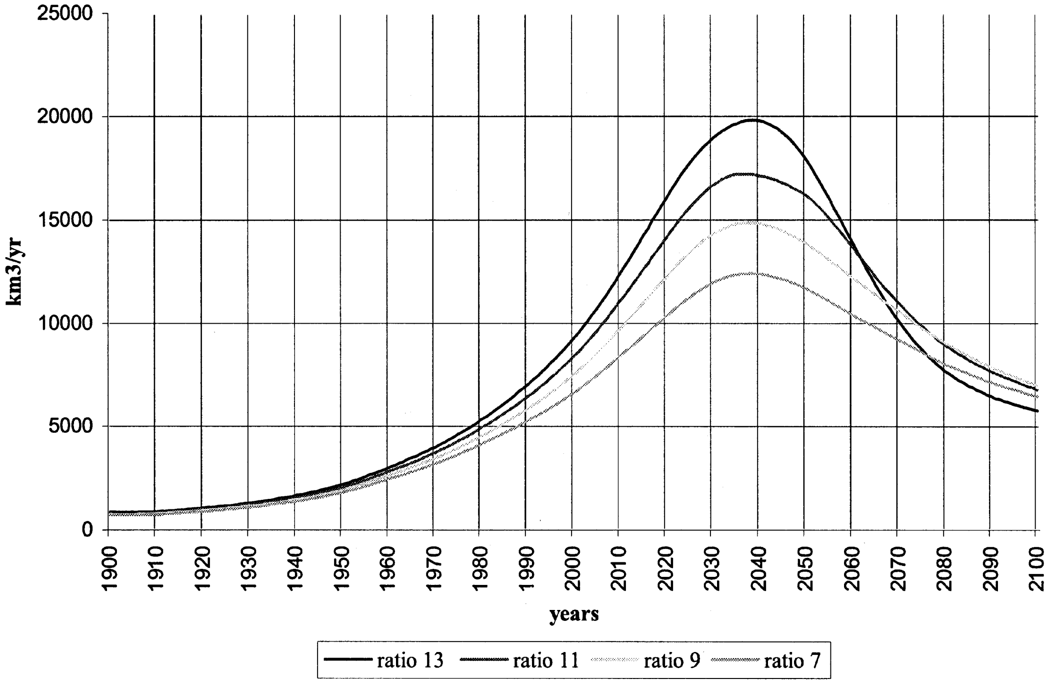


Figure 6. Sensitivity of water use to dilution rate.

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 8). 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 8). Industrial water use shows the very same behavior (line 2 in Figure 8). Reservoir losses rise with the moderate pace following the expected development of water storage around the world (line 4 in Figure 8).

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. Since, this use of water is so important, let me review again data and assumptions made in modeling this water use. IHP (2000) estimates for 1995 wastewater disposal in the environment to be in the amount of 1402 km^3/year. The assumption of the *WorldWater* model is that this waste requires a considerable amount of clean water resources for dilution and transport. Also, an assumption is made that polluted water cannot be used for other purposes. Both of these assumptions can be argued. Firstly, more and more wastewater is being treated before being disposed in the environment (Gleick, 2000). Secondly, industrial and agricultural water needs maybe partially satisfied with polluted water. In the absence of more precise global quantitative estimates of percentage of wastewater being treated and used for other purposes, a conservative estimate totaling 700 km^3/year of wastewater discharge in 1995 (representing only 50% of the total 1995 estimate in IHP (2000)) is used in the *WorldWater*. This value is then related to the pollution index from the persistent pollution sector of the model to help us develop a predictive relationship between persistent pollution and amount of generated wastewater. Fixed need for clean water for dilution of waste, in the ratio of 9 : 1, is then applied in the simulations. IHP (2000) estimates this need to be between 8 and 10 : 1.

Sensitivity analysis conducted with *WorldWater* did not show any significant change in world water dynamics to the change of this ratio. However, the total amount of water used for dilution and transport of wastewater has changed proportionally. Figure 6 presents the total water consumption for wastewater dilution for the range of dilution ratio values from 7 to 13. It can be seen that the maximum amount of water used for dilution varies between 12 500 and just under 20 000 km^3/year. However, this significant difference in the total amount does not change the shape of the diagram in Figure 5b that captures world water dynamics. Sensitivity analysis performed on another important variable—percent of cultivated land being irrigated, shows very similar result. In Figure 7 we

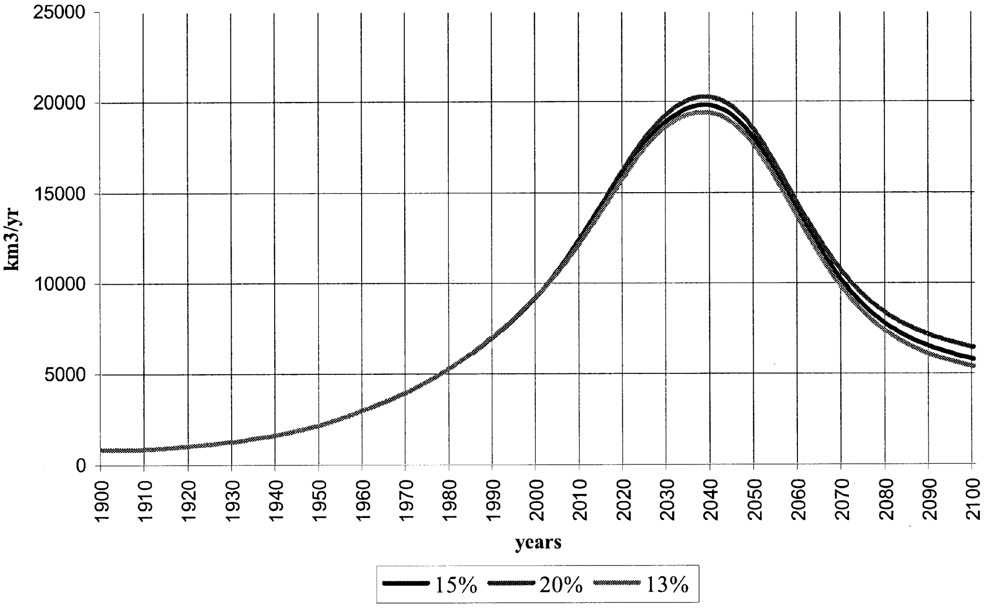


Figure 7. Sensitivity of water use to percent of cultivated land under irrigation.

can observe that the change in total use of water for irrigation does not change significantly with the change in the percent of cultivated land being irrigated. Obviously this change is not affecting world water dynamics significantly. Much more detailed sensitivity analysis can be easily performed on all variables in the *WorldWater*.

Two of the most significant global water studies, IHP (2000) and Cosgrove and Rijbersman (2000) provide static predictions of future water needs for the year 2025. These predictions are shown in Figure 8 and Table 2 together with the predictions of *WorldWater*. Interesting observations can be made from the prediction comparisons. First is that classical predictions are not taking into consideration the needs for dilution and transport of wastewater. Both studies do describe water pollution as one of the main future issues, but needs for dilution and transport are not incorporated explicitly in the future predictions. Second, despite good agreement between estimates of total water use for other purposes than dilution and transport, static predictions of particular water uses vary substantially from the *WorldWater* results. For example, estimated use of water for industrial water supply is according to Shiklomanov (IHP (2000)) going to reach 1170 km^3/year in 2025; 900 km^3/year according to Cosgrove and Rijbersman (2000); and only 520 km^3/year according to *WorldWater*. The main reason for this difference is that *WorldWater* is simulating the future water use of industry considering the dynamic behavior of industrial sector. On the other side, predictions of other models are based on the static future predictions of sector performance for a particular year. As shown in Figure 1 these predictions are demonstrating considerable variance as a function of: (a) factors used in making predictions; and (b) historical period of data used for predicting the future.

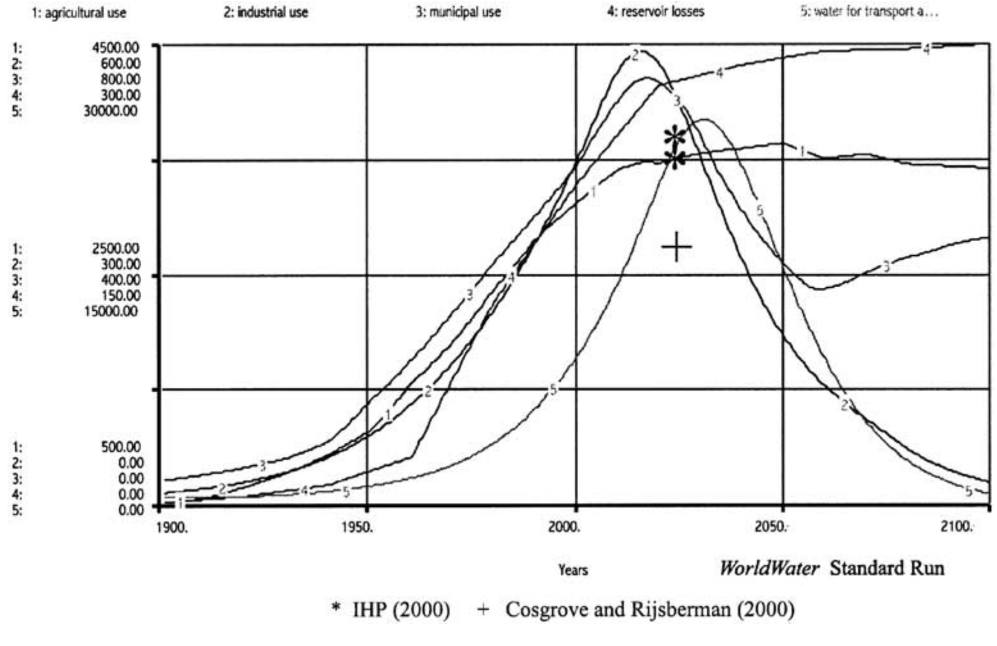


Figure 8. Use of water—'Standard run' results of *WorldWater*.

Table 2. Comparison of standard projections with results of *WorldWater* for year 2025 (km^3/year)

Use	Shiklomanov (2000); IHP (2000)	Cosgrove and Rijbersman (2000)	*WorldWater*
Agriculture	3189	2300	3554
Industry	1170	900	520
Municipal	607	900	723
Resevoir	269	200	276
Total withdrawal	5235	4300	5073

Conclusions

After working with the *WorldWater* model and examining different visions of the future, it is important to remind ourselves that we are not dealing with the 'real world' but a representation of the world. Meanings of exact numbers of model predictions are quite different in the context of global modeling. It is prudent to indicate at this stage that the value of *WorldWater* is not in estimating that the total municipal water supply of the world in 2063 is going to be 'so many' km^3/year but rather in understanding how municipal water supply relates to the population growth, food production and future industrial development. This model provides very valuable insight into the dynamic change in municipal water supply with time, as a function of numerous assumptions used to form a possible world development scenario.

Development of, and numerous simulations with *WorldWater* model documented in this article generated two very important conclusions:

(1) Water is one of the limiting factors that needs to be considered in global modeling of future world development. Attempts made by the World3 in the past to seek scenarios leading to sustainable world future should be carefully reexamined now with the clear understanding that water must be part of the global picture.

(2) Pollution of water is the most important future issue on the global scale. In spite of the rhetoric 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 policy makers.

WorldWater is a powerful tool. However, research presented in this paper is with equal power opening the future directions for model use and improvement. Probably the most important one will be the transformation of *WorldWater* into numerous '*RegionalWater*' models. Solutions for water problems are at the regional level and power of dynamic regional models developed using the same principles that are incorporated in the *WorldWater* can increase our understanding of water problems and our ability to reach sustainable solutions for them.

Acknowledgments

World3 model can be obtained from the Laboratory for Interactive Learning, I.P.S.S.R.—Hood House—UNH, Durham, NH 03824. *WaterWorld* can be obtained upon request from the author. The author is thankful for comments and assistance provided by D. Meadows, P. Gleick and I. Shiklomanov. Support of Natural Sciences and Engineering Council of Canada is gratefully acknowledged. Two anonymous reviews of an earlier version of the manuscript and assistance of C. Allan were useful in improving the paper.

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