Global water dynamics: issues for the 21st century

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Abstract The WorldWater system dynamics model has been developed for modeling the global world water balance and capturing the dynamic character of the main variables affecting water availability and use in the future. Despite not being a novel approach, system dynamics offers a new way of addressing complex systems. WorldWater simulations are clearly demonstrating the strong feedback relation between water availability and different aspects of world development. Results of numerous simulations are contradictory to the assumption made by many global modelers that water is not an issue on the global scale. Two major observations can be made from early simulations: (a) the use of clean water for dilution and transport of wastewater, if not dealt with in other ways, imposes a major stress on the global world water balance; and (b) water use by different sectors is demonstrating quite different dynamics than predicted by classical forecasting tools and other water-models. Inherent linkages between water quantity and quality sectors with food, industry, persistent pollution, technology, and non-renewable resources sectors of the model create shoot and collapse behavior in water use dynamics. This paper discusses a number of different water-related scenarios and their implications on the global water balance. In particular, two extreme scenarios (business as usual – named “Chaos”, and unlimited desalination – named “Ocean”) are presented in the paper. Based on the conclusions derived from these two extreme cases a set of more moderate and realistic scenarios (named “Conservation”) is proposed and their consequences on the global water balance are evaluated.

Keywords 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. Available choices are difficult. The call is out for all water professionals, policy makers, scientists and academics to enhance their collaboration and, together with the general public, take an active role in addressing the current and worsening fresh water crisis. 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. Methodologically, all the assessment studies are estimating quantitative characteristics of renewable water resources using observed river runoff data. Quantitative characteristics 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. Combination of these factors determines the volume and the character of water use, its dynamics and future tendencies (Gleick, 1993, 1998, 2000; Shiklomanov, 2000; IHP, 2000 and Cosgrove and Rijsberman, 2000). However, in the traditional assessment studies, 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.

System dynamics model for the assessment of world water balance
WorldWater model has been developed by Simonovic (1999, 2000, 2001a,b) using a system dynamics approach and on the basis of the World3 model (Forrester, 1973;
Meadows et al., 1974). The graphical presentation of causal relationships included in the *WorldWater* model is shown in Figure 1. The total water stock in the model includes the precipitation, ocean resources and non-renewable groundwater resources. The model also takes into account water recycling as a portion of water use (not visible directly in Figure 1). Water use 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 (Lundqvist, 1998). Assumptions used in the development of *WorldWater* model are: (a) water is a partially renewable resource; (b) water is limiting the growth of population, food production and industry; (c) water can be polluted; (d) water is a finite resource; (e) oceans are an important source of freshwater through desalination; and (f) pollution consequences of desalination are not part of the model.

One of the most important conceptual assumptions in the *WorldWater* is a 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 km³/year (Gleick, 1993; Shiklomanov, 2000)

![Figure 1](https://iwaponline.com/wst/article-pdf/45/8/53/425700/53.pdf)

*Figure 1* *WorldWater* model causal diagram (after Simonovic, 2001a,b)
and then reduced by 67% to account for variability of surface runoff. When the demand exceeds the available renewable surface water resources, up to 8.4 km$^3$/year in addition 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 is 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 resources, desalination of seawater is considered. 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 litre 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 possible reduction of the cost down to $0.55 per m$^3$ without the consideration of serious pollution being caused by desalination processes.

**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 model that captures the world development (Simonovic, 2001a,b). 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 (2000), Gleick (1998, 2000) and IHP (2000).

**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 of 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.

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 (Simonovic, 1999, 2000, 2001a,b). Calibration is performed using the period between 1900 and 1995. Data for a standard run of World3 are 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 interest, the standard run assumptions were perfectly acceptable. The 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).

**World water dynamics**

The initial runs of the **WorldWater** use a so-called “stable run” of World3 from *Beyond the Limits* (Meadows *et al.*, 1992) as an illustration of a possible path towards a sustainable world. In this World3 scenario population and industrial growth are moderated and technologies are developed to conserve resources, protect agricultural land, increase land yield, and reduce pollution. As a result, model simulations show that population levels off at just under 8 billion by 2060 and lives at the desired standard of living for the rest of the time (line 4 in Figure 2a). Pollution peaks and falls before it causes irreversible damage (line 5 in Figure 2a). Non-renewable 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. Note that water is not included in the World3 model.

WorldWater simulation that corresponds to the “stable run” of World3 is named “Chaos scenario”. It reveals a very different picture of the world (Figure 2b). 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 2b) and impact on population growth (line 4 in Figure 2b) that starts to decline in 2020. However, this collapse is reversible. With better handling of persistent pollution, water pollution is reduced and the demand for clean water for dilution and transport of wastewater goes down allowing more water for food production and use by population. In this scenario equilibrium is not reached within the simulation period.

WorldWater simulations are clearly demonstrating the strong feedback relation between water availability and different aspects of world development. Results of numerous simulations are contradictory to the assumption made by most of the global modelers that water is

![Figure 2](https://iwaponline.com/wst/article-pdf/45/8/53/425700/53.pdf)

**Figure 2** State of the world – “stable run” results of World3 (a) and WorldWater (b) models (after Simonovic, 2001a,b)
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.

WorldWater provides detailed insight into the dynamics of water use over the simulation horizon (Simonovic, 2000, 2001a,b). Figure 3 shows predicted water use patterns for one set of data from Simonovic (2001a,b). Two major observations can be made from this simulation. First, the use of clean water for dilution and transport of wastewater, if not dealt with 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 six times. Therefore the main conclusion of Simonovic (2001a,b) is that water pollution is the most important future water issue on the global scale. Second, water use by different sectors is demonstrating quite different dynamics than predicted by classical forecasting tools and other water-models. Inherent linkages between water quantity and quality sectors with food, industry, persistent pollution, technology, and non-renewable resources sectors of the model create shoot and collapse behavior in water use dynamics.

For the simulation run shown in Figure 3, water use is increasing in all sectors by the year 2015. Use of water for agriculture stops growing after 2015 but afterwards remains at approximately the 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 is on the rise again (line 3 in Figure 3). Industrial water use is showing the very same behavior (line 2 in Figure 3). Reservoir losses rise with 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 slowing down of the food production and the population growth, starts to decrease. Since, this use of water is so important, let me review again the data and the assumptions made in modeling this water use. IHP (2000) estimates 1995 wastewater disposal in the environment to be in the amount of 1,402 km³/year. The assumption of the WorldWater model is that this waste mobilizes a considerable amount of clean water resources for dilution and transport. Also, an assumption is made that polluted

![Figure 3](https://iwaponline.com/wst/article-pdf/45/8/53/425700/53.pdf)

**Figure 3** Use of water – simulation results of WorldWater (after Simonovic, 2001a,b)
water cannot be used for other purposes. Both of these assumptions can be argued about. The first argument is that more and more wastewater is being treated before being disposed into the environment (Gleick, 2000). The second argument is that industrial and agricultural water needs may be 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 km³/year of wastewater discharge in 1995 (representing only 50% of the total 1995 estimate of 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 clean water needs for dilution of waste, in the ratio of 9:1, is then applied in the simulation. IHP (2000) estimates this need to be between 8 and 10:1. A 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.

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 Table 1 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 a pretty 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 according to Shiklomanov and IHP (2000) is going to reach 1,170 km³/year in 2025; 900 km³/year according to Cosgrove and Rijbersman (2000); and only 520 km³/year according to WorldWater. The main reason for this difference is that WorldWater is simulating the future water use of industry from the dynamic behavior of the industrial sector. On the other side, predictions of other models are based on the static future predictions of sector performance for a particular year. These predictions are demonstrating considerable variance as a function of: (a) factors used in making predictions; and (b) the historical period of data used for predicting the future.

**Issues for the 21st Century**

WorldWater model is used in this paper to provide meaningful insight into the possible options for resolving global water balance problems identified in the research conducted earlier (Simonovic, 1999, 2000 and 2001a,b). Four water-driven scenarios are developed in order to come up with the possible solution for the looming world water crisis. The major global water problem that will be facing the world population in the 21st Century is the problem of water pollution that is closely linked to population growth, food production and persistent pollution of the environment.

### Table 1 Comparison of standard projections with results of WorldWater for year 2025 (km³/year)

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<tr>
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<tr>
<td>Industry</td>
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<td>Reservoir</td>
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<td>200</td>
<td>276</td>
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<tr>
<td>Total withdrawal</td>
<td>5,235</td>
<td>4,300</td>
<td>5,073</td>
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Chaos scenario
Continuation of “business as usual” in dealing with water could have major consequences on the future global development of the world. As shown in Figure 2b the impact on population could be disastrous. Within the next hundred years population growth will not continue, but may be reduced by half (around 4 billion people by year 2100) from the equilibrium (around 8 billion people as shown in Figure 2a). This might happen if the water pollution continues with the same intensity and dilution is used as the main process for eliminating negative impacts of the pollution. The main shock occurs around the year 2040 when the need for clean water to be used to dilute the polluted wastewater reaches its peak. This lack of water triggers the downward spiral and population starts to decline to approximately 3 billion by the year 2060. Dramatic reduction in the population, introduction of new technologies for reduction of persistent pollution, and improved wastewater treatment start to provide conditions for recovery allowing population increase to approximately 4 billion by the end of the 21st Century.

This scenario is highly unlikely. The world’s concern with water is already growing and population pressure on the Governments will produce policies that should prevent the chaos scenario from really occurring. What are the optional paths that we may explore to change the future described by the chaos scenario? This research explored two logical options: (a) use of desalination of world oceans as an unlimited source of clean water for dilution; and (b) a more moderate conservation scenario that will combine a rational increase in desalination, water reuse and an increase in wastewater treatment through the introduction of new treatment technologies and change of industrial processes. Three new water scenarios are developed for WorldWater simulations.

Ocean scenario
In this scenario the current limitation in the desalination capacity of 4.82 km$^3$/year has been removed. Unlimited ocean water is assumed to be available for desalination and cost has been kept at the same level of $1 per m$^3$. In this way the water quantity limits are replaced with their economic surrogate – capital needs for water production. Pollution from desalination is not taken into consideration and that limits the reality of this scenario. The main expectation of the author of this paper was that this scenario would show diversion of world economic capital into the water production (desalination). Therefore, impacts were expected to appear in the other sectors of the world model that need steady flow of economic capital.

Simulation results shown in Figure 4 present an unexpected behavior. Needs for clean water for dilution are met 100% through the use of desalination. Maximum desalination capacity needed around year 2040 is over 9,000 km$^3$/year. This, almost unimaginable figure however, did not affect the total world capital in a major way. World economic capital is at the level that, on the global scale, even an expensive solution like desalination can be implemented to the maximum capacity. Population of the world reaches equilibrium at about 8 billion people by the year 2060 and lives at the desired standard of living. Through the investment in desalination the world avoids an uncontrollable collapse and maintains its standard of living.

It is highly unlikely that the ocean scenario will occur in the future. Water problems are at the regional level and the expectation that the whole world will accept sharing capital for solving world water problems is unrealistic. Both water problems and their solutions are at the regional level and therefore two more rational scenarios were developed for comparative analysis.
Conservation-1 scenario

Solutions for the world water problems are needed at the regional level. Conservation-1 scenario is developed to integrate three policy options that may be applied at the regional level. First, the increase in desalination capacity is introduced from the current 4.82 km$^3$/year up to around 10 km$^3$/year by the end of the Century. Second, water reuse has been increased gradually from 20% now, up to 50% by the end of the Century. The third policy option is that a part of the conservation-1 scenario is an increase in wastewater treatment level. This policy can be implemented through either application of innovative treatment technologies or simply through the increase in the wastewater treatment level. Either option should result in the reduction of the dilution ratio. In this scenario a gradual decrease has been introduced from the current ratio of 9:1 to 5:1 by the end of the Century.

Simulation results of the conservation-1 scenario are presented in Figure 5. From the “state of the world” results (Figure 5a) it can be seen that conservation measures introduced
are not sufficient for protecting the world from pollution shock. Population decline occurs again around the year 2040 leading, after the recovery, to a stable population of about 4.2 billion people in year 2100. The shock is still strong and disturbance propagates through the system. Food production is affected by the change in population. Water for dilution of wastewater is again dominating the water use results (Figure 5b) leading to the reduction in municipal and industrial water supply.

Conservation-1 is definitely a more realistic development policy scenario that can be implemented in the regional context to solve the global world water problems. However, this scenario did not produce satisfactory results. Drastic shock and impact on the world population has not been successfully reduced using these measures. More aggressive conservation is considered in the conservation-2 scenario in order to find the policy that can minimize negative impacts of water quality on the world development.

**Conservation-2 scenario**

In this scenario the same reuse and desalination policy options are maintained. Increase in wastewater treatment is done in a much more aggressive way. An increase in the level of
treatment around year 2040 when the pollution peaks was carried out more aggressively. The move from the current ratio of 9:1 to 5:1 is done according to a typical s-shaped decline. This policy reflects a better understanding of the impacts of increased levels of wastewater treatment as well as more responsive timing for implementation of this policy measure.

Conservation-2 simulation results, shown in Figure 6, are demonstrating a better response of the world to the policy options proposed under this scenario. Impact of water pollution has not been completely absorbed but the magnitude of the shock is reduced. Population shock again occurs around the year 2040, but after the recovery, population stabilizes around 6 billion (Figure 6a). Water use results (Figure 6b) demonstrate minor impacts on the industrial and municipal water use.

**Conclusions**

*WorldWater* model implementation documented in this paper reinforces the main conclusions of the earlier research that water is one of the limiting factors in global modeling of...
future world development, and that the pollution of water is the most important global scale issue for the 21st Century. Additional important conclusions from the numerous simulations based on the four water-related scenarios are as follow.

1. If not dealt with, the pollution of the world’s water resources will have a dramatic impact on the world population in the 21st Century.

2. Alternative policy options can be used to address the main global water problem. Desalination can be used as a single policy solution for providing clean water supply for dilution. The world economy is strong enough to absorb the cost of additional desalination capacity without difficulties. However, it needs to be stressed that this conclusion is valid only on the global scale. It is the opinion of the author, that the implementation of such a unified world policy will be highly unlikely. Also it needs to be repeated that the impact of desalination on persistent pollution of the environment is not included in the model.

3. A more realistic solution to world water problems can be found on the regional scale. Integration of desalination, water reuse and wastewater treatment into more rational policy options demonstrates that the main global water problem can be addressed at the regional scale and different combinations of measures will lead to global solutions.

4. Action is required now. A global water crisis is already in progress and devastating consequences will be very hard to stop later. Implementation of mitigation policies at the later date would require solutions on the global level. Regional capital and capacity may not be sufficient for complete elimination of water quality related problems and populations may suffer. The gap between rich and poor countries may increase and populations in less developed regions could pay a very heavy price.

5. *WorldWater* has demonstrated that it is capable of increasing our understanding of water problems and our ability to reach sustainable solutions for them.

It is important to reiterate that meanings of exact numbers of model predictions are quite different in the context of global modeling. Every prediction needs to be evaluated with scrutiny taking into consideration all model assumptions and specific characteristics of the scenario under consideration. It is prudent to indicate at this stage that the value of *WorldWater* is not in estimating the total amount of water needed for dilution in the year 2047, but rather in understanding how this demand relates to the population growth, food production and future industrial development. Also, this model provides a very valuable insight into the dynamic change in dilution water needs with time as a function of numerous assumptions used to form a possible world development scenario.

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**References**


